

# ICSS-2026



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INTERNATIONAL  
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**SOIL  
SCIENCE**



## SOIL RESILIENCE FOR SUSTAINABLE DEVELOPMENT



Rawalakot, Azad  
Jammu & Kashmir



### Abstract Book

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## Foreword

Pakistan is among the countries most vulnerable to climate change, with agriculture forming the backbone of its economy. In this context, soil resilience is fundamental to ensuring sustainable development, food security, and environmental stability. However, increasing population pressure, rapid urbanization, and industrialization are continuously reducing productive land resources.

The soils of Pakistan are largely arid to semi-arid, characterized by low organic matter and limited water availability. More than 90% of soils contain less than 1% organic carbon, making them highly prone to degradation. Climate change and unsustainable management practices further intensify these challenges, threatening soil health, agricultural productivity, and ecosystem services.

Soils play a critical role in carbon sequestration, water regulation, and nutrient cycling, and are therefore central to climate change mitigation and adaptation strategies. Enhancing soil resilience through climate-smart and sustainable management practices is essential for maintaining long-term productivity and environmental quality.

The theme of the 21<sup>st</sup> International Congress of Soil Science (ICSS-2026), “*Soil Resilience for Sustainable Development*,” highlights the urgent need to address these challenges through scientific innovation, knowledge exchange, and collaborative efforts. The congress brings together researchers, policymakers, industry stakeholders, and farming communities to share insights and develop sustainable solutions.

The Congress has received an encouraging response from both national and international participants, with a wide range of high-quality contributions to be presented in plenary, technical, and poster sessions.

I sincerely acknowledge the efforts of the Technical Committee, the Executive Council of the Soil Science Society of Pakistan, and all contributors for their valuable support in organizing this event and compiling the abstract book.

It is hoped that the ICSS-2026 will serve as a significant platform for advancing soil science and promoting sustainable soil management for a resilient and food-secure future.

**Muhammad Ashraf**

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## Talks of Plenary Session

### Potential Fertilizer Zinc and Boron Requirement in Pakistan is Multiple Times Greater than Their Current Use Level

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Soil zinc (Zn) and boron (B) deficiencies are known to constrain crop productivity in ~22 million ha predominantly alkaline-calcareous soils of Pakistan since 1970s. Subsequent extensive field research, across the country, has demonstrated *highly cost-effective yield increases with Zn and B fertilization* in all major crops and cropping systems. Crop deficiencies can be corrected effectively by soil application 2–5 kg Zn ha<sup>-1</sup> and 0.75–1.0 kg B ha<sup>-1</sup> as well as by foliar sprays of 0.1% solution of Zn and B. Soil application of both micronutrients leaves beneficial residual effect. While writing the book “*Micronutrient Fertilizer Use in Pakistan: Historical Perspective and 4R Nutrient Stewardship*”<sup>2</sup>, the authors suspected inadequate fertilization to be a major cause of continued prevalence of wide scale Zn and B deficiencies in all susceptible crops. Major recipients of Zn and B fertilizer include wheat, cotton, rice, vegetables, and fruits. To arrive at the strategies for promoting their fertilizer use, we estimated their current use level and potential requirement in the country. According to the 2024 import data analysis, our crude estimates revealed that current fertilizer use in the country is around 2,287 t Zn yr<sup>-1</sup> and 388 t B yr<sup>-1</sup>. Based on the *recommended fertilizer rate approach*, and accounting for residual effect and cropped areas requiring their fertilization, potential annual requirement in the country is 12,537 t Zn yr<sup>-1</sup> and 2,396 t B yr<sup>-1</sup>. Thus, current use level is only ~18% Zn and ~16% B of their potential agronomic requirement, *confirming under-application despite strong economic returns*. Fragmented micronutrient fertilizer supply structure, combined with limited farmer awareness and weak integration into balanced fertilization practices, contributes to their low use adoption. Bridging the substantial gap between current use and agronomic requirement offers evident opportunities to improve crop yields, farmer profitability, soil health, and national food security. Recent encouraging fertilizer industry initiatives of launching micronutrient-embedded fertilizers products, such as *zinc sulfate-coated urea* and *boronated DAP*, are expected to enhance Zn and B use adoption and improve their crop use efficiency. Strategies to enhance farmer awareness, improve Zn and B fertilizer availability, and their integration into major nutrient management programs are discussed.

## Research Directions in Addressing Climate Change in Pakistan

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Pakistan is among the world's most vulnerable countries to climate change. Climate change is rapidly intensifying floods, droughts, heat waves, glacial melt, salinization, desertification, and land degradation, placing considerable pressure on soil systems, food security, water resources, and rural livelihoods. In this context, soil resilience emerges as a crucial pillar of sustainable development and climate change adaptation. This invited lecture presents a focused synthesis of research directions for addressing climate change in Pakistan, through the lens of soil resilience and sustainability. The presentation will outline priority research areas, including climate-smart soil management, carbon sequestration in agricultural soils, soil organic matter restoration, erosion control, sustainable nutrient management, rehabilitation of saline and sodic soils, and regenerative agriculture in arid and semi-arid conditions. The focus will be on challenges specific to Pakistan, such as the hydrology of the Indus River basin, irrigated agriculture, waterlogging and soil salinization, glacial river systems, arid-pluvial zones, and fragile mountain and coastal ecosystems. Key cross-cutting research areas include integrated soil-water-climate modeling, digital soil mapping, remote sensing, nature-based solutions and climate-resilient cropping systems, as well as community adaptation and indigenous knowledge systems. The role of policy-related research, institutional frameworks, and science-policy-society interfaces will be emphasized as critical for translating scientific knowledge into concrete, large-scale action. This summary proposes a nationally relevant research roadmap that positions soil resilience as a strategic foundation for climate change adaptation, mitigation, food security, and sustainable development in Pakistan. By aligning scientific innovation with local realities and development priorities, this presentation highlights how resilient soils can be a transformative solution to the challenges posed by climate change in regions weakened by this phenomenon, such as Pakistan.

### Bacterial Allelopathy for Resilient Soils and Sustainable Farming Systems

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Soil resilience is critical for sustainable agriculture because it ensures soil sustainability by enabling productive capacity, biological activity, and ecosystem functioning amid the growing biotic and environmental stressors. One of the main biological limitations to crop production is the weed population problem leading to the loss in yield due to resource competition, particularly access to moisture, nutrients, light, and space. Traditional weed elimination techniques including the application of multiple herbicide doses and deep tillage provided only short-term solutions while

causing soil depletion, biodiversity loss, environmental contamination, and herbicide resistance in weed populations. In this regard, the bacterial allelopathy appears to be a promising and environmentally friendly alternative for weed control as well as the promotion of soil properties. In particular, certain bacteria possess bioactive compounds allowing the inhibition of weed growth and reproduction. In addition, there are some types of bacteria that have characteristics for plant growth stimulation by facilitating nutrient solubility in the soil, biosynthesis of phytohormones, biological nitrogen fixation, and biosynthesis of different enzymes involved in various biochemical reactions. Hence, the use of the concept of bacterial allelopathy, as well as its advantages, can be regarded as an efficient technique that is used to boost soil resilience and develop sustainable agricultural practices. There are many opportunities offered by microbial technologies that help optimize the use of natural resources, ensure the diversity of soil microbiome, and develop environmentally friendly and sustainable practices despite climate changes. The purpose of this presentation is to discuss new approaches to utilizing bacterial allelopathy in weed control and soil resilience.

## **Drylands and Desertification: “Sustainable Approaches to Land and Water Management in Mediterranean Drylands”**

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Drylands across the Mediterranean basin and North Africa are increasingly exposed to desertification processes driven by climate change, unsustainable land and water use, demographic pressures, and socio-economic fragilities. Addressing these challenges requires moving beyond sectoral interventions toward integrated approaches capable of capturing the complexity of coupled social–ecological systems. The project *Sustainable Approaches to Land and Water Management in Mediterranean Drylands (SALAM-MED)* provides new insights into how participatory innovation, nature-based solutions, and locally adapted technologies can enhance resilience and restore ecosystem functionality in vulnerable dryland environments. The project adopted a Living Lab framework implemented across six case-study regions in Southern Europe and Northern Africa, where scientists, farmers, enterprises, civil society organizations, and policymakers jointly co-design and test sustainable land and water management strategies. This approach enables the integration of scientific knowledge with local practices, fostering social learning processes and reducing barriers to innovation uptake while ensuring that ecological effectiveness is evaluated alongside socio-economic impacts. Key insights emerge from comparative experimentation across diverse dryland systems, including agro-silvo-pastoral landscapes, olive orchards, Mediterranean forests, argan agroforestry systems, and hyper-arid desert environments. Results highlight the importance of improving soil fertility and water retention as foundational drivers of resilience. Nature-based interventions such as cover cropping, deficit irrigation aligned with crop phenology, Managed Aquifer Recharge, wadi water harvesting, and Subsurface Water Retention Technology demonstrate significant potential to increase water-use efficiency, reduce soil erosion, enhance plant establishment under arid conditions, and restore degraded ecosystems at relatively low cost. Cross-cutting innovations based on microbial biotechnologies, precision agriculture, and digital phenotyping platforms further support adaptive management by improving plant drought tolerance, monitoring ecosystem responses, and optimizing resource use. Evidence collected across Living Labs shows that sustainable land restoration can simultaneously deliver environmental benefits, including improved hydrology, biodiversity conservation, and climate resilience, while generating local economic opportunities and strengthening

social cohesion, particularly through the engagement of youth and women. The SALAM-MED experience challenges simplified narratives of desertification mitigation, emphasizing that effective restoration requires context-specific solutions rather than uniform greening strategies. The project demonstrates that coupling soil restoration with livelihood opportunities and stakeholder capacity development is essential for scaling sustainable practices. These insights contribute to advancing integrated responses aligned with the Sustainable Development Goals and reinforce the need for coordinated action across climate, biodiversity, and land degradation agendas within the framework of the Rio Conventions.

## Soil Fertility and Plant Nutrition

### Enhancing Nitrogen Use Efficiency in Forage and Potato Production Systems in Boreal Climate

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Nitrogen (N) fertilizer application plays a crucial role in crop growth, development and yield. However, excessive N fertilizer application leads to deterioration of soil health, environmental pollution and N losses (leaching, volatilization, runoff and gaseous losses) contributing to global warming. Specifically, crops with shallow root systems cultivated in short growing seasons increase the risk of nutrient losses and reduce nitrogen use efficiency (NUE). Integrating cover crops (CCs) in different cropping systems or in crop rotation emerges as a new phenomenon and the pragmatic and environment friendly approach to combat climate change. Enhanced Efficiency Fertilizers (EEFs) or controlled-release fertilizers like polymer-coated urea (PCU) or N stabilizers (urease and nitrification inhibitors or dual inhibitors) are known to synchronize N release with crop growth stages, enhance N uptake, increase yield, reduce reactive N losses, greenhouse gas (GHG) emissions and enhance NUE in different cropping systems. Integrating cover crops (CCs) in different cropping systems emerges as a promising, pragmatic and environment friendly approach to combat climate change and mitigate N losses. CCs are grown to cover soil during fallow period, reduce soil erosion, improve the soil quality and health by enhancing the nutrient cycling and N fixation. CCs seeding after harvesting primary crops are increasingly promoted as a strategy to capture residual soil nitrogen (NO<sub>3</sub><sup>-</sup>) and reduce N losses during the non-growing season, particularly in boreal regions. This talk will focus on maximizing NUE in Potato production system in podzolic soils using the combination of urea, and urea-PurYield blends. Additionally, results on N optimization in Oat-Pea mixture and effect of integrating CC mixture in Oat-Pea mixture on GHG emission, weed suppression and other N losses in boreal climate will be presented.

### Pressmud Application Restores Soil Health and Enhances Wheat Productivity in Wastewater-Irrigated Soils

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Use of wastewater for crop irrigation is a common practice in the country. However, its continuous application can adversely affect soil microbial activity and reduce crop

productivity. Therefore, effective management strategies are essential to restore soil health and sustain crop yields in wastewater-irrigated soils. Pressmud, a byproduct of the sugar industry produced in large quantities in Pakistan, can be used as an organic amendment to improve soil health and crop productivity. A series of greenhouse and field studies were conducted to evaluate the effectiveness of pressmud in enhancing wheat productivity on problematic soils. Characterization revealed that pressmud is rich in organic matter and essential nutrients. In soils irrigated with wastewater, pressmud application reduced dye residues in plant tissues, increased viable microbial counts, and enhanced nitrogen and phosphorus uptake, ultimately leading to higher crop yields. Growth-stage-specific irrigation studies further demonstrated that pressmud decreased water-extractable dye residues in soil at crop maturity and improved plant biomass. The application of wastewater at sowing exhibited more drastic effect on crop yield. Comparative evaluation with other organic amendments under arsenic stress showed the superior performance of pressmud in enhancing wheat yield and soil available phosphorus. Long-term field experiments in salt-affected soils confirmed substantial improvements in plant biomass, tiller number, grain yield, soil organic carbon, available phosphorus and microbial populations following continuous pressmud application. Overall, pressmud proved to be an effective alternative to conventional phosphate fertilizers. Its application at sowing is recommended to ensure sustainable wheat production and restoration of soil health in wastewater-irrigated soils.

## Mitigating Abiotic Stress in Crops of Pakistan: The Imperative of Potassium Fertilization for Climate-Smart Agriculture

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Climate change projections for Pakistan indicate a significant increase in annual mean temperature and inconsistent rainfall patterns by 2050. According to international reports Pakistan is the 14th most water-scarce nation globally. These changes have already correlated with yield declines in major staples such as wheat, maize, and sugarcane. While nitrogen (N) and phosphorus (P) management often receives primary focus, potassium (K) nutrition remains critically overlooked. Potassium balance sheets indicate a net negative balance in intensive cropping systems, yet current K application rates in major cropping zones remain critically below recommended doses. Emerging technologies, such as nano-coated DAP fertilizers, demonstrate a slower release pattern of extractable K in both loam and clay loam soils, resulting in enhanced grain yield and K uptake compared to conventional fertilizers. To bridge the gap between soil K mining and crop demand, a dual-pronged strategy is required: (1) Behavioral extension services encouraging incremental K application among cost-sensitive farmers, and (2) Investment in advanced fertilizer blends (nano-fertilizers and multi-nutrient complexes) to improve uptake efficiency. Policymakers must recognize K as a key abiotic stress mitigator and subsidize its inclusion in national soil health programs.

## Soil Carbon and Nitrogen Stocks under contrasting Land-Use Systems of a Western Himalayan Valley

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Land use systems influence soil organic carbon (SOC) and nitrogen (N), which are indispensable for soil health and food security. Different types of land use have different capacities to recycle SOC and TN, which is necessary to understand for sustainable ecosystem productivity. In this context, surface (0–15 cm) and sub-surface (15–30 cm) soils were sampled from five different land use types (e.g., cropland, paddy, apple orchard, grassland, and forest) of Leepa Valley, District Hattian Bala, Azad Jammu and Kashmir (AJK), to assess SOC and TN stocks and associated soil properties. The results showed that, irrespective of soil depth, both SOC and N varied significantly ( $p < 0.05$ ) across the land-use systems and were highest in soils under forest and lowest in paddy soils. On the other hand, SOC and N contents declined significantly ( $p < 0.05$ ) with increasing soil depth, being highest in surface soils. The mean total SOC and N stocks ranged from 22.12 to 42.36 Mg ha<sup>-1</sup> and 2.04 to 3.68 Mg ha<sup>-1</sup> in surface soils, and 18.06 to 40.89 Mg ha<sup>-1</sup> and 1.95 to 3.54 Mg ha<sup>-1</sup> in sub-surface soils, being highest under forest land use, respectively. The majority of the SOC and N were associated with macro-aggregates (Ma) in the 0–15 cm layer, with micro-aggregates (Mi) in the 15–30 cm layer, while the silt + clay fraction contained the least SOC and N across all land uses and soil depths. In terms of soil properties, bulk density (pb), pH, and electrical conductivity (EC) were directly proportional to soil depth. The soil pH, EC, and pb were higher in sub-surface soil than in surface soils. The results of the present study showed the impact of land use on SOC, TN, and associated soil properties. The findings of the study could be used to restore SOC and TN for sustainable livelihood security in the valley.

## Advances in Foliar Fertilization: Scientific Principles and Field Practices

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Foliar fertilization is a physiologically distinct nutrient delivery pathway that complements soil fertilization and provides strategic advantages under edaphic and climatic constraints. Building upon foundational principles of leaf surface chemistry and plant nutrition, this presentation synthesizes advances in understanding nutrient penetration across the cuticle and subsequent transport within plant tissues. Foliar uptake occurs primarily through diffusion across aqueous domains within the cuticle, with potential contributions from stomatal and trichome-associated pathways. Absorption efficiency is governed by solute properties (molecular size, charge, hygroscopicity), formulation chemistry (pH, surfactants, chelation), droplet retention dynamics, and environmental conditions during drying. Nutrient mobility in the phloem critically determines agronomic effectiveness. Elements such as nitrogen, potassium, and magnesium exhibit greater redistribution capacity than calcium and

boron, which are largely phloem-immobile. Consequently, foliar fertilization is particularly effective for correcting micronutrient deficiencies (e.g., Zn, Fe, Mn, Cu) and for targeted supplementation during critical growth stages or when root uptake is restricted by drought, salinity, calcareous soils, or low soil temperature. Despite its advantages, foliar feeding cannot substitute for soil-applied macronutrients due to limited absorption capacity and phytotoxicity risks at high concentrations. Optimizing concentration, spray timing, droplet size, adjuvant selection, and environmental conditions is essential to maximize nutrient use efficiency. Integrating mechanistic insights with field-based practices enables more precise, efficient, and climate-resilient nutrient management strategies in modern crop production systems.

## The Impact of Soil Resilience on Food Security in Pakistan: A Case Study of Challenges and Opportunities

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Soil resilience—the ability of soil systems to sustain productivity and recover from environmental and anthropogenic stresses—is a critical foundation of food security. In Pakistan, agriculture contributes approximately 19.5% to the national GDP and employs over 42% of the labor force, making soil health central to economic stability and rural livelihoods. However, widespread soil degradation caused by salinity, sodicity, erosion, nutrient depletion, and unsustainable farming practices threatens agricultural productivity. Recent estimates indicate that 30–40% of Pakistan’s arable land is degraded, significantly constraining crop yields and increasing vulnerability to climate change. The objective of this study was to assess the impact of soil resilience on food security in Pakistan by identifying key soil degradation challenges and evaluating opportunities for improving soil health and agricultural productivity through sustainable management practices. This study adopts a mixed-methods case study approach, integrating secondary data analysis, field observations, and stakeholder consultations. Data on soil health indicators (erosion, salinity, sodicity, and organic matter), crop yields, and food security metrics were collected from 2020 to 2025 across major agricultural regions of Pakistan. Relevant national and international reports were analyzed to establish linkages between soil condition, agricultural productivity, and food security outcomes. The results indicate that soil erosion affects approximately 11.2 million hectares, while salinity and sodicity impact nearly 6.2 million hectares of cultivated land. Crop yields on degraded soils are 20–50% lower than those on healthy soils, directly undermining food availability and farmer incomes. Projections suggest that yields of major staple crops—wheat, rice, and cotton—may decline by 10–20% by 2050 if soil degradation continues unchecked. Conversely, the adoption of conservation agriculture and climate-smart practices has the potential to improve soil health by 20–30% and increase crop yields by 15–25%. The study concludes that soil resilience is a decisive factor in ensuring food security in Pakistan. Persistent soil degradation poses a serious threat to agricultural sustainability, while investments in soil restoration and sustainable land management offer substantial gains in productivity, resilience, and livelihoods.

## Climate-Smart Innovations in Vulnerable Agro-Ecosystems through Integrated Nutrient Management

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Pakistan is badly affected by climate change and ranked among 10 most affected countries globally where shifting climatic pattern pose significant threat to agricultural sustainability. Rising temperatures, irregular precipitation patterns, extreme floods and the increasing frequency of drought are intensifying the biotic and abiotic stresses on cropping systems, leading to yield instability and progressive soil degradation. These challenges are further compounded by widespread soil fertility constraints, including critical deficiencies of nitrogen (N), phosphorus (P), potassium (K), and essential micronutrients. A series of field and laboratory trials conducted at the Soil Chemistry Section revealed good results through integrated nutrient management and climate-resilient soil amendments to battle these constraints. Many interventions such as balanced fertilization, combined application of organic and inorganic nutrient sources, crop residue incorporation, biochar application, mulching, green manuring, regenerative soil management practices, and the use of spent activated carbon significantly improved soil physicochemical properties, nutrient availability, carbon sequestration, and crop productivity under normal and stressed conditions. Additionally, climate-smart management practices including zero tillage, direct-seeded rice, mulching, and improved irrigation management resulted in enhanced water-use efficiency and also contributed to reduced greenhouse gas emissions. Comparative climatic analysis indicated a decline in average rainfall from 454 mm (1972-1981) to 443 mm (2010-2020), reflecting a reduction of approximately 11 mm. Similarly, an increase in mean temperature from 29.9°C to 31.7°C, representing a rise of 1.8°C during this decade. These findings highlighted that integrated soil fertility and plant nutrition management offers a scientifically sound and economically viable strategy for strengthening climate resilience, ensuring food security, and promoting sustainable agricultural productivity in vulnerable agro-ecosystems.

## Response of NPK and Zinc Fertilizers Combinations on Growth, Yield and Nutrient Use Efficiency of upcoming Wheat Genotypes

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Wheat (*Triticum aestivum*) is the most important staple food crop of Pakistan, providing a major share of daily caloric intake to the population. Integrated nutrient management improves nutrient uptake

efficiency, reduces nutrient losses, maintains soil fertility, and ensures sustainable wheat production. A field experiment was conducted at the Soil Fertility Research Institute, Agriculture Research Centre Tando Jam (25°41' N, 68°54' E) during the Rabi season of 2023–24 on integrated nutrient management and fertilizer regimes in a randomized complete block design (RCBD) with five treatments: T1: 110-70-50-4, T2: 120-80-60-5, T3: 130-85-70-7, T4: 140-90-85-9, T5: 150-95-90-11 (N, P, K, Zn kg ha<sup>-1</sup>) respectively, with three replications, on six wheat genotypes (SR-6026, E-107, HT-50, HT-25, and HP-1) for recommendation of fertilizer dose. The experiment results indicated that in both years' different fertilizer regimes significantly increased plant height, thousand-grain weight, seeds per spike, number of spikes, and grain yield. Results also showed that the highest grain yield among the varieties, approximately 37.5% grain yield improvement (40–55 mounds/acre), was observed at T4, followed by T3 and T5, respectively. We also observed that N, P, K, and Zn content in soil increased as the treatment doses increased. The enhanced nutrient balance, especially nitrogen, potassium, and zinc, markedly improved crop vigor, spike density, and grain filling efficiency. Consequently, the (140-90-85-9 kg ha<sup>-1</sup>) fertilization strategy is both agronomical efficient and economically sustainable for modern wheat cultivation under semi-arid climate conditions, which suits our environment.

## Organic Vermicompost as a Sustainable Alternative to Chemical Fertilizers for Enhancing Productivity and Oil Quality of Mustard

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Nutrient management is one of the most important factors that affect the quality and production of mustard, which is a crucial oilseed crop with significant global and economic importance. Application of all the needed chemical fertilizers can have deleterious effects on soil fertility; it is necessary to use organic fertilizer sources like vermicompost, which contains macro- and micronutrients useful for plant growth. A field experiment was conducted at the Soil Fertility Research Institute, Agriculture Research Centre Tando Jam (25°41' N, 68°54' E) during the Rabi season of 2024 on different forms of vermicompost to reduce the consumption of chemical fertilizers in a randomized complete block design (RCBD) with five treatments: V1 (control), V2 (farmyard manure), V3 (poultry manure), V4 (maize straw manure), and V5 (NPK), respectively, with three replications. The results indicated that the application of organic vermicompost had a positive response on the physiological and morphological characteristics of mustard plants compared with the control and chemical fertilizers. The results also showed that the highest plant height (137.52 cm), number of pods per plant (195), number of seeds per pod (11.12), seed index (4.32), seed production (1485.10 kg ha<sup>-1</sup>), and oil content (30.88%) were observed at V2. The lowest crop performance was observed at the control, followed by V5, where only chemical fertilizers were applied. It is concluded that plant height, number of seeds per pod, number of pods per plant, oil content, and yield significantly increased with the application of organic fertilizers compared with chemical fertilizers. It is recommended that the application of 2.5 t ha<sup>-1</sup> vermicompost reduces chemical loss and also increases mustard yield and oil content.

## Potential Role of Copper Sulphate Foliar Application on Wheat Yield, Quality, and Nutrient Content

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Copper (Cu) deficiency limits wheat productivity in calcareous, alkaline soils of arid and semi-arid regions. Despite its critical role in physiological and reproductive processes, Cu management through foliar nutrition remains under-explored. A field trial was conducted during the Rabi season 2024–25 at the Soil Fertility Research Institute, Tandojam, to optimize foliar Cu-sulphate concentrations and evaluate effects on wheat growth, yield, and nutrient dynamics. The experiment used a randomized complete block design (RCBD) with three replications and four treatments: recommended NPK (120–90–60 kg ha<sup>-1</sup>, control) and NPK combined with foliar Cu-sulphate at 0.1%, 0.25%, and 0.5%. Wheat variety ‘Imdad-2005’ was sown in November. Results showed that foliar Cu improved growth and yield compared to control. The 0.25% Cu treatment with NPK produced the tallest plants (98 cm), longest spikes (13 cm), highest grains per spike (81), and maximum grain yield (6786 kg ha<sup>-1</sup>), as well as the highest biological yield (14251 kg ha<sup>-1</sup>). The 0.5% Cu treatment caused a decline in grains per spike, 1000-grain weight, and grain yield, indicating Cu-induced phyto-toxicity. Soil pH, EC, and organic matter remained stable across treatments. Foliar application of 0.25% Cu with NPK significantly improves wheat productivity in alkaline, nutrient-deficient soils, emphasizing the importance of balanced micronutrient management.

## Soil-Specific Optimization of Nitrogen and Sulphur Fertilization for Enhanced Maize Growth and Nutrient Use Efficiency

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Nitrogen (N) and Sulphur (S) are essential macronutrients that play a critical role in optimizing maize growth, productivity, and nutritional quality. A controlled pot experiment was conducted at the University of Minnesota, USA, to assess the effects of varying N and S application rates on maize growth and nutrient uptake in two contrasting soils, Becker and Rosemount. The experiment was arranged in a completely randomized design (CRD) with a factorial arrangement consisting of two N levels (100 and 150 kg ha<sup>-1</sup>) and five S levels (0, 20, 40, 80, and 160 kg ha<sup>-1</sup>), resulting in ten treatment

combinations applied separately to each soil type. The results demonstrated that nitrogen rate, Sulphur rate, and soil type significantly affected plant height, fresh and dry biomass production, tissue sulphur concentration, and both N and S uptake. Nitrogen application exerted a non-significant effect on sulphate and mineral nitrogen concentrations, whereas sulphur application did not significantly influence mineral N content or tissue N concentration. Application of 150 kg N ha<sup>-1</sup> significantly increased plant height (125.3 cm), fresh biomass (109.3 g plant<sup>-1</sup>), dry biomass (17.6 g plant<sup>-1</sup>), sulphate concentration (10.5 mg kg<sup>-1</sup>), mineral N concentration (9.19 mg kg<sup>-1</sup>), tissue N concentration (0.17%), and total N and S uptake (186.7 and 29.7 mg pot<sup>-1</sup>, respectively) compared to 100 kg N ha<sup>-1</sup>. Across treatments, maize biomass production, nutrient uptake, and soil nutrient availability were significantly higher in Becker soil than in Rosemount soil. Maximum biomass yield in Becker soil was achieved with 150 kg N ha<sup>-1</sup> combined with 20 kg S ha<sup>-1</sup>, while in Rosemount soil the same N rate combined with 40 kg S ha<sup>-1</sup> produced the highest biomass. Optimal tissue N:S ratios associated with maximum dry matter ranged from 8–12 in Becker soil and 4–6 in Rosemount soil. These findings highlight the importance of soil-specific N and S fertilization strategies to enhance maize productivity, nutrient uptake, and nutrient use efficiency.

## Vermicomposting of Rock Phosphate with Phosphate-Solubilizing Microbes: A Climate Smart Strategy for Improving Soil Health and Crop Yield

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Soil health, crop yield, and the solubility of phosphorus from rock phosphate (RP) can be improved through vermicomposting together with phosphate-solubilizing microbes (PSMs). This approach can be adopted as a cost-effective climate-smart strategy. The current study was conducted to convert RP-mixed degradable organic wastes into phosphorus-rich vermicompost through earthworms and PSMs and to assess its role in potato yield and soil health. Three types of RP-enriched vermicomposts were produced by mixing powdered RP with biodegradable wastes in the presence of earthworms and PSMs through three different methods: vermi-boxes, pits, and piles. The efficiency of each vermicompost was evaluated for potato growth, yield, and nutrient uptake in a pot trial. The most efficient vermicompost identified in the pot trial was further assessed for potato growth parameters and soil health under field conditions. The results showed that, under the pot trial, half fertilization with RP-enriched vermicompost together with half doses of inorganic fertilizers (urea, SSP, and SOP) significantly enhanced post-harvest potato dry shoot biomass (22 g pot<sup>-1</sup>), tuber weight (356 g pot<sup>-1</sup>), plant height (25 cm), and N (308.7 mg pot<sup>-1</sup>) and P uptake (28.07 mg pot<sup>-1</sup>) compared to the control. Similarly, under field conditions, N and P uptake, shoot dry biomass, plant height, and tuber weight were significantly improved when treatments included half doses of both inorganic fertilizers and RP-enriched vermicompost compared with sole RP vermicompost. The study concluded that half doses of RP-enriched vermicompost combined with half doses of inorganic fertilizers have great potential to improve soil health, nutrient uptake, and potato growth under both pot and field conditions. RP-enriched vermicompost can therefore be used as a cost-effective and climate-smart strategy to enhance vegetable production while reducing chemical fertilizer use in alkaline calcareous soils.

## Integrated Soil and Foliar Sulphur Application Enhances Growth, Yield, and Oil Content in Mustard Crop (*Brassica juncea*)

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Sulphur is a vital nutrient for oilseed crops and is directly involved in enzyme activity, chlorophyll formation, and oil synthesis. Continuous cropping and the use of sulphur-free fertilizers have led to widespread sulphur deficiency in soils, resulting in reduced mustard productivity. Therefore, this study was conducted to evaluate the effects of different rates and methods of sulphur application on the growth, yield, and oil content of mustard (*Brassica juncea*). The experiment consisted of eight treatments. Treatment T<sub>1</sub> received the recommended dose of nitrogen, phosphorus, and potassium fertilizers (control, no sulphur). Treatments T<sub>2</sub>, T<sub>3</sub>, and T<sub>4</sub> received soil-applied sulphur at 40, 50, and 60 kg ha<sup>-1</sup>, respectively, along with the recommended NPK dose. Treatments T<sub>5</sub> and T<sub>6</sub> consisted of soil-applied sulphur at 40 and 50 kg ha<sup>-1</sup>, respectively, combined with a 0.5% foliar sulphur spray. Treatments T<sub>7</sub> and T<sub>8</sub> received soil-applied sulphur at 60 kg ha<sup>-1</sup> combined with foliar sulphur sprays at 0.5% and 1%, respectively. Growth parameters (plant height, number of branches per plant, number of pods per plant, and biological yield) and yield attributes (grain yield per plant, 1000-grain weight, and oil content) were recorded. All sulphur-treated plots (T<sub>2</sub>–T<sub>8</sub>) showed significant improvement in growth and yield compared to the control treatment (T<sub>1</sub>). The highest plant height (163 cm), branches per plant (27), pods per plant (472), biological yield (82.78 g plant<sup>-1</sup>), and grain yield (24.45 g plant<sup>-1</sup>) were recorded in T<sub>8</sub> (60 kg ha<sup>-1</sup> soil-applied sulphur + 1% foliar spray). However, these results were statistically similar to those obtained in T<sub>7</sub> (60 kg ha<sup>-1</sup> soil-applied sulphur + 0.5% foliar spray), indicating that increasing foliar sulphur concentration beyond 0.5% did not provide a significant yield advantage. Oil content increased with higher sulphur levels and foliar application. The maximum oil content (39.12%) was recorded in T<sub>7</sub>, whereas the lowest oil content (31.71%) was observed in the control treatment. In conclusion, integrated sulphur application through soil and foliar methods was more effective than soil application alone. Based on yield performance, oil content, and feasibility, treatment T<sub>7</sub> (60 kg ha<sup>-1</sup> soil-applied sulphur combined with a 0.5% foliar spray) is recommended for improving mustard growth, yield, and oil quality.

## Engineering Soil Resilience: A Nano-Enabled Strategy for Rhizospheric Modulation, Stress Alleviation, and Sustainable Soil Health

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As climate change intensifies, agricultural systems face increasing pressure from abiotic stresses and soil contamination, necessitating advanced strategies to engineer soil resilience. Carbon quantum dots (CQDs) have emerged as versatile and multifunctional nanomaterials with the potential to transform sustainable agriculture by modifying the soil–plant nexus. This study integrates a comprehensive review of CQDs as biogeochemical modulators with empirical evidence of their efficacy and ecotoxicological thresholds. CQDs influence soil health by interacting directly with the rhizosphere, enhancing nutrient cycling, and stimulating beneficial microbial communities. Beyond simple fertilization, CQDs act as nanocarriers capable of penetrating plant barriers to regulate gene expression and metabolic profiles, thereby priming plants against diverse climate-induced stresses. However, their application requires careful consideration of their dual role, where low doses stimulate physiological resilience, while concentrations exceeding threshold levels may induce phytotoxicity and disrupt ecological balance. To validate this biphasic dose–response relationship, nitrogen-doped CQDs (N-CQDs) were synthesized using a green hydrothermal technique and applied to rice (*Oryza sativa*) under arsenic stress (30–60 ppm). The results showed that an optimal dose of 100 ppm acted as an effective biostimulant, significantly increasing plant dry biomass (17%) and chlorophyll content (59%) compared with stressed controls. N-CQDs mitigated arsenic toxicity by upregulating antioxidant defense systems, particularly superoxide dismutase (SOD), ascorbate peroxidase (APX), and catalase (CAT). Furthermore, N-CQDs treatment increased proline accumulation—an important osmolyte and precursor of 2-acetyl-1-pyrroline (2-AP)—suggesting preservation of grain quality traits under stress conditions. Conversely, confirming the toxicity threshold hypothesis, concentrations of 300 ppm inhibited plant growth, highlighting the importance of precise dosing in nano-enabled agricultural interventions. Overall, N-CQDs offer a promising approach for restoring soil health and enhancing crop resilience against metalloid toxicity and climate-induced stresses. However, their application must be guided by rigorous ecotoxicological assessments to fully harness their biostimulatory potential while minimizing environmental risks.

## The Nitrogen Paradox in South Asia: Balancing Food Security, Climate Mitigation and Environment Sustainability

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Nitrogen is essential for food production but a major driver of environmental degradation. South Asia, including Pakistan, India, and Bangladesh, has intensified nitrogen fertilizer use to meet growing food demand, increasing cereal production (e.g., Pakistan’s output rose from 6.7 to 42.7 million tons, 1961–2020). Excessive fertilizer use has led to reactive nitrogen emissions ( $N_2O$ ,  $NH_3$ ,  $NO_x$ ,  $NO_3$ ), degrading soil, polluting water, threatening biodiversity, and accelerating climate change. Pakistan’s nitrogen use efficiency dropped from 50% to below 30%, creating a surplus and raising agriculture-derived emissions. Mitigation policies often shift problems rather than solve them. This presentation explores

systemic nitrogen challenges, evaluates regional readiness, and discusses integrated policy frameworks aligning food security, climate action, and sustainable industrial transition.

## Sustainable Nutrient Management of *Taxus wallichiana* (Himalayan yew) of Moist Temperate Forest of Galiyat-Himalayan-KP-Pakistan

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Forest management plans have largely overlooked soil nutrient management for nursery cultivation of *Taxus wallichiana* (Himalayan yew). This study aimed to develop a comprehensive database on soil nutrient status in the moist temperate forests of the Galiyat region, Khyber Pakhtunkhwa, Pakistan. Additionally, the study evaluated key soil factors influencing nutrient availability using bagging and random forest modeling approaches. Rhizosphere and bulk soil properties were analyzed to establish correlations between soil physical parameters and the availability of essential nutrients (N, P, and K) for yew growth. Model performance was evaluated by examining the increase in Mean Squared Error percentage (IncMSE%) when non-predictable variables were removed. Electrical conductivity (EC) was identified as the most influential variable affecting nutrient availability, followed by soil organic matter and pH. Nitrogen was found to be the most limiting nutrient and showed strong correlations with EC, organic matter, pH, iron, and potassium. Similarly, phosphorus availability was strongly associated with EC and iron, whereas potassium availability showed correlations with zinc and phosphorus. The results indicate that soil physical conditions significantly influence nutrient availability for *Taxus wallichiana*. The developed NPK prediction models provide valuable insights for nutrient optimization and can support sustainable forest management planning. Future studies should extend these models to diverse ecological zones and tree species.

## Effect of Graphene oxide on Growth and Biomass Production of Paize (*Zea mays* L) Crop

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Graphene oxide (GO) has gained substantial attention due to its unique physicochemical and biological properties, with promising applications in agriculture for enhancing crop growth and resource-use efficiency. However, systematic information on its dose-dependent effects under soil conditions remains limited. A pot experiment was conducted to evaluate the effects of different concentrations of GO on the growth and biomass accumulation of maize (*Zea mays* L.). GO was synthesized using the modified Hummers method and applied at five concentrations (0, 25, 50, 75, and 100 mg L<sup>-1</sup>) in a completely randomized design (CRD). The results showed a clear non-linear, dose-dependent

response to GO application. The 50 mg L<sup>-1</sup> concentration was optimal for most biomass traits, producing maximum root fresh weight (0.96 g), shoot fresh weight (1.07 g), and root dry weight (0.30 g). In contrast, the 75 mg L<sup>-1</sup> concentration was most effective for vertical growth and above-ground biomass, resulting in the longest root length (37 mm; 86.7% increase over control) and highest shoot dry weight (0.33 g). Higher concentrations did not provide additional benefits. Graphene oxide can act as an effective growth-promoting nanomaterial for maize when applied at appropriate concentrations. Identifying the optimal dose range (50–75 mg L<sup>-1</sup>) is critical for maximizing plant growth and ensuring its safe and sustainable use in agriculture.

## Phosphorus Availability in Soil-Plant System as Influenced by Farmyard Manure and Soil Temperature Regimes in Wheat-Maize Cropping System

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Phosphorus (P) availability in the soil–plant system is strongly influenced by soil organic carbon (SOC) mineralization and temperature variations. However, the combined effects of farmyard manure (FYM) levels and seasonal changes on P mineralization and phosphatase activity remain insufficiently explored. A four-year field experiment (2019–2022) was conducted to evaluate the effects of FYM application rates (0, 4, 8, and 12 t ha<sup>-1</sup>), with and without recommended NPK fertilizers, under winter and summer seasons. Soil samples were collected after each crop harvest and incubated at different temperature ranges (0–8°C, 8–15°C, and 15–22°C) to assess alkaline phosphomonoesterase (PME) and phosphodiesterase (PDE) activities. Plant physiological traits, grain yield, and nutrient uptake by wheat and maize were also measured. Results indicated that P mineralization increased with increasing FYM application rates. The combined application of FYM at 8 t ha<sup>-1</sup> with chemical fertilizers significantly improved SOC, available P, and P uptake in both crops across seasons. Grain yields of wheat and maize increased by 23% and 14%, respectively, under this treatment compared to control and sole fertilizer application. Higher soil P availability was observed during summer, which was strongly correlated with increased PME ( $r = 0.886$ ) and PDE ( $r = 0.907$ ) activities. Enhanced SOC and P availability contributed to improved crop growth and yield. In conclusion, the combined application of FYM (8 t ha<sup>-1</sup>) and recommended fertilizers enhances P availability, enzyme activity, and crop productivity. These findings provide a basis for optimizing nutrient management strategies under varying seasonal and temperature conditions.

## Improving Fertilizer Use Efficiency, Effectiveness, and Sustainability in Rice through 4R Nutrient Stewardship, Enhanced Efficiency Fertilizers, and Biofertilizers

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Improving fertilizer use efficiency, enhancing fertilizer effectiveness, and developing alternatives to conventional chemical fertilizers are essential for sustainable rice production. A field study was conducted during the 2025 rice season across four farmers’ fields in District Gujranwala to evaluate 4R-based nutrient stewardship, soil test-based (STB) fertilization, enhanced-efficiency fertilizers, and biofertilizer integration. Treatments included farmers’ practice (FP); FP with 4Rs and Leaf Color Chart (LCC)-based nitrogen management; STB-based nitrogen and phosphorus application; zinc- and neem oil-coated urea applied at reduced nitrogen rates; and Biozote combined with reduced fertilizer doses. Results showed that 4R- and STB-based nitrogen management increased paddy yield while reducing nitrogen use by 16–21% compared with FP. Enhanced-efficiency fertilizers applied at 80% of FP improved nitrogen use efficiency and reduced straw nitrogen uptake without a yield penalty. Biozote combined with 80% of STB nitrogen produced the highest paddy yield (4.53 t ha<sup>-1</sup>), achieved maximum nitrogen savings (≈33%), and generated superior economic returns. Overall, integrated nutrient management approaches provide a viable and sustainable alternative to conventional fertilizer practices in rice production.

## Qualitative Characterization of Different Pearl Millet (*Pennisetum Glaucum* L.) Genotypes for Nutritional Improvement of Fodder

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Pearl millet (*Pennisetum glaucum* L.) is a potential fodder crop for supporting livestock nutrition, particularly in arid and semi-arid regions. Improving nutritional quality through the screening and selection of superior genotypes based on quality traits is crucial for enhancing livestock production. The present study was conducted in 2024 at the Fodder Research Institute, Sargodha, to evaluate ten pearl millet genotypes based on their quality attributes. The experiment was laid out in a randomized complete block design (RCBD) with three replications for each genotype. At 50% flowering (60 days after sowing), plant samples were collected to analyze quality parameters, including dry matter, ash, crude fat, crude fiber, and crude protein content. The results indicated that genotype BS-99 showed significant higher dry matter (22.6%), crude fat (3.40%), crude fiber (10.56%), and crude protein (25.32%) compared to other genotypes. Genotype 8781 exhibited the highest ash content (10.43%). Bajra-2002 was also significantly different from other genotypes in terms of nitrogen-free extract (NFE) (56.36%). Overall, BS-99 performed better than the other genotypes for most of the quality traits of pearl millet.

## Humic and Fulvic Acid Integration Improves Phosphorus Availability and Wheat Productivity in Calcareous Soils

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Phosphorus (P) availability in calcareous soils is severely constrained by fixation reactions, limiting fertilizer efficiency and crop productivity. Considering sustainable strategies that enhance P bioavailability, a field study was conducted to evaluate wheat response to humic acid (HA), fulvic acid (FA), and their combined application (HFA) across five P fertilization levels (0%, 25%, 50%, 75%, and 100% of the recommended dose of P). The combined application of HFA at 4% consistently outperformed individual HA and FA treatments. Plant height increased to 78.55 and 79.72 cm under HFA4% at P75% and P100%, respectively, compared with 53.01 cm in the unfertilized control. Tillers plant<sup>-1</sup> (14.36–16.44) and flag leaf area (51.20–54.84 cm<sup>2</sup>) were significantly enhanced under the same treatments. Yield components, including spikes plant<sup>-1</sup>, spikelets spike<sup>-1</sup>, and grains spike<sup>-1</sup>, showed parallel improvements. Grain yield increased markedly under HFA4%, reaching 6176 and 6335 kg ha<sup>-1</sup> at P75% and P100%, respectively, compared with 3241 kg ha<sup>-1</sup> at P0%. The HFA4% mixture significantly increased P concentration in flag leaves (0.071%), straw (0.064%), and grain (0.56%), indicating improved P uptake and internal translocation. Overall, integrated application of humic and fulvic acids exhibited a strong synergistic effect, enhancing P availability and wheat productivity in calcareous soils.

## Nano-Zinc for Cereal Biofortification: Advances, Challenges, and Future Directions

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Zinc (Zn) is an essential micronutrient required for numerous physiological processes in both plants and humans. However, nearly one-third of the world’s cultivated soils and almost half of those under cereal-based cropping systems are deficient in Zn, with the problem most severe in alkaline and calcareous soils. This deficiency is particularly critical in developing countries, where cereals, inherently low in Zn, constitute the primary dietary staple. Consequently, Zn malnutrition affects

about 17% of the global population (approximately 1.5–2.0 billion people), leading to “hidden hunger” associated with stunted growth, weakened immunity, and other health complications. Biofortification of cereals with Zn, through both agronomic and genetic approaches, offers a promising strategy to address this issue. However, the efficiency of conventional Zn fertilizers is often limited. In contrast, nano-scale Zn fertilizers, such as zinc oxide nanoparticles (ZnO-NPs), have shown enhanced uptake and accumulation in plants compared to traditional Zn sources, thereby improving Zn use efficiency. This makes ZnO-NPs a potentially sustainable option for agronomic Zn biofortification in cereals. This review highlights the role of ZnO-NPs in improving cereal yield and grain Zn concentration, discusses their synthesis methods, and examines the mechanisms underlying their uptake, transport, and accumulation in plants. It also considers potential environmental risks associated with their use. Furthermore, key research gaps and challenges are identified, including the need to optimize application rates and delivery methods, evaluate long-term impacts on soil health and food safety, conduct large-scale field trials, establish supportive policy frameworks, perform cost–benefit analyses, and enhance farmer adoption. Addressing these challenges could enable ZnO-NPs to play a significant role in alleviating global Zn malnutrition while promoting sustainable agricultural practices.

## Zinc Dynamics and Accumulation Pattern in Standard and Zn-Biofortified Wheat Cultivars Across Eight Growth Stages under Soil Zinc Application

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Dietary zinc (Zn) deficiency is a global health concern. Understanding Zn uptake and grain accumulation, particularly in Zn-biofortified wheat cultivars, is essential for improving biofortification strategies in cereal crops. This study investigated Zn dynamics in standard and Zn-biofortified wheat cultivars under different Zn supply levels, with a focus on stage-specific uptake and accumulation patterns. A glasshouse pot experiment was conducted using two wheat cultivars, Jauhar-2016 (standard) and Zincol-2016 (Zn-biofortified), grown in alkaline-calcareous soil. Zinc was applied at 0 and 8 mg Zn kg<sup>-1</sup>. Plant samples were collected at eight key growth stages, from tillering to maturity, to assess yield, Zn uptake, partitioning, and remobilization in both cultivars. Soil Zn application significantly increased yield and Zn concentration in both cultivars. In both cases, remobilization of pre-anthesis shoot Zn reserves was the primary pathway for grain Zn accumulation. However, the Zn-biofortified cultivar exhibited a 72% greater contribution of post-anthesis Zn uptake to grain Zn accumulation compared to the standard cultivar. Consequently, Zn concentration and uptake in shoots were higher in the Zn-biofortified wheat. Despite this advantage, the biofortified cultivar achieved near-target grain Zn concentrations only when Zn was applied. These findings indicate that, in alkaline-calcareous soils, the enhanced grain Zn concentration in Zn-biofortified wheat is closely associated with increased post-anthesis Zn uptake.

# Enhancing Fruit Retention and Fiber Quality in Cotton through Combined Boron and Silicon Supplementation under Controlled Temperature Stress

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Shedding of fruiting structures (squares, flowers, and young bolls) in cotton is highly sensitive to elevated temperatures, leading to significant losses in yield and fiber quality. Climate-smart nutrient management may help mitigate temperature-induced abscission under changing environmental conditions. A glasshouse experiment was conducted using a completely randomized factorial design with five nutrient treatments: control, recommended dose of fertilizer (RDF), RDF + B, RDF + Si, and RDF + B + Si, across three temperature regimes (35°C, 40°C, and 45°C), each replicated three times. Elevated temperatures significantly reduced plant height, number of sympodial branches, fruiting points, boll number, boll weight, and seed cotton yield, while increasing fruit shedding. Physiological traits, including chlorophyll content, membrane stability index, and proline accumulation, were also adversely affected by temperature stress. Fiber quality parameters (staple length, fiber strength, micronaire, and uniformity index) showed temperature-dependent variation. The combined application of B and Si with RDF significantly improved fruit retention, physiological performance, and yield under high-temperature conditions compared to the control and single-nutrient treatments. Significant temperature × nutrient interactions were observed for most parameters, indicating a synergistic role of B and Si in enhancing heat stress tolerance. These findings suggest that the combined application of B and Si can mitigate temperature-induced shedding and sustain cotton yield and fiber quality under heat stress, offering a practical strategy for climate-resilient cotton production.

## Nutrient Status of Citrus and Guava Fruits Grown in Alkaline Calcareous Soils of Punjab

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Citrus and guava fruits are highly nutritious, providing essential vitamins, minerals, and beneficial plant compounds. However, the average yield of orchards in Pakistan (9.5 t ha<sup>-1</sup>) is considerably lower than the global average of over 25 t ha<sup>-1</sup>. The injudicious use of chemical fertilizers, particularly micronutrients, is a major factor contributing to reduced yields in many orchards, especially in Punjab.

While considerable emphasis has been placed on macronutrient application, limited attention has been given to identifying micronutrient deficiencies that constrain fruit yield and quality. Both macro- and micronutrients are essential for optimal plant growth, yield, and fruit quality. Although deficiencies have been reported in Punjab, information on the extent of specific nutrient deficiencies across different areas remains limited. To address this gap, it is necessary to assess the current nutrient status of orchard crops. Accordingly, this study was conducted to evaluate the nutrient status of citrus and guava orchards in Faisalabad, Toba Tek Singh, Sheikhpura, Jhang, Sahiwal, and Sargodha districts. A total of 1,200 samples were collected from orchards in these districts and analyzed for N, P, K, Ca, Fe, Zn, Cu, and Mn concentrations. The results revealed significant deficiencies of both macro- and micronutrients in citrus orchards, with more than 85% of orchards affected. Nutrient levels in these samples were below the required thresholds ( $<22 \text{ g kg}^{-1}$ ,  $<1.2 \text{ g kg}^{-1}$ ,  $<12 \text{ g kg}^{-1}$ ,  $<10.9 \text{ g kg}^{-1}$ ,  $<60 \text{ mg kg}^{-1}$ ,  $<25 \text{ mg kg}^{-1}$ ,  $<5 \text{ mg kg}^{-1}$ , and  $<25 \text{ mg kg}^{-1}$  for N, P, K, Ca, Fe, Zn, Cu, and Mn, respectively). In guava orchards, the situation was comparatively better, although deficiencies were still observed in over 50% of orchards. These findings highlight the urgent need for balanced fertilization practices that include both macro- and micronutrients to enhance fruit yield and improve fruit quality.

## Nano-Engineered $\text{TiO}_2$ @NPK and $\text{Fe}_3\text{O}_4$ Fertilizers: A Sustainable Strategy for Crop Yield Enhancement and Microbial Control in *Capsicum annuum*

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The application of nano-fertilizers in agriculture has the potential to enhance food production and increase crop yields. Owing to their small size, high surface reactivity, and unique properties, nano-fertilizers enable more efficient nutrient uptake and can be more economical than conventional fertilizers. In this study, iron oxide nanoparticles ( $\text{nFe}_3\text{O}_4$ ) and nitrogen-, phosphorus-, and potassium (NPK)-immobilized  $\text{TiO}_2$  ( $\text{nTiO}_2$ ) nano-fertilizers were synthesized and applied to chili plants (*Capsicum annuum* L.) via foliar spray. Conventional fertilizers were also applied for comparison. Each treatment was sprayed three times at a concentration of 100 mg/L at 15, 35, and 45 days after planting. Results showed that leaf length, stem length, and root mass were significantly improved with  $\text{nFe}_3\text{O}_4$  and  $\text{nTiO}_2$  compared to treatments with conventional fertilizers. Similarly, total chlorophyll content increased by 7%, 8%, 41%, and 136% with  $\text{nTiO}_2$ ,  $\text{nFe}_3\text{O}_4$ , DAP, and urea treatments, respectively. Additionally,  $\text{nTiO}_2$  demonstrated potential as a pesticide due to its large surface area, photocatalytic activity, and low toxicity. Its antimicrobial activity was evaluated against microorganisms, including bacteria and fungi.  $\text{nTiO}_2$  exhibited strong inhibitory effects against *S. aureus*, *E. coli*, and *Aspergillus flavus* at a minimum concentration of 250  $\mu\text{g/mL}$ . Overall, the results highlighted the effectiveness of nano-fertilizers in improving plant growth and protection.

# Integrated Nitrogen and Phosphorus Management for Sustainable Soil Fertility and Crop Productivity

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Integrated Soil Nutrient Management (ISNM) emphasizes the judicious integration of organic, inorganic, and biological nutrient sources to sustainably enhance soil fertility and crop productivity. This review synthesizes findings from a series of field trials conducted across diverse agro-ecological zones, with a particular focus on the management of nitrogen (N) and phosphorus (P). The selected trials evaluated the combined use of mineral fertilizers with compost, green manures, biofertilizers, biochar, and rock phosphate to assess their interactive effects on crop yield, nutrient use efficiency, and soil health indicators. Across locations and seasons, integrated nutrient strategies consistently outperformed sole fertilizer applications by improving nutrient availability, reducing nutrient losses, and maintaining soil organic matter. Overall, the findings highlight the effectiveness of ISNM in promoting balanced fertilization, mitigating environmental risks, and enhancing the resilience of farming systems. The conclusions provide valuable guidance for improving nutrient management practices and informing policy initiatives aimed at sustainable agricultural development.

## Physico-Chemical Characterization of District Swabi Soils

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This study was conducted to assess the physico-chemical properties of soils in village Malak Abad, District Swabi. Six soil samples were collected from different farmers’ fields at a depth of 0–15 cm and analyzed for pH, electrical conductivity (EC), texture, and NPK concentrations. Laboratory analysis revealed that the soils were alkaline (pH 8.26–8.51), non-saline (0.34–0.38 dS m<sup>-1</sup>), and ranged from sandy loam to silty loam in texture. The soils were deficient in available nitrogen (1.49–2.45 mg kg<sup>-1</sup>), phosphorus (0.32–2.44 mg kg<sup>-1</sup>), and potassium (40–140 mg kg<sup>-1</sup>), except in a field where potassium levels were adequate (140 mg kg<sup>-1</sup>). Based on these findings, the application of balanced NPK fertilization from both organic and inorganic sources is recommended to achieve optimal crop yields in the soils of village Malak Abad, District Swabi.

## Integrated Nitrogen (N) and Phosphorus (P) Management for Improving Wheat Productivity and Soil Health

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Organic and inorganic fertilizers, when applied at appropriate rates and timings, can significantly enhance crop productivity and soil fertility. A field experiment was conducted on wheat at the Agricultural Research Station, Swabi, Khyber Pakhtunkhwa, Pakistan, during the 2018–19 rabi season. The study was laid out in a randomized complete block design (RCBD) with six replications. A total of 11 treatments were tested: control; urea 120 kg N ha<sup>-1</sup>; urea 120 kg N ha<sup>-1</sup> + single super phosphate (SSP) 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>; poultry manure (PM) 10 t ha<sup>-1</sup>; farmyard manure (FYM) 20 t ha<sup>-1</sup>; urea 120 kg N ha<sup>-1</sup> + SSP 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup>; urea 60 kg N ha<sup>-1</sup> + SSP 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup>; urea 60 kg N ha<sup>-1</sup> + SSP 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + PM 10 t ha<sup>-1</sup>; urea 60 kg N ha<sup>-1</sup> + SSP 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + FYM 20 t ha<sup>-1</sup>; urea 40 kg N ha<sup>-1</sup> + SSP 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + PM 5 t ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup>; and urea 40 kg N ha<sup>-1</sup> + SSP 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + FYM 10 t ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup>. Analysis of soil after harvest indicated that organic amendments, particularly FYM (20 t ha<sup>-1</sup>), improved soil pH (8.39), electrical conductivity (1.49 dS m<sup>-1</sup>), organic matter (1.52%), organic carbon (0.88%), and CaCO<sub>3</sub> content (8.65%) compared to synthetic fertilizers. Statistical analysis showed significant differences ( $P \leq 0.05$ ) among treatments for all measured parameters except lodging and loose smut, which were non-significant. Phenological observations revealed that the application of urea 120 kg N ha<sup>-1</sup> + SSP 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup> delayed key growth stages: days to tillering (66), booting (95), heading (116), anthesis (136), and milking (154), compared to the control (tillering 57, booting 83, heading 96, anthesis 106, milking 128). Maximum growth and yield parameters were observed with urea 40 kg N ha<sup>-1</sup> + SSP 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + FYM 10 t ha<sup>-1</sup> + legume residue 5 t ha<sup>-1</sup>, which produced the highest biological yield (16,389 kg ha<sup>-1</sup>), grain yield (5,703 kg ha<sup>-1</sup>), and straw yield (10,685 kg ha<sup>-1</sup>) compared to the control. Integrated nutrient management (urea 60 kg N ha<sup>-1</sup> + SSP 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + FYM 20 t ha<sup>-1</sup>) significantly improved soil fertility, enhancing physiochemical properties such as pH, EC, organic matter, organic carbon, CaCO<sub>3</sub>, and available N, P, and K. In conclusion, the combined application of urea 40 kg N ha<sup>-1</sup> + SSP 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> + FYM 10 t ha<sup>-1</sup> + legume residues 5 t ha<sup>-1</sup> is recommended for achieving high wheat yield and maintaining soil health under the agro-climatic conditions of District Swabi.

## Digital Mapping of Soil Fertility Parameters in Adaptive Research Cum Demonstration Institute Matora, Lakki Marwat

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Assessment of soil fertility is critical for sustainable agriculture and site-specific nutrient management. This study was conducted at the Adaptive Research cum Demonstration Institute, Matora, Lakki Marwat, to evaluate the spatial variability of key soil fertility parameters and to develop digital maps for field-scale nutrient management. Soil samples were collected systematically and analyzed for their physico-chemical and nutritional properties, including electrical conductivity (EC: 0.2–2.5 dS m<sup>-1</sup>), nitrate nitrogen (0.01–0.08 %), available phosphorus (2–18 mg kg<sup>-1</sup>), available potassium (60–180 mg kg<sup>-1</sup>), and boron (0.2–1.5 mg kg<sup>-1</sup>). The soils were predominantly sandy loam to loam in

texture. Digital mapping of the analytical data revealed considerable spatial variation in nutrient availability and soil constraints across the study area. Localized deficiencies of phosphorus, potassium, and boron were identified, while salinity and sodicity were higher in low-lying areas. These results highlight the importance of site-specific nutrient management instead of uniform fertilizer application. The generated digital maps offer a practical tool for pinpointing problem areas, optimizing nutrient inputs, and enhancing soil health and crop productivity. Overall, the study demonstrates the effectiveness of integrating soil analytical data with digital mapping to achieve precise and informed soil fertility assessment.

## Humic Acid Treated Acidified Rock Phosphate Enhances Phosphorus Diffusion, Availability and Use Efficiency in Alkaline Soil Conditions

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There is a need to develop a phosphorus (P) fertilizer that remains highly available in the soil for longer periods without being lost through adsorption, precipitation, or other reactions. To address this, a series of laboratory, pot, and field experiments were conducted at the Department of Soil and Environmental Sciences, The University of Agriculture Peshawar. The study evaluated the effects of humic acid (HA)-treated acidulated rock phosphate (ARP) compared to conventional commercial fertilizers on phosphorus diffusion, availability, uptake, and the growth of maize and wheat. Humic acids were extracted from two sources: lignitic coal (HA1) and farmyard manure compost (HA2). These HAs were applied to ARP through three methods: physical blending, coating over ARP granules, or incorporation during the acidulation process (HA-complexed ARP). The results showed that maize plant height, fresh and dry biomass, and total P uptake significantly improved with HA-treated ARPs. Differences between HA1 and HA2 were not statistically significant. In field trials, HA-complexed ARP produced taller maize plants (214 cm), higher biomass (11,872 kg ha<sup>-1</sup>), greater grain yield (4,824 kg ha<sup>-1</sup>), and total P uptake (29.56 kg ha<sup>-1</sup>), which were 7.6%, 15%, 23.6%, and 37.2% higher than single superphosphate (SSP) applied at 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, respectively. The residual wheat crop also benefited from this treatment, showing increases in plant height (9.5%), biomass (13%), and grain yield (13.8%) compared to SSP. Additional field trials confirmed that HA-treated ARP outperformed commercial fertilizers, enhancing yield while reducing application rates and input costs. Overall, the study concludes that HA-treated ARPs can effectively replace conventional phosphorus fertilizers. Application at 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> is recommended to improve phosphorus movement in soil, availability, use efficiency, economic returns, and optimized yields of maize and wheat under the soil and climatic conditions of Peshawar.

## Synthesis of Boron Chelated Humic Acid and its Effect on Maize Yield as Foliar Spray and Soil Application

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A field experiment was conducted at the Agriculture Research Farm, Malakandher (Peshawar), to evaluate the effects of humic acid-chelated boron (HA-B) on maize (*Zea mays* L.) growth, yield, B uptake, and agronomic performance under both soil and foliar application methods. The study aimed to synthesize a stable HA-B complex and assess its efficiency in enhancing maize productivity. Nine treatments were tested: a control, untreated boric acid at 5 kg ha<sup>-1</sup> (soil), and HA-B applied at 5, 10, and 20 kg ha<sup>-1</sup> for soil application. For foliar application, boric acid (0.1%) and HA-B at 0.1%, 0.2%, and 0.3% were applied. Treatments were arranged in a randomized complete block design (RCBD) with three replications. Results showed that both soil and foliar applications of HA-B significantly improved plant height, leaf area, stover yield, ear weight, and grain yield compared to the control and untreated boric acid. The highest values for plant height (166 cm), leaf area (663 cm<sup>2</sup>), stover yield (8,955 kg ha<sup>-1</sup>), and biological yield (12,633 kg ha<sup>-1</sup>) were recorded with 20 kg ha<sup>-1</sup> soil-applied HA-B, which also produced the highest grain yield (3,677 kg ha<sup>-1</sup>). Foliar application of 0.3% HA-B similarly enhanced yield components, boron uptake, and use efficiency. Boron concentrations in soil, plant tissues, and grains increased with higher HA-B levels, with maximum values observed at 20 kg ha<sup>-1</sup> soil application and 0.3% foliar HA-B. Total B uptake (178.5 g ha<sup>-1</sup>) and use efficiency (18.0%) were significantly improved by HA-B treatments. The study concludes that HA-B is a more efficient and effective source of B than conventional boric acid. Both soil and foliar applications improve maize yield, B use efficiency, and overall plant performance under field conditions.

## Comparative Study on Zn-HA: Boosting Maize Early Growth, Root, Shoot Biomass, and Zn Uptake via Soil and Foliar Application, and Seed Priming in Alkaline Soils under Greenhouse Condition

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Zinc (Zn) deficiency in calcareous soils of Khyber Pakhtunkhwa, characterized by high pH, elevated bicarbonate, and low organic matter, limits maize (*Zea mays* L.) productivity by reducing Zn bioavailability. Two successive pot experiments were conducted in a completely randomized design (CRD) with three replications using Zn-deficient calcareous soil (pH 7.62, AB-DTPA Zn 0.76 mg kg<sup>-1</sup>) from Agricultural University Peshawar. Experiment 1 evaluated soil-applied Zn formulations at 5, 10, and 20 kg Zn ha<sup>-1</sup>: ZnSO<sub>4</sub> alone, ZnSO<sub>4</sub> + humic acid (HA), and pre-complexed Zn-humate (Zn-HA). Maize (cv. Jalal) was grown under greenhouse conditions at 70% field capacity. Experiment 2 assessed seed priming and foliar spray of Zn-HA at 0.5%, 1.0%, and 1.5% on seedling performance. Plant growth (shoot height, fresh and dry biomass) was recorded at V6 (40 days after sowing). Zn concentrations in roots and shoots were determined by wet digestion and atomic absorption spectroscopy, with uptake calculated as concentration × biomass. Post-harvest soil Zn was measured using AB-DTPA extraction. Data were analyzed by ANOVA and LSD at p<0.05. Results showed that soil-applied Zn-HA outperformed ZnSO<sub>4</sub> and ZnSO<sub>4</sub> + HA, with 20 kg Zn ha<sup>-1</sup> increasing shoot height by 27% (59.6 cm vs. 47.1 cm), shoot fresh weight by 44–46%, root fresh weight (2.83 g), shoot dry weight (1.72 g), root dry weight (0.72 g), and total dry matter (2.44 g pot<sup>-1</sup>). Zn concentrations and uptake also improved (roots 48.6 mg kg<sup>-1</sup>, shoots 44.8 mg kg<sup>-1</sup>, uptake 223.5 µg pot<sup>-1</sup>). In Experiment 2, 1.5% foliar Zn-HA increased

shoot height (32 cm), shoot fresh weight (11.33 g), root fresh weight (2.44 g), total dry matter (2.15 g), and Zn uptake ( $136 \mu\text{g pot}^{-1}$ ), outperforming seed priming. These findings demonstrate that soil-applied Zn-HA ( $20 \text{ kg ha}^{-1}$ ) and foliar Zn-HA (1.5%) can enhance maize growth, yield, and grain Zn content, potentially increasing yields by 25–40% and improving human nutrition across Khyber Pakhtunkhwa's 1.2 million ha maize area, where 65% of soils are Zn-deficient.

## Influence of Different Levels of Silicon Applied to Soil and Foliar Application With Various Levels of Nitrogen on Yield and Yield Parameters of Wheat

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A field experiment was conducted at the Agriculture Research Institute Mingora, Swat, during 2024 to study the effect of silicon (Si) applied to soil and as a foliar spray, along with nitrogen (N), on wheat yield and yield components. The experiment was laid out in a randomized complete block design with three replications. Four levels of silicon (as super silica) were applied: S1 (control), S2 ( $280 \text{ kg Si ha}^{-1}$  soil-applied), S3 ( $260 \text{ kg Si ha}^{-1}$  soil +  $20 \text{ kg Si ha}^{-1}$  foliar spray), and S4 ( $240 \text{ kg Si ha}^{-1}$  soil +  $40 \text{ kg Si ha}^{-1}$  foliar spray). Three levels of nitrogen were applied as urea: N1 (control), N2 ( $100 \text{ kg N ha}^{-1}$ ), and N3 ( $140 \text{ kg N ha}^{-1}$ ). The results showed that Si application significantly enhanced yield and yield components, nutrient uptake, and N use efficiency under the prevailing alkaline, non-saline, and moderately calcareous soil conditions. Compared to sole soil application, splitting the Si dose between soil and foliar application was more effective. The highest values for plant height (94.61 cm), number of tillers ( $415 \text{ m}^{-2}$ ), grain yield ( $4,130 \text{ kg ha}^{-1}$ ), biological yield ( $10,634 \text{ kg ha}^{-1}$ ), and harvest index (39%) were recorded in plots receiving  $240 \text{ kg Si ha}^{-1}$  soil-applied +  $40 \text{ kg Si ha}^{-1}$  foliar spray along with  $100 \text{ kg N ha}^{-1}$ . Increasing N beyond  $100 \text{ kg ha}^{-1}$  did not significantly improve yield or yield components, indicating potential fertilizer savings. This treatment also resulted in higher Si and N content in plant tissues and increased uptake of N, P, and K. N use efficiency reached 76% with the 240+40 kg Si treatment compared to 47% and 36% for 100 and 140 kg N applied without Si. Soil analysis corroborated these results, showing increased soluble Si and improvements in related soil properties. It is concluded that Si application in wheat enhances N use efficiency and yield. Further studies on other soils and crops are recommended to evaluate Si's effectiveness under diverse conditions for broader adoption.

## Comparative Study of Soil Health Indicators in Organic and Conventional Farming under Semi-Arid Climate

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Soil degradation is a major concern in semi-arid regions due to limited rainfall, high evapotranspiration rates, and intensive agricultural practices. This study presents a comparative evaluation of soil health indicators under organic and conventional farming systems in a semi-arid climate. Key soil parameters including soil organic carbon (SOC), pH, electrical conductivity (EC), bulk density, aggregate stability, and microbial biomass were assessed to determine differences in soil quality and sustainability. Soil samples were collected from adjacent organic and conventional farms with similar cropping patterns to ensure comparability. Laboratory analyses revealed significantly higher soil organic carbon, improved aggregate stability, and enhanced microbial biomass in organic fields. In contrast, conventional systems showed higher bulk density and reduced biological activity, likely due to continuous chemical fertilizer application and limited organic input. Organic farming demonstrated improved soil structure and greater water holding capacity, which are critical under semi-arid conditions where moisture conservation determines crop productivity. The findings suggest that organic management practices enhance soil resilience, reduce degradation risks, and support long-term agricultural sustainability in water-limited environments. This study emphasizes the importance of adopting organic soil management strategies to maintain soil health and productivity under semi-arid climatic stress.

## Effects of Soil and Crop Management Practices on Soil Quality and Health Indicators in the Rice-Wheat Cropping System under Semi-arid Climate: Current Status and Challenges

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Assessment and monitoring of soil health and its links with sustainability and food security has gained paramount significance on global scale. The rice-wheat cropping system (RWCS) is backbone of agriculture and food security in South Asia including Pakistan. We analyzed 95 soil samples from the rice-wheat belt in Pakistan for physico-chemical and biochemical properties and tested the effects of soil and crop management practices on these soil quality indicators. Crop management practices included rice (direct-seeded vs puddled conditions sowing) and wheat (zero tillage vs seed-bed sowing) whereas soil management practices were organic amendments (no amendment vs animal manure), irrigation sources (tube well vs canal plus tube well mixed), rice residue management (burning, removal, incorporation and zero tillage), and wheat residue management (removal vs incorporated). Soil pH, bulk density (BD; g cm<sup>-3</sup>), soil basal respiration (mg CO<sub>2</sub>-C g<sup>-1</sup> 24 h<sup>-1</sup>) and total organic carbon (TOC; g kg<sup>-1</sup>) ranged from 7.31-8.84, 0.79-1.65 g cm<sup>-3</sup>, 0.21-3.10 mg CO<sub>2</sub>-C g<sup>-1</sup> 24 h<sup>-1</sup> and 0.66-11.5 g kg<sup>-1</sup>, respectively. Application of manure and mixing tube well and canal water reduced soil pH. Crop residue retention and zero tillage resulted in lower soil pH than removing or burning the residues. Application of mixed irrigation significantly reduced soil BD compared to tube well irrigation.

Incorporation of both rice and wheat residues and zero tillage practices reduced soil BD than burning and removing the crop residues. Soil basal respiration was nearly two-fold higher under mixed water irrigation compared to the tube well irrigation. We also found that incorporation of rice and wheat residues significantly enhanced soil basal respiration and values were two-times higher compared to burning, removing and retaining crop residues under zero tillage practices. Soil basal respiration was significantly higher under puddled nursery sowing than the direct-seeded rice. Addition of animal manure and mixed irrigation practices increased TOC contents. Moreover, rice and wheat residue incorporation enhanced TOC contents when compared with residue removal and burning. Data was also assessed in terms of chronosequence of adaptation of RWCS i.e. <10, 10-30, 30-60 and >60 years and the data revealed that soil pH did not change much, BD decreased over the years and was the lowest after >60 years of adopting RWCS, soil basal respiration was the highest at <10 years chronosequence and was the lowest at >60 years chronosequence and TOC contents increased with increasing duration of adopting RWCS. Our study demonstrated that BD, soil basal respiration and TOC were influenced more by the crop and soil management practices than soil pH and, hence, were more sensitive indicators of soil quality. Data also suggested that these soil quality indicators strongly reflect the long-term changes in productivity and soil health of RWCS. Application of animal manure, retaining crop residue, mixing tube well and canal water, adopting zero tillage practices and continuity of these practices on long-term basis could enhance the sustainability of the RWCS under semi-arid climate and ensure local and regional food security.

## Assessing Zinc Requirement of Newly Developed Wheat Variety NWB-50

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Zinc (Zn) deficiency is a widespread micronutrient constraint affecting more than half of the arable soils in Pakistan, significantly limiting wheat growth, productivity, and grain nutritional quality. As an essential element involved in numerous enzymatic and physiological processes, Zn plays a vital role in protein synthesis, photosynthesis, and maintenance of cellular membrane integrity. Improving Zn concentration in wheat grains is essential not only for crop performance but also for human health, as wheat is a staple food and a major dietary Zn source for the population. Understanding wheat responses to soil-applied Zn is therefore critical for developing efficient fertilization strategies that enhance Zn accumulation and biofortification potential. To investigate this, a field experiment was conducted to evaluate the patterns of Zn uptake and distribution in wheat, as well as the effects of different Zn fertilizer levels on growth, yield, and grain Zn content. The experiment followed a Randomized Complete Block Design (RCBD) consisting of five Zn treatments (0, 1.25, 2.5, 5.0, and 7.5 kg Zn ha<sup>-1</sup>), each replicated three times. Analytical-grade zinc sulphate heptahydrate (ZnSO<sub>4</sub>·7H<sub>2</sub>O) served as the Zn source. The experimental soil was silty loam in texture, medium alkaline, low in organic matter and Zn, and marginal in phosphorus and potassium. Wheat variety NWP-50 was planted during the Rabi season 2024–25 following standard agronomic practices, with uniform N–P–K fertilization applied across all experimental plots. Results showed that Zn fertilization significantly enhanced wheat growth and yield attributes. The highest Zn level (7.5 kg ha<sup>-1</sup>) produced superior performance across most physiological and agronomic traits, including plant height (99.7 ± 0.80 cm),

tiller number ( $372.3 \pm 6.74$ ), spikelet number ( $21.7 \pm 0.88$ ), spike length ( $12.2 \pm 0.15$  cm), grains per spike ( $68.2 \pm 0.70$ ), 1000-grain weight ( $40.7 \pm 0.85$  g), grain yield ( $4387.3 \pm 16.34$  kg ha<sup>-1</sup>), and biological yield ( $8526.7 \pm 64.71$  kg ha<sup>-1</sup>). Grain Zn concentration ( $41.7 \pm 0.49$  mg kg<sup>-1</sup>) and straw Zn content ( $24.1 \pm 0.69$  mg kg<sup>-1</sup>) were also maximized under this treatment. Statistical analysis confirmed significant ( $p < 0.05$ ) variations among treatments for most measured parameters, indicating a strong response of wheat to soil-applied Zn. The study concludes that Zn application at 7.5 kg ha<sup>-1</sup> is highly effective in improving wheat growth, yield, and Zn content under Zn-deficient soils. These findings demonstrate that Zn fertilization is a cost-effective and practical strategy to alleviate Zn deficiency, enhance crop productivity, and improve the nutritional value of wheat grains, contributing to improved human dietary Zn intake in Pakistan.

## Recycling Banana Pseudostem Waste into Biochar and Compost for Sustainable Crop Production

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Pakistan produces large quantities of agricultural waste such as wheat husks, rice residues, cotton sticks, and sugarcane byproducts. Among these, banana pseudostem waste is significant, with Sindh alone generating about 3.79 million tonnes annually. Most of this biomass is burned in the open, releasing smoke and carbon dioxide. Owing to its high moisture and organic content, banana waste is highly degradable and suitable for recycling into biochar and compost (Kakar, 2021; Arnisah et al., 2023). Each square kilometer of farmland hosts around 173,000 banana trees, producing substantial residues. Converting this waste into biochar and compost offers a sustainable alternative to open burning (Silva et al., 2022). The objectives of this study were to produce biochar and compost from banana pseudostem and to evaluate and compare their effects with chemical fertilizer on the growth and yield of wheat under field conditions. Biomass of banana pseudo stem was collected from different banana-growing regions. Biochar produced under controlled laboratory conditions using the slow pyrolysis process at 350–500°C in a modified furnace. Compost prepared from banana pseudostem through the open cemented pit method, in which alternating layers of approximately 9 inches of chopped pseudostem and 3 inches of cattle manure placed until the pit was filled. The resulting biochar and compost were characterized for their physicochemical properties, including pH, electrical conductivity (EC), and macro- and micronutrient contents. The developed biochar (BC) and compost derived from banana pseudostem were evaluated for their effects on wheat growth and yield under field conditions. Six treatments were applied: T1 (control), T2 (recommended NPK), T3 (10 t ha<sup>-1</sup> Biochar), T4 (5 t ha<sup>-1</sup> Biochar + 50% NPK), T5 (10 t ha<sup>-1</sup> compost), and T6 (5 t ha<sup>-1</sup> compost + 50% NPK), arranged in a randomized complete block design with three replications. Agronomic observations indicated that both organic and inorganic amendments positively influenced wheat performance. The greatest plant height (78.63 cm) was recorded in T6, followed by T4 (76.50 cm). The highest number of tillers per plant (7.67) and spike length (5.80 cm) were observed in T4, demonstrating the synergistic effect of biochar with reduced NPK on vegetative growth and nutrient use efficiency. Grain yield was highest in T6 (3777 kg ha<sup>-1</sup>), closely followed by T4 (3767 kg ha<sup>-1</sup>). Compost application also enhanced N, P, and K concentrations in plant tissue (1.95%, 24.0 mg kg<sup>-1</sup>, and 58.0 mg kg<sup>-1</sup>, respectively). Overall, the results suggest that integrating banana pseudo stem-derived biochar and compost with partial

NPK fertilization improved wheat productivity while promoting sustainable and environmentally safe agricultural practices.

## Spatial Assessment of Organic Carbon Stocks in Urban Green Spaces on Medium Textured soils

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Soil organic carbon (SOC) represents one of the largest terrestrial carbon reservoirs and plays a crucial role in regulating the global carbon cycle, mitigating climate change, and sustaining soil ecosystem functions. However, rapid urbanization and unplanned land-use changes have increasingly degraded and fragmented urban green spaces, reducing their capacity for carbon sequestration and soil quality improvement. Understanding SOC dynamics across different vegetation types is therefore essential for evaluating carbon stabilization mechanisms in urban ecosystems. This study assessed the distribution and variability of SOC stocks and fractions across urban green spaces in Faisalabad under contrasting vegetation covers. Soil samples were collected from sites dominated by trees, shrubs, grasses, forbs, and unvegetated control areas at two soil depth intervals. Samples were analyzed for total SOC and its functional fractions, including mineral-associated organic carbon (MAOC), particulate organic carbon (POC), and microbial biomass carbon (MBC). A two-way analysis of variance (ANOVA) was applied to evaluate the effects of vegetation type, soil depth, and their interaction on SOC fractions. The results revealed significant variations in SOC and its fractions across vegetation types and soil depths. Tree- and shrub-dominated soils exhibited significantly higher SOC concentrations and carbon fractions compared with grasses, forbs, and control sites. Notably, MAOC and MBC were substantially higher under woody vegetation, indicating enhanced microbial activity and stronger carbon stabilization mechanisms. SOC fractions generally declined with increasing soil depth; however, appreciable carbon stocks persisted in subsoil layers under woody vegetation. In contrast, unvegetated control soils consistently showed the lowest SOC and associated carbon fractions. These findings demonstrate that vegetation type strongly influences SOC accumulation and stabilization in urban soils. Incorporating diverse and woody vegetation into urban green spaces can significantly enhance soil carbon sequestration and improve soil quality, thereby contributing to climate-resilient urban ecosystem management.

## Mitigating Premature Fruit Drop in Apple through Targeted Magnesium and Boron Nutrition in Azad Jammu and Kashmir

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Apple production in Azad Jammu and Kashmir (AJK) is constrained by low yields, largely attributed to premature fruit drop associated with nutrient deficiencies in mountain soils. This study evaluated the role of macro- and micronutrient supplementation in improving fruit retention and quality of apples. Three cultivars (Kashmir Amri, Red Delicious, and Star Crimson) grown at three locations (Rawalakot, Bagh, and Dhirkot) were subjected to foliar applications of magnesium (Mg) as magnesium sulfate (1000 and 2000 ppm) and boron (B) as boric acid (100 and 200 ppm), with water-treated plants as control. The experiment was conducted in a randomized complete block design with a three-factor factorial arrangement. Data on flowering, fruit set, fruit drop, yield, and fruit quality attributes were recorded and analyzed using three-way ANOVA, with means separated by Tukey's HSD at  $P \leq 0.05$ . Results indicated that foliar Mg at 2000 ppm significantly improved reproductive and yield parameters. The highest number of flowers per branch (99.0), fruit set (78.33%), fruit weight (213.67 g), and yield per tree (901.9 kg) were recorded in Star Crimson. Enhanced fruit firmness (12.76 kg  $\text{cm}^{-2}$ ), total soluble solids (14.82%), antioxidant activity (103.0 mg  $\text{FeSO}_4$   $\text{FW}^{-1}$ ), phenolics (122.87 mg GAE 100  $\text{g}^{-1}$  FW) and flavonoids (16.70 mmol quercetin 100  $\text{g}^{-1}$  FW) were also observed under Mg 2000 ppm treatment. In contrast, premature fruit drop was highest in Kashmir Amri at Rawalakot. The findings demonstrate that targeted foliar nutrient management, particularly magnesium supplementation, can significantly reduce premature fruit drop and improve productivity and fruit quality of apples in the mountainous agroecosystems of AJK.

## Assessment of Soil Physico-Chemical Properties of Mastung and Musakhail Districts, Balochistan

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This study assessed the physico-chemical characteristics of agricultural soils collected from Mastung and Musakhel districts of Balochistan. The samples were analyzed for soil texture, electrical conductivity (EC), pH, organic matter, calcium and magnesium (Ca + Mg), carbonate ( $\text{CO}_3^{2-}$ ), bicarbonate ( $\text{HCO}_3^-$ ), chloride ( $\text{Cl}^-$ ), and essential plant nutrients such as potassium (K), phosphorus (P), and sodium ( $\text{Na}^+$ ). The results revealed significant variation between the two districts. Soils from Mastung exhibited textures ranging from silt loam to sandy loam and loamy sand. These soils showed very high EC values (up to 21.7 dS/m) and strongly alkaline pH levels (8.57–9.75), indicating pronounced salinity and sodicity problems. Organic matter content remained low (0.43–0.59%), while concentrations of Ca + Mg, carbonate, and chloride were comparatively higher. Nutrient evaluation indicated low phosphorus availability (3.49–4.52 ppm), variable potassium levels (23.5–87 ppm), and elevated sodium concentrations in several samples. Conversely, soils from Musakhel displayed textures ranging from loamy sand to sandy loam, with low EC values (0.71–0.91 ds/m) and near-neutral pH (7.68–7.80), suggesting relatively non-saline and chemically favorable conditions. Organic matter content was slightly higher (0.67–0.73%) compared to Mastung. Although Ca + Mg and carbonates were present in greater amounts, nutrient analysis revealed low phosphorus levels (2.76–4.45 ppm) but considerably higher potassium concentrations (141–151 ppm). Sodium levels were lower (26–39 ppm) than those recorded in Mastung. Overall, the study concludes that Mastung soils

are affected by salinity, sodicity, and alkalinity constraints, whereas Musakeil soils present more favorable chemical conditions for crop production. However, both districts show deficiencies in key soil fertility components such as phosphorus and organic matter. These findings provide a scientific basis for informed soil management, fertility improvement, and sustainable agricultural planning in the region.

## Growth Inhibition and Stress Physiology Alterations in Wheat Exposed to Chromium Toxicity

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Heavy metal contamination, particularly chromium (Cr), significantly threatens agricultural productivity and food security. This study investigates the interactive effects of chromium exposure on the morphological traits and stress-related physiological indicators in wheat (*Triticum aestivum* L.). Wheat plants were subjected to varying chromium concentrations under controlled conditions to evaluate changes in growth parameters such as plant height, root length, leaf area, and biomass accumulation. Concurrently, stress indicators, including chlorophyll content, proline accumulation, malondialdehyde (MDA) levels, and antioxidant enzyme activities (SOD, CAT, and POD) were analyzed to assess the plant's oxidative stress response. The results revealed a concentration-dependent decline in morphological attributes, accompanied by a marked increase in oxidative stress markers and antioxidative defense mechanisms. These findings highlight the phytotoxic nature of chromium and the adaptive strategies employed by wheat to mitigate metal-induced stress. Understanding these responses is critical for developing effective strategies to enhance wheat tolerance to heavy metal contamination in agroecosystems.

## Evaluation of Natural and Synthetic Nitrification Inhibitors for Regulating N Transformations, Nitrification Inhibition, and Their Potential Use in Crop Production

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Nitrogen (N) is essential for crop productivity, yet its rapid transformation through nitrification can lead to environmental losses. This study compared the efficacy of a synthetic nitrification inhibitor, dicyandiamide (DCD), with natural inhibitors derived from Mint (*Mentha spicata*), Neem (*Azadirachta indica*), Karanj (*Pongamia glabra*), and Bhung (*Cannabis sativa*) in regulating N transformations under laboratory incubation conditions. Soils amended with urea (200 mg N kg<sup>-1</sup>) and inhibitors were

monitored for 60 days for changes in  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$ , and nitrification inhibition (NI) potential. DCD recorded the highest NI (58% at day 20), while Mint (55%) and Neem (53%) were the most effective among natural inhibitors. Bhung maintained the highest  $\text{NH}_4^+\text{-N}$  concentration ( $160 \mu\text{g g}^{-1}$ ) at day 5, while all natural inhibitors significantly reduced  $\text{NO}_3^-\text{-N}$  accumulation compared to urea alone. Although inhibitory effects declined over time, natural extracts maintained elevated  $\text{NH}_4^+\text{-N}$  levels longer than the control. The findings highlight the potential of plant-based inhibitors as sustainable alternatives or complements to synthetic options in N management strategies.

## Unraveling The Effect of Synthetic and Biodegradable Micro-Plastic on Plant Growth and Soil Biochemical Functions

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Microplastics have emerged as one of the most pressing environmental challenges of our time, threatening not only aquatic ecosystems but also terrestrial environments. Their accumulation in soil layers is particularly concerning, as soil is a non-renewable natural resource essential for sustaining life. Soil represents a complex fusion of water, minerals, air, organic compounds, and diverse organisms, all of which interact to support plant growth and ecosystem stability. The infiltration of microplastics into this delicate system poses risks to soil health, nutrient cycling, and agricultural productivity. Maize (*Zea mays* L.), the third most important cereal crop globally and a major staple in Pakistan, provides an ideal model to study these impacts. With an average yield of  $2,850 \text{ kg ha}^{-1}$  in Pakistan, maize is a  $\text{C}_4$  plant with high genetic potential and photosynthetic efficiency, making it highly responsive to environmental stressors. The present study was designed to investigate the effects of synthetic and biodegradable microplastics on maize growth, physiological performance, and nutritional attributes. Specifically, the objectives were: (1) to evaluate the influence of microplastic type and dose on plant growth and biochemical responses; (2) to assess the additive effects of both microplastic types on rhizosphere biochemistry and residual soil nutrient balance; and (3) to determine whether microplastic-driven effects are dose- and/or type-dependent. Soil samples were collected from two distinct sites in Punjab, Pakistan: silt loam from Ayub Agriculture Research Institute, Faisalabad, and clay loam from Nankana Sahib. Two types of microplastics—synthetic and biodegradable—were applied at concentrations of 0%, 2%, and 5%, with three replicates for each treatment. Maize plants were subsequently analyzed for growth parameters, chlorophyll content, enzymatic and non-enzymatic activity, and stress-related biochemical markers. Results revealed that biodegradable microplastics consistently promoted maize growth compared to synthetic microplastics, irrespective of soil type or dose. Plants grown in soils amended with biodegradable microplastics exhibited significant increases in shoot and root length, enhanced photosynthetic activity, and improved chlorophyll content. Moreover, antioxidant activity was markedly up-regulated, with higher levels of ascorbate peroxidase and peroxidase observed. Membrane stability was also improved, as indicated by reduced hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and malondialdehyde (MDA) accumulation. In addition, plants exposed to biodegradable microplastics synthesized greater amounts of stress-related osmoregulatory compounds, including proline and total phenolic content, compared to those exposed to synthetic microplastics. These findings suggest that biodegradable microplastics not only mitigate stress responses but also enhance physiological resilience in maize.

Overall, the study demonstrates that biodegradable microplastics exert growth-promoting effects on maize plants, while synthetic microplastics tend to induce stress responses and hinder plant performance. The positive impact of biodegradable microplastics was consistent across soil types and application rates, highlighting their potential role in reducing the adverse effects of plastic pollution in agricultural systems. This research underscores the importance of considering microplastic type and concentration in evaluating their ecological consequences. It also provides valuable insights into the interactions between microplastics, soil health, and crop productivity, offering a foundation for sustainable agricultural practices in the face of rising plastic contamination.

## Improving the Productivity of Drought-Stressed Wheat and Chickpea through Foliar Application of Absciscic Acid (ABA) and Salient Nutrients

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About one-quarter of Pakistan's cultivated land is rainfed, where crop productivity is severely constrained by water scarcity, soil degradation, and inefficient fertilizer use. Erratic rainfall, high evapotranspiration, and increasing climate variability further intensify water deficits, making drought the dominant limitation to sustainable crop production in these eco-systems. In this context, foliar fertilization, alone or in combination with stress-regulating compounds such as abscisic acid (ABA), may offer a practical strategy to enhance nutrient uptake and mitigate drought-induced yield losses in rainfed cropping systems. Two field experiments were conducted to evaluate the effects of foliar application of nitrogen, phosphorus, potassium, and zinc (NPKZn), applied alone or in combination with ABA, on the growth and yield of rainfed wheat and chickpea crops. Under rainfed (no-irrigation) conditions, foliar application of NPKZn increased grain yield of wheat from 2724 to 3174 kg ha<sup>-1</sup> (+17%) and chickpea from 1278 to 1608 kg ha<sup>-1</sup> (+26%). Combined foliar application of NPKZn and ABA further enhanced grain yield by 21% in wheat and 30% in chickpea. Yield improvements in response to foliar application of NPKZn and ABA were associated with increases in grain size and the number of tillers or branches. However, soil application of NPKZn resulted in greater yield gains under drought stress, achieving increases of 43% in wheat and 32% in chickpea. Overall, the results demonstrate that foliar application of nutrients, particularly when combined with ABA, can partially meet the nutrient requirements of rainfed, unfertilized wheat and chickpea crops under rainfed conditions.

## Growth and Selenium Uptake in Maize as Influenced by Nitrogen Sources and Application Rates in Selenium-Amended Soil

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Selenium (Se) concentration is low in animal-derived food and humans due to its insufficient levels in forage and feed sources. This study investigated the effects of nitrogen (N) rates and forms on improving the biomass and Se concentration in maize forage. The soil in the pots was fertilized with N at the rates of 165 and 330 mg kg<sup>-1</sup>, without and with 3,4-dimethylpyrazole phosphate (DMPP). DMPP was added to soil at the rate of 0.01% of the applied N, while Se was added at the rate of 40 µg kg<sup>-1</sup>. In the second experiment, the effect of N forms (NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N+NO<sub>3</sub><sup>-</sup>-N) was evaluated on the growth and the accumulation of Se, N and phosphorus (P) in maize shoots in Se-fertilized (40 µg kg<sup>-1</sup>) and control soils. The Se-fertilized and controls soils were designated as Se(+) and Se(-), respectively. The soil texture was sandy and its pH was moderately acidic (5.40). The DMPP-treated soil had 27-42% higher NH<sub>4</sub><sup>+</sup>-N content at harvest than the non-treated soil. The DMPP treatment of soil also increased shoot Se content by 19-23% and Se uptake by 37-42%. A negative correlation was found between NO<sub>3</sub><sup>-</sup>-N: NH<sub>4</sub><sup>+</sup>-N ratio and shoot Se uptake, suggesting that NO<sub>3</sub><sup>-</sup>-N negatively affected Se uptake by maize. Results of second experiment depicted that of NH<sub>4</sub><sup>+</sup>-N application led to higher shoot Se content and uptake than NO<sub>3</sub><sup>-</sup>-N. In Se-unfertilized soil, NH<sub>4</sub><sup>+</sup>-N application increased Se content and uptake by 4 and 56%, respectively, whereas these increases were 39 and 83% on Se-fertilized soils. Similar to Se uptake, plants fed with NH<sub>4</sub><sup>+</sup>-N had higher P and N uptake by maize shoots than that fed with NO<sub>3</sub><sup>-</sup>-N. The SPAD value and shoot biomass were also higher under NH<sub>4</sub><sup>+</sup>-N application than NO<sub>3</sub><sup>-</sup>-N. These results imply that N fertilization, specifically combined application of Se and ammonium-based fertilizers could improve biomass yield and Se content of maize, which is likely to yield maize grains with improved Se contents.

## An Evaluation of the Effectiveness of Nano-Silicon Derived from Rice Husks as a Fertilizer for Wheat Production and Phosphorus Use Efficiency

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Nowadays, soil scientists are highly interested in the use of nanotechnology in agriculture. Hence, plant growth and nutritional interactions need to be investigated. Specifically, this study explored wheat growth and phosphorus (P) uptake in response to Nano-silicon (Si) derived from rice husk. Nano-Si was applied at 200 mg kg<sup>-1</sup> and traditional P was applied at 100 mg kg<sup>-1</sup> to wheat plants. The highest dry weight was obtained with the application of Nano Si+P treatment; while no significant effect was observed over the applied 100 mg P kg<sup>-1</sup>. Phosphorus fertilization significantly reduced Si concentrations in wheat plants. However, the decrease in Si concentration was partly satisfied by Nano-Si treatment. When P was applied together with Nano-Si, its uptake and phosphorus use efficiency (PUE) significantly increased in wheat plants as compared to other treatments. Nano-Si is derived from rice husk a sustainable waste biomass and is an important alternative Si fertilizer source, which can be a valid strategy for the effective use of P fertilizers. The depletion of available Si in soil can be recovered by applying Nano-Si as a fertilizer. The overall results obtained from the current research were encouraging.

## Soil Health Improvement through Green Manuring in Rice-Berseem Rotation under Calcareous Soils

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Soil health is degrading owing to improper use of agricultural practices. The use of organic amendments and the application of chemical fertilizers provide a window of opportunity in ameliorating soil health damage and managing it for sustainable use. Green manuring is the best strategy to overcome low soil fertility and aids plants in the absorption of nutrients by exploring the deep root system. A field study was conducted at Soil Chemistry Section during 2018-2021 to evaluate the effect of green manuring on soil physicochemical properties, soil health, and sustainable crop production under a rice-based cropping system. The berseem crop was grown, and after taking four cuttings, the fifth cutting was incorporated into the soil using a rotavator. Subsequently, the rice crop was sown on the same experimental unit. For this purpose, treatments T1: control, T2: recommended dose of NPK, T3: 100% of recommended dose of NPK+ green manuring, T4: 75% of recommended dose of NPK+ green manuring, T5: 50% of recommended dose of NPK+ green manuring were used. Pre-sowing soil analysis indicated that the experimental soil was deficient in available nitrogen (N), phosphorus (P), and potassium (K). Growth parameters of rice, including plant height, number of tillers per plant at maturity, and yield attributes, were recorded at harvest. The results demonstrated that green manuring significantly improved rice grain and straw yields compared to the conventional system. The highest grain yield (5.81 t ha<sup>-1</sup> in Year III) was obtained with green manuring combined with 75% of the recommended NPK dose. Moreover, post-experimental soil analysis revealed that green manuring caused significantly reduction in bulk density but improved in soil porosity, organic carbon content, and available N, P, and K. The findings suggested that the regular incorporation of green manure crops enhanced soil fertility, improved physicochemical properties, and promotes sustainable crop productivity under calcareous soil conditions. Therefore, green manuring can be recommended as an effective strategy for improving soil health and crop performance in rice-based cropping systems.

## Comparative Effects of Conservation and Conventional Tillage Systems on Soil Physicochemical Properties under Maize in Alkaline Calcareous Soils of Faisalabad

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Tillage practices play a critical role in regulating soil health and crop productivity, particularly in alkaline calcareous soils where nutrient availability is often very low. This study evaluated the comparative effects of conservation tillage and conventional tillage systems on soil physicochemical properties and maize (*Zea mays* L.) performance in the alkaline calcareous soils of Faisalabad. A field experiment was conducted at Soil Chemistry Section, Faisalabad using a Split Plot Design design with replicated treatments of conservation tillage and conventional tillage under maize cultivation. Main plots were Minimum tillage and conventional tillage, sub plot treatments were T1: Organic matter @ 01 ton ha<sup>-1</sup>(RD fertilizer)T2: Organic matter @ 02 ton ha<sup>-1</sup> (RD fertilizer), T3: Mulch @ 01 ton ha<sup>-1</sup> (RD fertilizer),T4: Mulch @ 02 ton ha<sup>-1</sup> (RD fertilizer),T5: No Mulch (RD fertilizer). Soil samples were collected at specified depths and analyzed for bulk density, soil organic matter, pH, electrical conductivity, available phosphorus, and potassium. Results indicated that conservation tillage significantly improved soil organic matter content, reduced bulk density, and enhanced available phosphorus compared to conventional tillage. Slight reductions in soil pH and improved soil aggregation were also observed under conservation practices. Moreover, maize growth parameters and grain yield showed positive responses under conventional tillage and T2 followed by T4, attributed to improved soil structure and nutrient availability. The findings suggest that conservation tillage enhances soil physicochemical properties and supports sustainable maize production in alkaline calcareous soils. Adoption of conservation-based practices may therefore contribute to improved soil health, resource-use efficiency, and long-term agricultural sustainability in semi-arid regions.

## Response of Wheat to Phosphate Fertilizer Sources in Multi-location Trials

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Multi-location wheat field trials were conducted at Sahiwal, Multan, and Kala Shah Kaku in Punjab, Pakistan, to evaluate the agronomic and economic performance of NIAB nutrient-enriched manure (NEM)-Phosphate compared with conventional di-ammonium phosphate (DAP). Across all locations, NEM-Phosphate produced a significantly higher mean grain yield of 5.11 t ha<sup>-1</sup>, over DAP (4.67 t ha<sup>-1</sup>), reflecting its improved nutrient use efficiency. Site-wise analysis indicated statistically similar yields at Sahiwal (5.35 t ha<sup>-1</sup>) and Multan (5.05 t ha<sup>-1</sup>), while Kala Shah Kaku recorded a lower yield (4.27 t ha<sup>-1</sup>), highlighting the influence of local agro-ecological conditions. Economic evaluation revealed superior profitability of NEM-Phosphate. The benefit–cost ratio (BCR) was 2.19, an 18.4% increase over DAP (1.85), while net returns reached Rs. 242,753 ha<sup>-1</sup>, approximately 29% higher than DAP. NEM-Phosphate also achieved a higher profit margin (54% vs. 46%) and a lower break-even price per 40 kg (Rs. 1601 vs. Rs. 1891), indicating greater financial efficiency. These improvements were primarily driven by higher yields combined with lower production costs. Overall, the strong positive correlation between enhanced grain yield and economic indices demonstrates that NEM-Phosphate consistently provides both agronomic and financial benefits. Across diverse wheat-growing environments, NEM-Phosphate proved to be a cost-effective, high-yielding, and economically sustainable fertilizer alternative to DAP, offering farmers increased productivity and profitability.

## Legume-Based Diversified Cropping Systems Increase Soil Organic Carbon Labile Pools and Microbial Carbon Use Efficiency under Long-Term Field Trial

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**Purpose:** Considering the pressing concerns regarding food security amid climate change, it is imperative to adopt sustainable agricultural practices that enhance soil organic carbon (SOC) sequestration and crop productivity. Therefore, the objective of this study was to investigate the changes in SOC pools, microbial metabolic quotient ( $qCO_2$ ), and extracellular enzymes activities under long-term cropping systems. **Materials and methods:** A long-term field experiment ( $\geq 12$  years) consisted of rice-wheat (W-R), maize-wheat (W-M), and legume-wheat (W-L) was established as randomized complete block design with three replications. The W-R system was used as reference, as it represents the most traditional cereal based rotation in the region. **Results and discussion:** After 12 years of experimentation, SOC increased by 20% in W-M and 43% in W-L compared to W-R ( $5.42 \text{ g kg}^{-1}$ ). Nitrogen (N), phosphorus (P), and potassium (K) availability was significantly enhanced under diversified systems ( $W-L > W-M > W-R$ ). Soil microbial biomass carbon (SMBC) and nitrogen (SMBN) increased by up to 43%, while cellobiohydrolase and  $\beta$ -glucosidase activities increased by 90% in the W-L and W-M systems compared to the W-R system. Similarly, SOC mineralization was 12–31% higher in W-L and W-M, and positively correlated with elevated labile SOC fractions. Recalcitrant carbon was unaffected by cropping systems. Notably, W-L reduced the microbial metabolic quotient ( $qCO_2$ ) by 19%, indicating a likely higher microbial carbon use efficiency. **Conclusions:** These findings demonstrate that diversified cropping systems, particularly those including legumes (W-L), increase SOC labile pools by improving  $qCO_2$  and stabilizing carbon pools, thereby offering a viable strategy for carbon sequestration and climate change mitigation, improving soil quality, and supporting global food security.

## Isolation and Characterization of Rice Residue Decomposing Bacteria and Their Role in Enhancing Soil Fertility and Wheat Productivity

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Wheat (*Triticum aestivum* L.) is an important staple cereal crop feeding 4.5 billion people globally. It is an important food source in many countries meeting the nutritional requirements of 30% of the world’s population. The optimization of wheat yield remains a challenge due to the poor soil fertility. Notably, in Punjab, Pakistan, soils commonly exhibit a deficiency in organic matter. Retention of rice crop residue in the field is a sustainable method by which the carbon and nutrients can be recycled in the soil. Conventional residue burning causes significant environmental pollution and leads to the loss of valuable soil nutrients. Bacteria can colonize the substrate faster and degrade the rice straw more efficiently. This study aimed to isolate and characterize rice residue-decomposing bacteria and to evaluate their effects on soil fertility and wheat productivity. Soil samples from natural degradation sites were collected and analyzed. Bacterial isolates were obtained through serial dilution and cultured on selective media based on their ability to produce cellulase enzyme. Morphological, biochemical and enzymatic characterization revealed several efficient lignocellulolytic bacterial strains belonging mainly to *Bacillus*, *Pseudomonas* and *Cellulomonas*. Enzyme activity assays indicated substantial cellulase production ranging from 2.3 to 4.8 IU mL<sup>-1</sup>, confirming their strong residue-degrading potential. A field experiment was conducted using a randomized complete block design in split-split plot arrangement with three replications to evaluate the impact of selected bacterial inoculants on rice residue decomposition, soil nutrient dynamics and wheat performance. In field experiment under different incubation periods [control, 0, 07, 14, 21 and 28 (days after culture application)] with four best performing bacterial strains and wheat seed inoculation (control=BS0 and BS1) were performed. Rice residue analysis, soil analysis, microbial characteristics and wheat attributes (physiological, growth and yield parameter) were recorded and analyzed by using analysis of variance (ANOVA) technique. Bacterial inoculation significantly accelerated residue decomposition by 35-45% along with soil organic matter increasing from 0.62% to 0.84%, available nitrogen by 18-24%, phosphorus by 12-16% and potassium by 10-14%. Enhanced nutrient availability translated into improved wheat growth and yield attributes. The highest grain yield (4.25 t ha<sup>-1</sup>) was recorded representing a 23.7% increase over the control (3.32 t ha<sup>-1</sup>). These findings demonstrate that lignocellulolytic bacterial inoculants can effectively accelerate rice residue decomposition, improve soil fertility and enhance wheat productivity, providing a sustainable alternative to residue burning in rice–wheat systems.

## Slow Mineral Nitrogen Release from Boron Coated Urea Improves Productivity of Sunflower Grown in Alkaline Soil

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Low nitrogen use efficiency (NUE) of urea fertilizer and widespread soil boron (B) deficiency are important factors limiting crop productivity. Boron coated urea (BCU) may be applied to compensate B requirements as well as help improve NUE of crop plants grown in alkaline soils. Present study aimed to slow down mineral nitrogen (N) release and B fortification of sunflower grown in alkaline soils using

BCU. In laboratory experiment, soil was treated with different formulations of BCU at 150 kg N ha<sup>-1</sup> and incubated for one month. Based on incubation study results, the best performing formulations in managing mineral N release from incubation study [BCU 1 (borax at 1% + castor oil at 0.6%) and BCU 2 (borax at 1% + mustard oil at 0.6%)] were tested under pot experiment. To examine B coating on urea, BCU was further characterized for various morphological and structural traits. Results indicated that BCU inhibited the release of ammonium-N and subsequently slowed down its conversion to nitrate-N compared to commercial urea. In a pot experiment, both BCU 1 and BCU 2 formulations improved the growth, yield, NUE, and B uptake of sunflower, however, BCU 2 accomplished the maximum position in competing the all treatments. Moreover, morphological and structural characterization further affirmed the BCU 2 as slow release formulation. Overall the findings demonstrate that BCU is an effective and sustainable alternative to conventional urea fertilizer for sunflower cultivation.

## Foliar Application of Macro- and Nano-silicon to Improve Wheat Growth in Herbicide-Contaminated Soil

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Herbicide contamination in agricultural soils negatively affects wheat growth, physiological performance, and productivity. Silicon (Si) has been widely reported to enhance plant tolerance against biotic and abiotic stresses, including chemical toxicity. The plants absorb Si from the soil solution primarily in the form of monosilicic acid. The present study aimed to evaluate the effectiveness of foliar-applied macro-silicon (MSi) and nano-silicon (NSi) in improving wheat growth under herbicide-contaminated soil. Buctril Super was sprayed on wheat seedlings after 15 days of germination. Five levels of NSi and MSi (0, NSi-25, NSi-50, MSi-25, and MSi-50 mg/L) were sprayed on two wheat crops at the tillering stage. The findings suggested that foliar application of NSi and MSi can effectively alleviate herbicide-induced stress and improve wheat productivity. Under non-stress conditions, NSi-25 mg L<sup>-1</sup> increased spike number in Akbar by 7.14%, whereas MSi-50 and NSi-50 mg L<sup>-1</sup> enhanced spike number in Dilkash by 7.69% compared to the control. The foliar application of MSi-25 and NSi-25 mg L<sup>-1</sup> improved plant height by 2.06% and 11.83% in Akbar and Dilkash, respectively. Under stress conditions, MSi-25 mg L<sup>-1</sup> increased plant height by 5.43% in Akbar and 11.24% in Dilkash relative to the control, demonstrating its stress-alleviating potential at lower concentrations. The foliar application of MSi-25 and NSi-25 mg L<sup>-1</sup> increased tiller number by 50% and 14.3% in Akbar and Dilkash, respectively. Herbicide stress reduced RWC and chlorophyll contents in Dilkash; however, foliar application of MSi-25 and NSi-50 increased chlorophyll a, and MSi-50 enhanced chlorophyll b in Akbar, while MSi-25 and NSi-25 improved carotenoid contents in Dilkash. Overall, silicon application mitigated herbicide toxicity, and both varieties responded positively, with slight varietal differences in performance.

## Integrating Polyhalite for Sustainable Potassium Nutrition in Cropping Systems

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Potassium (K) deficiency and the declining availability of secondary nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S) are major constraints to crop productivity in many agricultural soils, particularly in South Asia. Polyhalite (Poly4), a naturally occurring multi-nutrient mineral fertilizer containing K, Ca, Mg, and S, offers a sustainable alternative to conventional potash fertilizers. Field experiments were conducted to evaluate the agronomic potential of polyhalite as a partial or complete substitute for muriate of potash (MOP) and sulfate of potash (SOP) in major crops including cotton, wheat, and canola. The trials were arranged using different N, P, and K nutrient management combinations involving polyhalite, MOP, and SOP, while maintaining recommended rates of nitrogen and phosphorus. Results demonstrated that integrating polyhalite with conventional potash fertilizers significantly improved plant growth, yield components, and nutrient use efficiency (N, P, and K). In cotton, integrated potassium management increased seed cotton yield, lint yield, and fiber quality. In wheat and canola, polyhalite application enhanced tiller formation, grain yield, biomass production, and oil content. The combined use of polyhalite with conventional potash sources also improved nutrient uptake and potassium use efficiency compared with standard fertilization practices. These findings highlight the potential of polyhalite as a sustainable multi-nutrient fertilizer capable of improving crop productivity and soil fertility while reducing reliance on conventional potash fertilizers.

## Long-Term Raw Crop Residue Incorporation Improves Soil Multifunctionality in Semi-Arid Agroecosystems

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Globally, topsoil in most agroecosystems is being increasingly eroded by intensive land use practices. In semi-arid regions, restoring topsoil is particularly an important cue to optimize soil

multifunctionality, as the loss of soil organic carbon (SOC) is often accompanied by the loss of soil fertility. Here, we test the additive effects of different crop residue incorporation regimes on topsoil multifunctionality in a decade long field experiment on a maize-maize-potato cropping system. In each year, crop residues of a double maize rotation (Spring-Summer) were exposed to three contrasting managements, i.e., no residue incorporation (NRI), burnt residue incorporation (BRI) and raw residue incorporation (RRI), before planting a potato crop in the Fall. Our results showed a proportional increase in SOC stocks of up to 49–69% for RRI compared to BRI and NRI, respectively. Similarly, RRI also contributed to greater qualitative C stocks, such as particulate (PAOC) by 74–86% and mineral (MAOC) associated organic carbon by 63–107% than BRI and RRI. In contrast, BRI showed no discernible change in organic C stocks, but a significant destabilizing effect on soil pH, electrical conductivity (EC), and bulk density (BD). The water extractable organic carbon (WEOC) and the C-lability index were significantly reduced in BRI plots and consequently curtailed soil microbial activity and microbial biomass synthesis. Interestingly, BRI showed a decrease in P-acquiring enzymes compared to C- and N-cycling enzymes, possibly reflecting the different demand of soil microbes for different nutrients. In contrast, an ensured availability of C substrate by RRI significantly increased the population of cultivable microflora (e.g., bacteria, fungi, actinomycetes). Above all, RRI was very effective in improving soil ecosystem multifunctionality, as evidenced by improved soil structural stability due to greater C accumulation and stabilization, resulting in enhanced NPK availability, although the low soil structural stability index (SSI  $\leq 3\%$ ) still highlights the pervasive risk of land degradation.

## Effect of Compost Tea Application on Soil Health and Plant Growth

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Soil nutrient depletion and declining soil fertility are major challenges in agricultural systems relying heavily on chemical fertilizers. Long term use of chemical fertilizers has deteriorated soil quality. There is need to resort to organic sources of nutrients to improve soil quality. Compost tea is relatively very less used organic product. Compost tea is in fact extract of organic manures and compost. This study evaluated the agronomic performance and soil health responses to various organic amendments, including vermicompost, vermicompost tea, broiler litter compost, broiler litter compost tea, and municipal solid waste compost and its tea, compared with a conventional NPK fertilizer treatment. Compost tea was prepared by mixing compost and water in 1:5 ratio and leaving for 48 hours. Intermittent shaking was done. Then this mixture was passed through cotton cloth to get clear filtrate. A pot experiment was conducted under greenhouse conditions using maize as test crop. Treatments included, T0: Control, T1: NPK, T2: Vermicompost, T3: Vermicompost Tea, T4: Broiler litter compost, T5: Broiler litter compost tea, T6: Municipal waste compost, T7: municipal waste compost tea. Soil and plant samples were collected at different growth stages and analyzed using standard laboratory procedures. Results showed significant improvements in soil quality with the application of organic amendments. The highest soil organic matter (2.7%) and soil organic carbon (2.15%) were recorded in plots treated with broiler litter compost, while the highest cation exchange capacity (26 cmol kg<sup>-1</sup>) was observed with broiler litter compost tea. Soil pH did not show significant differences while soil EC

showed significant difference where broiler litter tea (3 dS/m), Vermi tea (2.5 dS/m) and municipal waste compost tea (2.7 dS/m) was applied. However, the highest nitrate nitrogen (18 mg kg<sup>-1</sup>) and available phosphorus (14.5 mg kg<sup>-1</sup>) were found in the NPK treatment. Plant nutrient analysis indicated the highest shoot nitrogen (2.9%) and phosphorus (0.36%) in the NPK treatment. All the treatments receiving compost and compost tea had plant K in sufficient range (1.5-3%). Overall, organic amendments improved soil quality and showed strong potential for sustainable nutrient management and enhanced soil productivity.

## Soil Health Responses to the Burning and Retention of Crop Residues in Wheat–Rice Cropping Systems

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The practice of burning crop residues at field results into substantial losses of plant nutrients, deterioration of soil health, and adverse environmental impacts. On the contrary, incorporation of crop residues in soil through rotavation ameliorates soil properties, enhances nutrient availability and uses organic crop residues efficiently. Moreover, it is also a step towards conservation and protection of environment from adverse effects of burning practices. For this comparative study, a long-term field experiment was conducted from 2014 to 2024 under wheat–rice cropping system at the Soil Chemistry Section, Ayub Agricultural Research Institute, Faisalabad. The study evaluated residue management practices including traditional method, residue burning, and residue incorporation through rotavation, under varying fertilizer doses using a split-plot design with three replications. The burning of crop residues significantly decreased the soil organic matter content during subsequent years and resulted in reduced crop yield. Continuous residue burning caused a marked decline in soil organic matter from 0.75% to 0.50% over the study period. Traditional cultivation also resulted in a reduction in soil organic matter (0.72%), though the decline was less pronounced than under residue burning. In contrast, residue incorporation through rotavation significantly enhanced crop growth and grain yield through improved soil organic matter content (0.91%) and nutrient use efficiency. Overall, findings from the 2014–2024 study demonstrate that crop residue incorporation through rotavation is an effective and sustainable management strategy for improving soil health, nutrient use efficiency, and productivity in wheat–rice cropping systems.

## Comparative Effects of Organic Manures on Labile Carbon Fractions under Integrated Nutrient Management

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Soil nutrient depletion and declining organic carbon levels are major threats to sustainable crop production and long-term soil health. Integrated nutrient management (INM) presents a promising solution to enhance nutrient availability and improve soil quality while maintaining crop productivity. This field study evaluated the impact of various combinations of organic manures and mineral fertilizers on nutrient dynamics, labile soil organic carbon (SOC) fractions, and the yield of hybrid maize (*Zea mays* L.). The experiment was conducted at Latif Experimental Farm, Sindh Agriculture University, Tandojam, using a randomized complete block design (RCBD) with 17 treatments and three replications. Treatments included sole applications of organic materials—farmyard manure (FYM), poultry manure (PM), sugarcane filter cake (FC), banana waste compost (BWC), wheat straw (WS)—and their combinations with 50% and 75% of the recommended dose of fertilizer (RDF). Results showed that integrated applications significantly improved maize growth, grain yield, and nutrient uptake compared to control and sole fertilizer use. The highest grain yield (70 maunds ha<sup>-1</sup>) and nutrient availability (N: 0.045%, P: 8.66 mg kg<sup>-1</sup>, K: 301.67 mg kg<sup>-1</sup>) were observed in T11 (BWC + 75% RDF). This treatment also showed the highest organic matter content (1.08%) and labile C fraction (12.95 mg g<sup>-1</sup>), alongside a notable increase in soil microbial populations. These findings confirm that banana waste compost, when combined with reduced mineral fertilizer, significantly enhances soil fertility, boosts beneficial carbon fractions, and sustains high maize productivity. Integrated nutrient management not only ensures crop yield but also restores soil health, offering a sustainable pathway for future agricultural systems.

## Integrated Nutrient Management Strategies for Plant Growth under Stress Environment

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Pakistan is ranked among the top 10 countries vulnerable to climate change, experiencing severe impacts including intensified floods, drought, heat waves, leading to agricultural productivity loss and severe food insecurity. Further increasing soil degradation, nutrient imbalance, changing climate and excessive reliance on chemical fertilizers have severely constrained crop performance and soil health worldwide. Integrated nutrient management (INM) has emerged as climate-resilient strategy to enhance plant growth and productivity under stress environments. In this context, INM offers a holistic approach by integrating chemical fertilizers, organic amendments, and biological inputs to optimize nutrient availability, improve soil productivity, and enhance crop resilience under adverse environmental conditions. The integrated nutrient management plays a vital role in regulating nutrient dynamics, improving soil physical, chemical, and biological properties, and enhancing plant physiological responses under stress environments. A series of pot and field experiments were conducted at Soil Chemistry Section and Soil bacteriology Section, AARI to evaluate the synergistic

interaction of inorganic fertilizers with organic sources (farmyard manure, compost, crop residues) and biofertilizers such as plant growth-promoting rhizobacteria (PGPR), mycorrhizae, and microbial metabolites improves nutrient use efficiency, soil organic carbon sequestration, and microbial activity and crop yield. These interactions contribute to improved root architecture, enhanced nutrient uptake, phytohormone production, and activation of plant defense mechanisms, thereby increasing tolerance to both biotic and abiotic stresses. Furthermore, INM plays a critical role in mitigating climate change impacts by reducing nutrient losses, lowering greenhouse gas emissions, and promoting long-term soil fertility. Evidence from recent studies demonstrated that INM-based systems performed better than sole chemical fertilization by improving crop yield stability, soil health indicators, and sustainability indices under stress-prone agroecosystems. It is concluded that integrated nutrient management is a climate-smart, resource-efficient, and environmentally sustainable strategy for improving plant growth under stress environments. Adoption of INM practices can significantly contribute to resilient agricultural systems, enhanced food security, and sustainable soil management under changing climatic scenarios.

## Bio-Fortification of Zn and Cu Improves Yield and Quality of Sorghum (*Sorghum Bicolor* L.) Fodder

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Sorghum is the primary summer fodder crop in Pakistan and across the world. Sorghum is deficient in a number of essential elements especially copper, zinc and iron, but it is a good source of energy. Animals are currently experiencing dietary shortages, particularly in zinc and copper and other trace elements, which has larger ramifications on cattle and ultimately on human health. The innovative method for enhancing the nutritional quality of crops is called bio fortification. Adding nutrients to sorghum by bio-fortification might enhance the biomass and quality of fodder, which would benefit both human and animal health. Hence, a field trial was carried out to know impacts of bio-fortification of Zn and Cu on quality and biomass production of sorghum fodder. The experiment was carried out in the research area, Department of Agronomy, College of Agriculture, university of Sargodha, Pakistan during summer 2024. The treatments were comprised of control (No application), foliar application of Zn at 0.5%, Zn at 1.0%, Cu at 0.25%, Cu at 0.5% alone, Zn at 0.5% with Cu at 0.25%, Zn at 0.5% with Cu at 0.5%, Zn at 1.0% with Cu at 0.25% and Zn at 1.0% with Cu at 0.5%. All these treatments were applied 40 DAS. Experiment was arranged in randomized complete block design having four replications. Combined foliar application of Zn at 1% + Cu at 0.5% enhanced plant height (25.77%), leaf area (24.77%), stem diameter (21.41%), number of leaves (69.56%), fresh fodder yield (47.17%), dry matter yield (43.17%), dry matter contents (27.64 %), crude protein contents (93.8%), ash contents (128.47%), plant Zn contents (131.52%) and Cu contents (201%). Moreover, lowest performance of these parameters was recorded under control. Maximum crude fiber content (56.83%) was produced

under control. So, it is concluded that bio fortification of Cu and Zn increase the yield and enhanced the quality of sorghum fodder, moreover it also enhanced the Zn and Cu contents of sorghum fodder.

## Appraisal of Best Method for Zn Biofortification in Selected Wheat Varieties in Sindh

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Zinc (Zn) is an essential micronutrient for plant growth and human nutrition, yet Zn deficiency is widespread in soils and diets of many developing countries, A field study was conducted to evaluate growth, yield, and grain Zn bioavailability of three high yielding Zn-efficient wheat varieties (Anmol-91, NIA-Amber, and NIA-Sarang) at ARC, Tandojam. The experiment was laid out in a randomized complete block split-plot design (RCB) with Zn application methods, using ZnSO<sub>4</sub>·H<sub>2</sub>O (33% Zn) and Zn-EDTA (5% Zn) applied as basal, foliar, and combined (basal + foliar) treatments at tillering, booting, and milky stages. The Zn fertilization significantly improved growth and yield: plant height by 4.0–6.6%, tillers per plant 14.8-20.7%, spike length 16.6-24.2%, spikelets per spike 5.8–8.6%, 1000-grain weight 7.7-13.8%, straw yield 8.9–15.7%, and grain yield 9.0–15.8% compared to control. Grain Zn increased from 47.53 ± 0.27 to 53.50 ± 0.44 mg kg<sup>-1</sup>, representing a 21.1 to 36.34% increase over control values, phytic acid decreased from 9.40 ± 0.05 to 5.79 ± 0.02 g kg<sup>-1</sup>, and PA:Zn ratios ranged 10.7-23.7, approaching ≤18 for improved Zn bioavailability. Total daily absorbed Zn (TAZ) ranged 1.20-2.64 mg day<sup>-1</sup>, and Anmol-91 showed the highest Zn accumulation. The combined basal and foliar application of 0.250 kg Zn ha<sup>-1</sup> as Zn EDTA with 0.3% foliar spray was most effective in enhancing wheat growth, yield, and Zn bioavailability, providing a practical strategy for Zn biofortification in Pakistan and similar developing countries.

## Evaluating Zinc Bio-Fortification Potential of Newly Evolved Rice Genotypes under Agro-Climatic Conditions of Tandojam

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Rice (*Oryza sativa* L.) is the most crucial cereal globally and serves as a vital source of energy, carbohydrates and zinc (Zn) for individuals whose diets are primarily rice-based. To improve the Zn content in rice, it is essential to know biofortification potential of rice genotypes. In this regard a field study was carried out to evaluate the biofortification potential and yield response of rice genotypes (Sarshar-200-1, Shandar-100-3, NIA-Mehran-100-2, Shadab-100-3, and Shua-92-200-2) under agro-climatic conditions of Tando Jam, at Experimental Farm of Nuclear Institute of Agriculture (NIA), Tando

Jam (Longitude North 25° 26'0" and 68° 32'0" East latitude), Sindh Pakistan. Different Zn management strategies: no Zn (control), soil application (10 kg Zn ha<sup>-1</sup>), foliar application (0.25% Zn at booting and grain-filling stages), and combined soil plus foliar application (5 kg Zn ha<sup>-1</sup> with 0.25% foliar spray at booting and grain filling). The findings indicated that zinc application had a notable influence on rice yield and biofortification capability of genotypes. The concentration and accumulation of zinc in potential genotypes showed significant increases, particularly at integrated applications (soil and foliar). Across genotypes, the combined soil–foliar Zn treatment produced the highest paddy yield (6.7 t ha<sup>-1</sup>), followed by soil Zn (6.4 t ha<sup>-1</sup>), foliar Zn (6.2 t ha<sup>-1</sup>), and the control (5.8 t ha<sup>-1</sup>). Moreover, the combined Zn application proved most effective in enhancing both grain yield and grain Zn concentration, achieving the highest grain Zn content (55.36 mg kg<sup>-1</sup>) across genotypes. Therefore, combined application can be suggested to achieve yield and Zn biofortification potential of rice genotypes for end users and concerned rice breeding program.

## Soil Physicochemical Properties and Maize Yield Responses to Organic Nutrient Amendments

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Soil fertility decline resulting from prolonged reliance on inorganic fertilizers has become a major constraint to sustainable maize (*Zea mays* L.) production in Pakistan. Organic nutrient management offers a promising strategy to restore soil health while sustaining crop productivity. This study assessed the comparative effectiveness of different organic amendments on soil physical quality, soil organic matter accumulation, and maize growth and yield under field conditions. A field experiment was conducted using a randomized complete block design with three organic amendments: poultry manure (PM), farmyard manure (FYM), and compost (COMP) prepared from sugarcane (*Saccharum officinarum* L.) leaves, water hyacinth (*Eichhornia crassipes* (Mart.) Solms), cow dung, and urine, alongside an unamended control. Organic amendments significantly improved soil physical properties. Soil dry bulk density decreased by up to 11.30%, while soil porosity increased by 13% compared with the control. Compost application markedly enhanced soil structural stability by increasing the proportion of medium-sized aggregates (56.33%) and reducing both large (15.87%) and fine aggregates (24.80%). Soil organic matter content increased significantly ( $P \leq 0.005$ ), showing improvements of 122%, 101%, and 66.66% under COMP, PM, and FYM treatments, respectively. Enhanced soil quality resulted in improved crop performance. Compost treatment significantly increased ( $P \leq 0.01$ ) seedling emergence, plant height, cob length, grains per cob, 1000-grain weight, and grain yield relative to other treatments. These findings demonstrate that compost-based nutrient management substantially improves soil structure, enhances organic matter accumulation, and increases maize productivity. Adoption of compost as a key organic amendment can contribute to sustainable soil restoration, reduced dependency on synthetic fertilizers, and climate-resilient maize production systems.

## Optimization of Nitrogen, Phosphorus and Potassium Fertilizer Levels For Yield and Mineral Content of Okra (*Abelmoschus esculentus* L.) Genotypes

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A field study was conducted at ARI Mingora, Swat, to evaluate the effect of different N-P-K levels on growth, yield, and nutrient content of three okra genotypes: Swat Green, Shangla Green, and ARI-OS19. The experiment used a randomized complete block design with split-plots, including four N-P-K levels (0, 90-60-45, 120-90-60, and 150-105-75 kg ha<sup>-1</sup>) and three replications. Results showed that both genotypes and N-P-K levels significantly influenced growth, yield, and leaf and fruit nutrient content. Swat Green exhibited the tallest plants (187 cm), while Shangla Green achieved higher pod yield (14872 kg ha<sup>-1</sup>) and mineral accumulation. The highest growth and yield were recorded at 150-105-75 kg N-P-K ha<sup>-1</sup>, while control plots performed lowest. Nutrient concentrations in leaves and fruits increased with fertilizer application, enhancing quality. Genotype × fertilizer interaction was generally non-significant, indicating similar responses among genotypes. In conclusion, application of 150-105-75 kg N-P-K ha<sup>-1</sup> optimally improved growth, yield, and mineral content of okra, with Shangla Green showing superior overall performance under Swat conditions.

## Enhancing Phosphorus Use Efficiency of Wheat by Applying Polymer Coated Phosphatic Fertilizers

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Phosphorus availability is low in Pakistani soils due to their alkaline calcareous nature. Poor wheat production is the major problem all over the world and it is also associated to low phosphorus use efficiency (PUE) along with other factors. Polymer coated fertilizer is comparatively a new idea among the various technologies that are being used to increase the phosphorus use efficiency. A field trial was conducted to compare the performance of polymer coated diammonium phosphate (DAP), triple super phosphate (TSP), single super phosphate (SSP) and nitro-phosphate (NP) for increasing growth, yield and phosphorus use efficiency of wheat. Polymer coated and uncoated fertilizers were applied at different rates i.e. 25, 50, 75 and 100% of the recommended rate. The study was planned according to randomized complete block design (RCBD) along with three replications. Standard procedures were used to determine different yield and growth parameters. Yield, growth and physicochemical parameters such as number of tillers, plant height, number of grains per spike of wheat, 1000 grain

weight, number of spikes, phosphorus, nitrogen and potassium concentrations in grain and straw and phosphorus use efficiency (PUE) of wheat were determined.

## Contrasting Effects of Sewage Sludge and Sewage Sludge-Derived Biochar on Wheat Straw Mineralization in Sandy and Clayey Textured Soils

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Deleterious effects of sewage sludge (SSL) on soil quality can be overcome by converting SSL into SSL-biochar (SSL-B). Sewage sludge was pyrolyzed into biochar at 600 °C for 30 minutes. Sandy and clayey textured soils were amended with wheat straw, SSL and SSL-B and incubated for 30 days following a completely randomized experimental design. Sewage sludge and SSL-B had contrasting effects on wheat straw decomposition, but cumulative CO<sub>2</sub> efflux was higher in clayey than sandy soil. Sewage sludge biochar caused positive priming of native soil C in clayey whereas suppressed wheat straw decomposition in sandy soil. Microbial biomass C was significantly higher in SSL-B and wheat straw treatments in both soils. Cold water-, hot water- and salt-extractable organic C fractions indicated significant changes in soil organic matter quality. Changes in specific ultraviolet absorbance (SUVA), aromaticity and, hydrophobic and hydrophilic properties of dissolved organic C suggested contrasting effects of SSL and SSL-B on soil organic C quality. Total organic C contents were significantly higher in both soils when wheat straw was amended with SSL-B and SSL. Significantly less values of microbial metabolic quotient (qCO<sub>2</sub>) in wheat straw amended SSL-B than wheat straw amended with SSL could suggest higher microbial C utilization efficiency in both soils. Our study provided evidence that SSL can be better utilized as SSL-B to improve microbial activity, soil organic C and soil biochemical quality in nutrient and organic matter depleted soils in semi-arid regions.

# Soil Microbiology, Biochemistry and Biotechnology

## Microbial and Enzymatic Drivers of Microplastic Biodegradation in Agricultural Soils: A Systematic Review

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Agricultural soils are major sinks for microplastics, but evidence on the microbial and enzymatic drivers of biodegradation remain fragmented. This review examined microorganisms, enzymatic mechanisms, environmental conditions, polymer types, and methodological approaches associated with microplastic biodegradation in agricultural soil environments. We included English-language primary empirical studies of agricultural soils, or microbiologically relevant systems derived from them, that examined microplastic polymers and reported biodegradation-related outcomes. Scopus, Web of Science Core Collection, and PubMed/MEDLINE were searched on 15 March 2026. Two reviewers independently screened records and appraised study quality using design-appropriate Joanna Briggs Institute tools. Findings were synthesized using structured narrative synthesis with supplementary vote counting based on direction of effect. Fifteen studies published between 2022 and 2026 were included, representing at least 1001 experimental units across 12 studies reporting a single analyzable sample size. Ten studies reporting mass loss favored the intervention or more biologically active condition (low certainty). Molecular-weight reduction was reported in five studies, four favoring the intervention and one showing no clear difference (very low certainty). Direct mineralization was reported in only one study and favored the intervention (very low certainty). Surface or structural change and enzyme or biodegradation-rate metrics were each reported by 12 studies and uniformly favored the intervention (both low certainty). Favorable signals clustered in rhizosphere systems, amended soils, inoculated consortia, gut-mediated models, and alkaline or biochar-modified contexts, with stronger evidence for Polybutylene Adipate Terephthalate-based polymers, Polybutylene succinate-based polymers, and PLA-based polymers than for PE-dominant materials. Agricultural soils may support context-dependent biological transformation of some microplastics, especially in biologically active microsites and for hydrolysable biodegradable polyesters. However, the evidence is much stronger for early-stage transformation than for complete biodegradation, and confidence is constrained by proxy-heavy outcomes, sparse field evidence, and suspected reporting bias. Claims of rapid or complete mineralization under field conditions therefore remain premature.

## Isolation and Characterization of Rice Rhizosphere Microbes for Rice Residues Management

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Punjab contributes nearly 70% of Pakistan’s national rice production, generating over 20 million tons of rice straw annually. Much of this straw is burned in fields, causing greenhouse gas emissions, particulate pollution, soil microbiome disruption, and fertility loss. Sustainable rice straw management is essential to mitigate environmental impacts. This study aimed to isolate and characterize rhizosphere-associated microbial communities from major rice-growing districts of Punjab. Soil samples from rice rhizospheres were subjected to serial dilution and purification using streak plate methods. Enzymatic assays (lignin, cellulose, starch hydrolysis) were performed to assess decomposition potential. Out of 105 bacterial strains, those positive for hydrolytic enzymes will be further evaluated under incubation studies to explore their role in straw degradation.

## Biodegradation of Hydrocarbons and Mitigation of Greenhouse and Toxic Gas Emissions from Anaerobic Environments

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Hydrocarbon contamination is ubiquitous globally due to oil exploration, production and/or transportation posing a significant threat to the terrestrial and marine environments. Hydrocarbons persist in anaerobic environments such surface water bodies and groundwater, wetlands, estuaries and coastal sediments, and subsurface soils. Hydrocarbon biodegradation under anaerobic conditions is a complex process that involves various microbial communities and metabolic pathways. We investigated the biodegradation of different groups of hydrocarbons (aliphatic and aromatics) under different anaerobic (nitrate-, iron-, and sulfate- reducing, and methanogenic) conditions in oil sands tailings. Oil sands tailings are produced during petroleum recovery from oil sands ore with hot water. More than 1.5 billion m<sup>3</sup> of tailings have been deposited in ponds, covering an area of ~270 km<sup>2</sup> in Alberta Canada, pending reclamation. We also investigated the nature of gas emissions during hydrocarbon biodegradation under anaerobic conditions. Our results inform the oil sands industry to strategize microbial redox processes to biodegrade hydrocarbons while mitigating the emissions of greenhouse (methane) and toxic (reduced sulfur) gases during tailings storage in ponds and reclamation in wetlands or end-pit lakes.

## Potential of Bioactivated Co-Composted Biochar for the Remediation of Chromium and Nickel-Contaminated Soil

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Accumulation of heavy metals (HMs) adversely affects soil biological and physicochemical properties, leading to poor nutrient availability and reduced crop productivity. Biochar (BC), due to its stability, affordability, and eco-friendliness, has gained attention for remediation of metal-contaminated soils and long-term carbon sequestration. This study investigated co-composted biochar derived from plant leaf compost and walnut peel biochar for mitigating chromium (Cr) and nickel (Ni) toxicity in maize. A pot experiment was conducted in the greenhouse of the Department of Forestry, Shaheed Benazir Bhutto University Sheringal, with eight treatments: Control, Compost, Biochar, Co-composted biochar, Bioactivated Co-composted biochar, Cr + Ni stress (25 mg kg<sup>-1</sup> Cr + 90 mg kg<sup>-1</sup> Ni), and their combinations with amendments, arranged in a completely randomized design. Results showed maximum growth, yield, and physiological improvement with bioactivated co-composted biochar under Cr and Ni stress. Minimum Ni concentration in shoot (5.0 mg kg<sup>-1</sup> DW) and root (2.33 mg kg<sup>-1</sup> DW) occurred under bioactivated co-composted biochar treatment. Similarly, minimum Cr accumulation in shoots (8.83 mg kg<sup>-1</sup> DW) and roots (6.17 mg kg<sup>-1</sup> DW) occurred under normal conditions. Maximum remediation factors for Ni (0.05%) and Cr (0.21%) were recorded with compost under combined stress. In conclusion, co-composted biochar alleviates Cr and Ni stress in maize, enhancing growth, physiology, and heavy metal bioaccumulation efficiency.

## Enhanced Biodegradation of Microplastic in Soil Using Bacteria Isolated from Mangrove Ecosystem

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With growing plastic use (~300 million tonnes annually), micro plastics (MPs) accumulate in soil, disrupting properties, microbiota, and plant growth. MPs enter the food chain and may affect human and ecosystem health. Their aging alters chemical and physical characteristics, influencing reactivity. This study addressed soil pollution by MPs in mangrove ecosystems. Soil samples were collected, serially diluted, and bacterial strains were isolated, identified, and evaluated for plastic degradation. Optimal degradation conditions were determined (pH 5–9, temperature 25–35°C, MPs 500–2000 ppm). Degradation was measured by weight loss, and products analyzed using GC-MS, FTIR, and SEM. One-way ANOVA was used for statistical analysis.

## Precursor–Inoculum Synergy for Enhanced Glyphosate Degradation and Legumes Performance in Naturally Contaminated Soils

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Glyphosate contamination in soil adversely affects plant growth, physiological performance, and food safety. Microbial remediation offers a sustainable approach to mitigate these negative impacts. Three bacterial cultures (BCs), applied alone and in combination with L-tryptophan (L-TRP) as a co-substrate, were evaluated for their ability to degrade glyphosate and improve the growth of mungbean and soybean grown in glyphosate contaminated soil (368 mg kg<sup>-1</sup>). Glyphosate stress significantly reduced agronomic, physiological, and biochemical attributes of both crops. However, bacterial inoculation mitigated these adverse effects. Compared with the uninoculated control, BC treatments improved plant growth (up to 55.9%), physiological traits (57.7%), nutrient uptake (51.3%), and soil microbial biomass carbon and nitrogen by up to 50.1% and 39.6%, respectively. Among treatments, BC3 combined with L-TRP showed superior performance, increasing plant growth (72.2%), physiological traits (82.4%), and nutrient uptake (65.2%), while reducing stress-related enzymatic activity (70.2%). It removed 99.4% glyphosate and significantly reduced its accumulation in roots (80.9%), shoots (70.1%), and grains (93.3%). Bacterial cultures, particularly when combined with L-TRP, are highly effective for glyphosate degradation and improving crop performance. This integrated approach offers a sustainable solution for remediating glyphosate contaminated soils and reducing risks to the food chain.

## Field Based Assessment of Nano-DAP as an Alternative Phosphorus Source for Sustainable Maize Production

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Phosphorus (P) management remains a critical challenge in sustainable maize production due to low P use efficiency arising from fixation and limited bioavailability in soils, particularly under intensive fertilization systems. Emerging nano-fertilizer technologies offer a potential strategy to enhance nutrient use efficiency while reducing fertilizer inputs. This field study was conducted to compare the performance of conventional diammonium phosphate (DAP) and Nano-DAP applied at 80% and 100% of the recommended P dose on maize growth, yield, and relative fertilizer use efficiency under spring season conditions. The experiment was carried out at the Maize and Millet Research Institute, Sahiwal,

Pakistan, using a randomized complete block design with three replications and five treatments, including an unfertilized control. Fertilizer application resulted in numerical improvements in plant height, ear length, and grains per ear compared with the control; however, these growth attributes did not differ significantly among treatments, indicating adequate baseline nutrient availability for vegetative development. In contrast, grain yield responded significantly to phosphorus fertilization, with all fertilized treatments outperforming control. Both Nano-DAP applied at the full recommended dose and conventional DAP applied at 80% of the recommended dose produced the highest grain yields, highlighting improved fertilizer use efficiency under optimized P management. The enhanced yield response under Nano-DAP, despite limited changes in morphological traits, suggests improved P availability during reproductive stages and more efficient assimilate partitioning. The comparatively lower yield under reduced Nano-DAP application indicates a dose-dependent response, emphasizing the importance of meeting minimum crop P requirements. Overall, the findings demonstrate that Nano-DAP has the potential to enhance phosphorus use efficiency and sustain maize productivity, offering a promising pathway for reducing fertilizer inputs and improving the sustainability of soil fertility management in maize-based cropping systems.

## River-Polluted Water Transformation in to Agronomically Beneficial Vermiwash via Eisenia Fetida-Based Vermifiltration System and its Impact on *Spinacia Oleracea*

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Rivers are vital water resources supporting domestic, industrial, agricultural, and livestock needs, yet anthropogenic activities degrade their quality through toxic and microbial contamination, posing risks to ecosystems and human health. This study aimed to develop an earthworm-based filtration system for wastewater remediation, transforming polluted water into nutrient-enriched vermiwash, and to evaluate the effects of vermicompost and vermiwash on seed germination and seedling growth of *Spinacia oleracea*. Different germination media (soil with polluted water, vermicompost, and vermiwash at 20%, 40%, and 60%) were tested. Physicochemical properties (pH, nutrients, EC, and organic carbon) were measured before and after plant growth. Germination indices (IoG, MGT, MDG, SoG, CoG, GP, PV, GV) and growth parameters (shoot and root length, leaf traits, biomass) were recorded, along with bacterial diversity in vermiwash. Results showed that vermifiltration effectively converted polluted water into nutrient-rich vermiwash, reduced heavy metals, and improved substrate quality. Vermicompost and vermiwash treatments significantly enhanced germination (78.8–85.5%), reduced germination time, and improved growth parameters compared to control. The highest improvements in leaf traits and biomass were observed with vermiwash-60. Nutrient depletion after growth indicated active plant uptake. Beneficial bacterial species, including *Bacillus* spp. and *Lysinibacillus fusiformis*, were identified in vermiwash. Overall, vermiwash and vermicompost proved effective as organic biofertilizers, improving water quality and enhancing germination and growth of *S. oleracea*.

## Integrated Application of Salicylic Acid and Beneficial Bacterial Cultures for Sustainable Mungbean Production under Salinity Stress

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Soil salinity is a major constraint to crop production worldwide and poses a serious challenge to sustainable agriculture and food security. Mungbean (*Vigna radiata* L.), despite its high nutritional value, is particularly sensitive to salinity stress, which severely limits its growth and yield. This study investigated the potential of foliar-applied salicylic acid (SA) and plant growth-promoting rhizobacteria (PGPR) to improve mungbean performance under saline conditions. A pot experiment was conducted using two PGPR strains, *Achromobacter denitrificans* MH-6 and *Alcaligenes faecalis* MH-2, applied individually and in combination with SA under salinity levels of EC 5 and EC 7 dS m<sup>-1</sup>. Salinity stress significantly reduced plant growth, causing declines in root length (11.0% and 27.8%), shoot length (13.0% and 28.0%), and fresh biomass (14.5% and 30.0%) compared with the corresponding non-saline controls. In contrast, the combined application of SA and PGPR effectively mitigated these negative effects, increasing root and shoot lengths by 66.0% and 53.0%, and root and shoot fresh weights by 51.1% and 52.7%, respectively, relative to the saline control. Improvements in photosynthetic performance were evident, with marked increases in fluorescence yield (64.7%), quantum yield (72.7%), photosynthetically active radiation (71.4%), and electron transport rate (48.8%), accompanied by enhanced potassium and phosphorus uptake. Furthermore, the combined SA and PGPR treatment reduced the activities of antioxidant enzymes, including superoxide dismutase (50.0%), peroxidase (50.6%), and catalase (46.8%), compared with the unamended saline control, indicating lower oxidative stress and improved cellular balance. Overall, the synergistic application of salicylic acid and PGPR emerges as an effective and environmentally friendly approach to alleviate salinity-induced stress and enhance the growth and productivity of mungbean under saline conditions.

## Developing Climate-Resilient Rice Production Systems through Integrated Biochar, Plant Growth Promoting Rhizobacteria, and Fertilizer Management

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Climate-resilient agricultural systems are essential for sustaining crop productivity and ensuring food security under increasing climate variability and extreme weather conditions. This study was conducted to evaluate the effects of biochar combined with plant growth-promoting rhizobacteria (PGPR) on soil health, plant growth, and rice yield as a strategy for developing a climate-resilient

production system. Biochar was prepared from rice straw, while potential PGPR strains were obtained from the Gene Bank of the Soil Microbiology Laboratory, Soil and Environmental Sciences Division, Nuclear Institute of Agriculture (NIA), Tandojam, Sindh. Rice was cultivated at Gharo, District Thatta, Sindh. Biochar combined with PGPR was applied to the soil before transplanting along with different rates of chemical fertilizers. Treatments receiving biochar alone consistently maintained higher bacterial populations ( $123 \times 10^7$  cfu g<sup>-1</sup> soil) compared to other treatments. In contrast, fertilizer only treatments exhibited lower bacterial counts, while the control maintained moderate microbial levels. The combined application of biochar and PGPR with either 75% or 100% of the recommended chemical fertilizer dose resulted in the maximum plant height (105.35 cm) and the highest number of tillers (29 plant<sup>-1</sup>), were observed at 100% fertilizer application. Moreover, the addition of biochar alongside full fertilizer rates significantly enhanced yield components, producing the maximum number of panicles (16.92 plant<sup>-1</sup>), longest panicles (28 cm), and highest grain (8.65 t ha<sup>-1</sup>) and straw yields (14.80 t ha<sup>-1</sup>), followed by treatments combining biochar with 75% of chemical fertilizers. Furthermore, biochar-amended treatments slightly reduced soil electrical conductivity (2.01 dS m<sup>-1</sup>), indicating improved soil conditions and reduced salinity stress. These treatments also increased soil organic matter and organic carbon contents, with biochar-alone treatments showing the greatest improvement. In conclusion, the integrated application of biochar and PGPR bio-inoculants has strong potential to improve soil health and enhance rice growth and productivity, thereby supporting the development of climate-resilient agricultural systems.

## Impact of Gibberellic Acid and Cytokinin in Improving Growth and Physiology of Maize (*Zea mays* L.) under Drought Stress

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The drought stress is among the main factors that limit the production of maize (*Zea mays* L.), particularly in the semi-arid regions. Cytokinin (CK) and gibberellic acid (GA), plant growth regulators (PGRs), can assist in reducing the damage of drought by affecting physiological and biochemical processes. This experiment was conducted to evaluate the effects of GA and CK individually and combined with each other on the growth of maize and physiological reactions to drought. Completely Randomized Design (CRD) was followed in designing the research with four replications and seven treatments. The treatments were GA 5 ppm and 10 ppm, CK 5 ppm and 10 ppm, a combination of GA + CK, and a control. The PGR was utilized as a soil treatment prior to sowing and as a foliar spray after emergence, and drought was maintained throughout the experiment. The combination of GA and CK with a concentration of 10 ppm demonstrated the best result overall. This treatment had a positive impact on the following parameters: germination (84.2%), plant height (84.5 cm), area of the leaf (235.3 cm<sup>2</sup>), relative water content (RWC) (83.3%), and chlorophyll concentration (1.57 mg/g). The nutrient uptake by treated plants was greatly improved, particularly with the combined application of GA and CK. The available nutrients and soil organic matter were also enhanced in pots to which PGRs had been placed, according to the post-harvest soil analysis. It is revealed that GA and CK at 10 ppm can be an efficient yet cost-effective factor to mitigate drought stress and preserve maize yield in the areas with limited water resources.

## Synergistic Use of Biochar and ZnSB under Cadmium Stress in Spinach (*Spinacia oleracea*)

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Cadmium (Cd) contamination in agricultural soils of Pakistan, particularly in Punjab, severely impacts spinach (*Spinacia oleracea*) production by inhibiting germination, increasing heavy metal accumulation in edible parts, and reducing plant growth. This poses a serious threat to human health and the food chain. Biochar is an important organic amendment that immobilizes heavy metals in soil, while zinc-solubilizing bacteria (ZnSB) enhance zinc (Zn) availability and reduce Cd uptake by plants. This pot trial was conducted to assess the combined and individual effects of biochar and a ZnSB consortium (ZM27 + AN31) on germination, growth, and nutrient status of spinach under Cd stress, as well as their impact on Cd uptake by the plant. The objectives of this study were to evaluate germination rate, morphological parameters (shoot and root length, and biomass), Cd concentration in edible parts, and physiological responses such as antioxidant production. The experiment was carried out in a wirehouse at the Department of Soil Science, The Islamia University of Bahawalpur. Pots containing 3 kg of soil were arranged in a completely randomized design (CRD) with three replications per treatment. The treatments included: T<sub>0</sub> (control), T<sub>1</sub> (ZnSB consortium), T<sub>2</sub> (biochar at 1%), T<sub>3</sub> (biochar at 2%), T<sub>4</sub> (ZnSB + biochar at 1%), and T<sub>5</sub> (ZnSB + biochar at 2%). Three levels of Cd stress were applied to evaluate Cd availability under different treatments. The combined application of ZnSB and biochar produced the best results, significantly increasing germination rate, shoot and root length, and biomass, while reducing Cd bioavailability. This synergistic effect can be attributed to improved adsorption, enhanced nutrient solubilization, and stress mitigation. The findings indicate that the application of ZnSB and biochar, both individually and in combination, offers a sustainable strategy for Cd remediation in leafy vegetables, particularly spinach, thereby improving yield and food safety in contaminated soils. Further field trials are recommended to validate these results under diverse environmental conditions.

## Synergistic Application of Arsenic Resistant Endophytic Bacteria and Ag-Fe-CNTs Composite to Improve the Growth and Yield of *Zea mays* L. in Arsenic Contaminated Soil

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Arsenic contamination in soil poses serious environmental and public health challenges in Pakistan. Carbon nanotubes (CNTs), due to their high surface area and strong adsorption capacity, have been widely applied in environmental remediation. This study investigated a composite remediation strategy for arsenic immobilization in contaminated soil by combining silver–iron-doped CNTs (Fe–Ag CNTs) with arsenic-resistant endophytic bacteria to reduce arsenic bioavailability and improve maize (*Zea mays* L.) growth. The research was conducted in four stages. First, arsenic-resistant endophytic bacteria were isolated from plants growing in contaminated sites and screened for arsenite tolerance and oxidation potential. Second, selected strains were evaluated under controlled growth conditions for plant growth-promoting traits. Third, CNTs were synthesized from rice straw via chemical vapor deposition and modified with iron and silver using a binary salt treatment. Finally, a pot experiment was performed to assess the combined effects of Fe–Ag CNTs and bacterial strain RS-13 on arsenic immobilization and maize performance. Results showed that arsenic application (40 and 80 mg kg<sup>-1</sup>) significantly induced phytotoxicity, reducing plant growth, physiological performance, and biochemical attributes. However, combined application of Fe–Ag CNTs and RS-13 alleviated arsenic stress by enhancing growth, chlorophyll content, root development, and grain quality, supported by increased antioxidant enzyme activity. The integrated treatment significantly improved arsenic immobilization in soil, with higher proportions of arsenic associated with Fe, Al, and Mn fractions, showing 157% and 74% increases compared to control at 40 and 80 mg kg<sup>-1</sup> arsenic, respectively. Moreover, the combined treatment reduced arsenic accumulation and translocation in maize, thereby lowering health risk and cancer indices. Correlation analyses revealed strong interactions between bacterial functional traits, nanocomposite properties, and plant responses, indicating synergistic effects between microbial activity and CNT-mediated arsenic stabilization. Overall, the findings demonstrate that Fe–Ag CNTs coupled with arsenic-resistant endophytic bacteria provide an effective and sustainable strategy for arsenic remediation and crop productivity enhancement, aligning with SDG 2, SDG 12, SDG 13, and SDG 15.

## Stimulating Native Microbial Electrical Networks to Reduce Methane Emissions in Flooded Rice Paddy Soils

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Flooded rice paddy soils are a major anthropogenic source of methane, a potent greenhouse gas contributing significantly to global climate change. Under continuous flooding, oxygen is rapidly depleted, creating anaerobic conditions that promote the activity of methanogenic microorganisms. These microbes generate methane during the decomposition of organic matter, resulting in high emissions from rice cultivation systems. Reducing methane emissions without compromising crop productivity remains a central challenge in sustainable agriculture. This study explores a natural, microbial-based approach to suppress methane formation by stimulating native microbial electrical networks in flooded rice soils. The proposed mechanism involves enhancing the activity of iron-reducing bacteria, which compete with methanogens for electrons during organic matter degradation. The addition of ferric iron [Fe(III)] provides an alternative, energetically favorable electron acceptor, thereby diverting electrons away from methanogenic pathways. This process promotes direct

interspecies electron transfer (DIET), where electrons are exchanged directly between microbial partners through conductive biological structures. Stimulating these electrical interactions within the soil microbial community is expected to reduce methane production while preserving natural biogeochemical processes. Laboratory incubation experiments will be conducted using soil collected from active rice paddies and maintained under flooded, oxygen-free conditions to simulate field environments. Treatments will include ferric iron-amended soils and untreated controls. Over a four-to eight-week incubation period, methane emissions will be monitored periodically alongside changes in iron speciation to assess the extent of iron reduction. These measurements will enable comparison between treatments and provide insight into microbial competition for electrons. Soils amended with ferric iron are expected to exhibit substantially lower methane emissions than control soils, indicating that stimulation of native iron-reducing microbial communities and their electrical interactions can effectively suppress methanogenesis. This approach offers a low-cost, environmentally friendly, and scalable strategy for methane mitigation in rice agriculture, supporting climate-smart farming and sustainable soil management.

## Unravelling The Mechanisms by which Iron Doped Silicon Nanoparticles Regulate Uptake, Transport and Detoxification of Cd in Rice (*Oryza sativa* L.)

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Cadmium (Cd) is highly toxic and mobile in soils, posing significant risks to rice quality and productivity. Innovative strategies are needed to reduce Cd uptake and accumulation in rice while enhancing its resilience to contamination. The current study focused on the synthesis, characterization, and evaluation of iron oxide nanoparticles (IONPs), silicon dioxide nanoparticles (SIONPs), and iron-doped silicon nanoparticles (IDSNPs) for their potential to enhance rice tolerance to Cd stress. Soils were amended with SIONPs, IONPs, and IDSNPs at 1% and 2% (w/w). Results showed that the greatest improvements in plant growth occurred with 2% IDSNPs (T6), where shoot dry weight, root dry weight, root length, and shoot length increased by 38%, 42%, 53.3%, and 27%, respectively. Similarly, T6 significantly enhanced photosynthesis, internal CO<sub>2</sub> concentration, stomatal conductance, and transpiration rates, with increases of 20.9%, 18.8%, 126.6%, and 22.8%, respectively. T6 also mitigated Cd-induced oxidative stress by elevating APX, SOD, and CAT activities by 36.3%, 76.8%, and 41.5%, respectively. Additionally, T6 modulated phytohormone levels and downregulated genes associated with Cd transport, notably reducing OsNRAMP5 expression by 49.5% in roots and 53.7% in shoots. Soil supplementation with 2% IDSNPs significantly decreased Cd accumulation in rice, with reductions of 19.36% in roots, 31.2% in stems, and 29.9% in leaves. These findings demonstrate that IDSNPs can enhance safer rice production on Cd-contaminated soils, providing an environmentally friendly and cost-effective strategy for mitigating heavy metal stress.

## Growth Response of Onion Seedlings to Zinc Solubilizing Bacteria

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Zinc is an essential micronutrient required for optimal plant growth and development. Zinc-solubilizing bacteria (ZSB) represent a promising alternative to conventional zinc fertilization by converting insoluble inorganic zinc into bioavailable forms. Seven bacterial isolates exhibiting zinc-solubilizing activity were identified through biochemical characterization. These strains were selected based on their zinc-solubilizing potential and subsequently evaluated in a pot experiment. Onion seedlings were individually inoculated with each bacterial strain to assess their effects on growth and zinc accumulation. Plant growth parameters included shoot length, root length, shoot and root fresh and dry weights, and zinc concentration in soil and plant tissues. Among the tested strains, *Bacillus altitudinis* produced the most significant improvement in plant performance, achieving a maximum shoot length of 44.73 cm, an average of eight leaves per plant, a shoot dry weight of 0.87 g, a shoot fresh weight of 5.26 g, and root fresh and dry weights of 0.80 g and 0.03 g, respectively. The remaining strains also showed positive effects compared with the uninoculated control, though to a lesser extent. These findings suggest that the evaluated ZSB isolates, particularly *Bacillus altitudinis*, have strong potential as biofertilizers for enhancing onion growth and improving zinc bioavailability in soil.

## Evaluating the Efficiency of *Centella asiatica* L. in Extracting Heavy Metals from Wastewater: Insights from Hazara University

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Due to lack of freshwater, wastewater have been used for irrigation purposes, causes health risk and contaminate the food chain. Like other sector, higher education institutes, including Hazara University, Mansehra Pakistan generated wastewater and its id crucial to treat wastewater prior to release in the nearby water bodies. This study was conducted to assess the potential of *Centella Asiatica* (pennywort) for the treatment of wastewater. For this purpose, wastewater was collected from distinct locations at the university to determine the level of contaminants. Afterward, wastewater was collected from the outlet and plants were grown for one month. After exposure, plants samples and treated wastewater was collected and analysed for physicochemical parameters including heavy metals. Results showed that the concentration of total suspended solids (TSS), total solids (TS) and total dissolved solid (TDS) were reduced by 88%, 34%, and 35%, respectively in post-harvest water.

Moreover, *Centella Asiatica* was able to remove 96% of the lead (Pb), 91% chromium (Cr), 90% Arsenic (As), 21% Cadmium (Cd), and 99% Iron (Fe) from wastewater. The concentration of heavy metals in roots/shoots of *Centella Asiatica* followed the sequence: Cr>Pb>Fe>Cd>As. The lower accumulation of heavy metals in roots/shoots is due to the presence of lower concentration of heavy metals in wastewater. The translocation factor (TF) for Cd, As and Cr was > 1 and BCF for Pb and Cr was > 1. From the present study it is clear that *Centella Asiatica* has potential for the treatment of wastewater.

## Temporal Dynamics of Soil CO<sub>2</sub> Emissions in Response to Organic Amendment Application

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This study explores how different organic carbon sources and concentrations impact CO<sub>2</sub> emissions in a maize-wheat cropping system. Organic amendments were applied at 0.25%, 0.5%, and 1.0% of soil carbon, combined with 75%, 50%, and 25% reductions in recommended NPK fertilizer doses. Soil samples were collected throughout two cropping seasons, and CO<sub>2</sub> emissions were assessed after 2, 4, 8, and 16-day incubation periods. Cumulative CO<sub>2</sub> production was calculated based on the measured data. The rate of CO<sub>2</sub> emission was higher in the second year compared to the first year, attributed to increased degradation of organic sources over time, leading to greater CO<sub>2</sub> release. Further analysis of cumulative CO<sub>2</sub> emissions at different stages of maize and wheat cultivation indicated that higher application rates of organic amendments led to higher CO<sub>2</sub> emissions. Additionally, organic amendments with higher carbon and nitrogen content and lower pH were more likely to enhance CO<sub>2</sub> emissions. Biochar was found to reduce the decomposition of soil organic matter, facilitating carbon and nitrogen sequestration in low organic carbon soils. While biochar produced at high pyrolysis temperature was relatively stable and resulted in slow organic matter decomposition and low CO<sub>2</sub> evolution, the mixture of biochar and compost showed a decrease in cumulative CO<sub>2</sub> emissions compared to biochar alone. Overall, the study highlights the complex relationship between organic carbon sources, levels, and CO<sub>2</sub> emissions. The findings contribute to the understanding of soil carbon dynamics and provide insights into strategies for mitigating greenhouse gas emissions from agricultural soils. The findings suggest that although the build-up of organic matter in the soil was relatively lower and resulted in higher CO<sub>2</sub> emissions from organically amended soils, the slow release of biochar could potentially reduce CO<sub>2</sub> emissions from the soil to the atmosphere.

## Phosphate-Solubilizing Bacteria from the Maize Rhizosphere: Potential for Rock Phosphate Utilization and Plant Growth Promotion

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Phosphate-solubilizing bacteria (PSB) enhance plant phosphorus (P) nutrition by improving soil P dynamics through solubilization and mineralization processes. This study evaluated the individual and combined effects of indigenous PSB, poultry manure, and compost on rock phosphate (RP) solubilization and their subsequent impact on maize (*Zea mays* L.) growth and P accumulation. Soil samples were collected from the maize rhizosphere across varying altitudes (655–2,576 m) in Rawalakot, Azad Jammu and Kashmir, Pakistan, yielding 57 bacterial isolates, of which 11 showed strong phosphate-solubilizing potential. Selected isolates exhibited P solubilization indices ranging from 1.94 to 3.69 and efficiencies between 94.1% and 269.0%, with isolates MRS18 and MRS27 performing best. Maximum P solubilization in liquid culture (9.91–44.04 mg mL<sup>-1</sup>) occurred after 6–9 days, while six isolates also produced indole-3-acetic acid (2.66–28.41 mg mL<sup>-1</sup>). Incubation studies revealed that combining PSB with RP significantly increased P mineralization (30.6–36.3 mg P g<sup>-1</sup>) compared to RP alone (11.8 mg P g<sup>-1</sup>), with further enhancement observed when organic amendments were added. Greenhouse trials showed that PSB inoculation with RP significantly improved maize growth, biomass, chlorophyll content, and P accumulation. Overall, the combined use of PSB and organic amendments with insoluble RP presents an effective strategy for improving soil P availability and crop productivity in intensive farming systems.

## Alternative Growth Media for Culturing *Bacillus* spp. to Enhance Wheat Growth and Productivity

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Plant Growth-Promoting Rhizobacteria (PGPR), particularly *Bacillus* spp., are widely recognized for their potential as biofertilizers, especially under arid and semi-arid conditions. Their application represents a sustainable strategy to enhance crop productivity while reducing dependence on chemical fertilizers. However, large-scale commercialization is often constrained by the high cost of conventional nutrient media used for bacterial mass culture production. The present study aimed to evaluate the effectiveness of *Bacillus* spp. cultured on alternative low-cost media compared with standard nutrient media for promoting wheat growth and yield. Two strains, PB-4 and PB-16, were cultured on standard nutrient media as well as on modified alternative media based on molasses, jaggery, and sugarcane extract. A pot experiment was conducted under a Completely Randomized Design (CRD) in the greenhouse of the Department of Soil and Environmental Sciences, Muhammad Nawaz Shareef University of Agriculture, Multan. Growth and yield parameters including plant height, total number of tillers, spike length, and grain yield were recorded. Results indicated that performance of *Bacillus* strains cultured on alternative media statistically same to those grown on standard nutrient media for promoting wheat growth and productivity. These findings suggest that alternative media

provide a cost-effective and sustainable option for mass multiplication of *Bacillus* spp., facilitating the development of affordable biofertilizers for sustainable wheat production.

## Enhancing Viability and Storage Stability of *Bacillus* and *Rhizobium* Bio-Inoculants for Sustainable Agriculture

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Microbial bio-inoculants based on *Bacillus* and *Rhizobium* spp. are sustainable alternatives to chemical fertilisers. Still, their adoption is constrained by viability losses during preparation and storage, particularly in tropical and subtropical regions lacking cold-chain infrastructure. This study aimed to develop genus-specific lyophilisation cryoprotectant formulations and identify carrier matrices that enable shelf-stable *Bacillus subtilis* and *Rhizobium ciceri* products suitable for ambient and elevated-temperature storage (35°C). In Experiment I, a single-factor completely randomised design evaluated 16 formulations comprising individual and binary combinations of sucrose (1.5–15% w/v; including 0–15% in the treatment set) and skim milk (2–10% w/v; including 0–10%), with post-lyophilisation performance assessed by CFU enumeration, OD600 recovery, and microscopy. Mixed cryoprotectants significantly outperformed single agents, yielding genus-specific optima: 7.5% sucrose + 5% skim milk maximised *B. subtilis* viability (86.9%), while 15% sucrose + 5% skim milk was optimal for *R. ciceri* (82.3%), compared with <20% in controls. The synergistic protection was consistent with sucrose-mediated vitrification and membrane stabilisation coupled with extracellular protein-based protection by skim milk. It differed by cell envelope architecture (Gram-positive, peptidoglycan-rich *B. subtilis* favoured moderate osmolyte levels, whereas Gram-negative *R. ciceri* required higher sucrose). In Experiment II, optimised powders were blended with five carriers (biochar, silica gel, kaolin clay, rice starch, fly ash) at a 1:9 ratio and stored at 4°C, 20°C, and 35°C for six months in a two-factor factorial CRD (three replications), with monthly viability and hygroscopicity measurements. Two-way ANOVA showed highly significant effects of carrier, temperature, and their interaction ( $p < 0.001$ ). Biochar and silica gel, exhibiting low hygroscopicity and strong moisture exclusion, maintained  $\geq 10^6$  CFU/g for >6 months even at 35°C, reaching  $>10^8$  CFU/g, whereas hygroscopic carriers and no-carrier controls declined rapidly under thermal stress. Viability inversely correlated with carrier hygroscopicity (*B. subtilis*  $R^2=0.85$ ; *R. ciceri*  $R^2=0.87$ ), and *B. subtilis* was consistently more resilient than *R. ciceri*. Overall, the study provides an evidence-based formulation-to-storage framework and cost-effective recipes for refrigeration-free, field-deployable bio-inoculants that meet commercial viability standards in tropical supply chains, supporting sustainable agriculture in developing countries.

# Screening of Native Rhizobial Isolates for Symbiotic Effectiveness and Plant Growth Promotion in Common Bean (*Phaseolus vulgaris* L.) from Azad Jammu and Kashmir

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Rhizobia contribute significantly to sustainable agriculture through biological nitrogen fixation in symbiosis with legumes. Common bean (*Phaseolus vulgaris* L.) is an important grain legume and a major source of dietary protein worldwide; however, in Pakistan, there is no commercial bacterial inoculum is available for its cultivation. This study aimed to evaluate the symbiotic effectiveness and plant growth-promoting potential of native Rhizobial isolates associated with common bean from Azad Jammu and Kashmir. Soil samples were collected from 15 sites across an altitudinal range of 909-2054 m and analyzed for physicochemical properties. Soil organic matter ranged from 0.16% to 2.14%, pH from 6.32 to 8.37, and Rhizobial populations estimated by the most probable number (MPN) technique ranged from  $2.0 \times 10^4$  to  $6.0 \times 10^4$  cells g<sup>-1</sup> soil. Pot experiments were conducted to assess nodulation potential. Rhizobial strains were isolated and purified from nodules. Plant infectivity tests, morphological characterization, and biochemical assays-including nitrogen fixation, indole-3-acetic acid (IAA) production, phosphate solubilization, and zinc mobilization-were performed to assess isolate functionality. Among the 15 isolates evaluated, eight exhibited nitrogen-fixing ability, 6 produced IAA, 3 showed zinc mobilization, and 2 solubilized phosphate. Based on biochemical performance, eight promising isolates were further evaluated under greenhouse conditions. All selected isolates successfully induced nodulation upon reinoculation. Isolates B13 and B6 showed enhanced growth-promoting potential significantly enhancing shoot and root length, biomass, and nodule number and weight, followed by B8, B12, B5 and B2,. These results demonstrate that native rhizobial isolates from Azad Kashmir possess strong potential for improving common bean growth and may serve as effective candidates for the development of bio-fertilizers.

# Production of Vermicompost for Improving Soil Health and Soybean Growth

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The continuous use of synthetic fertilizers has contributed to soil degradation and declining sustainability of crop production systems. Vermicomposting provides an environmentally sound

approach for converting organic wastes into nutrient-rich organic manure through the activity of earthworms and associated microorganisms. The present study was conducted to evaluate the effectiveness of vermicompost in improving soil health and soybean growth, and to compare its performance with recommended chemical fertilizer under field conditions. Vermicompost was produced using cow dung as the primary substrate and red wigglers (*Eisenia fetida*) for decomposition process with the following treatments: T1 (cow dung alone), T2 (cow dung + banana peels), T3 (cow dung + sugarcane residue), and T4 (cow dung + sawdust). Each treatment was replicated four times and maintained for four months under controlled moisture and aeration conditions. Earthworm population was monitored during the composting process, and a significant increase in worm numbers was observed across all treatments. The highest worm multiplication and biomass were recorded in T2, followed by T3, whereas T4 showed comparatively lower population growth. After maturity, the vermicompost was analyzed for key physicochemical properties. Results indicated that all treatments produced stabilized vermicompost with near-neutral pH and electrical conductivity within permissible limits. Organic matter content increased substantially, and nutrient analysis showed improvement in total nitrogen, available phosphorus, and exchangeable potassium. Among the treatments, T2 exhibited comparatively higher nutrient concentrations, indicating better compost quality. A field experiment has been established to assess the agronomic effectiveness of the prepared vermicompost. The field treatments include T1 (control), T2 (recommended chemical fertilizer), T3 (vermicompost from cow dung + banana peels), T4 (vermicompost from cow dung + sugarcane residue), and T5 (vermicompost from cow dung + sawdust), each replicated four times. Soybean has recently been sown, and growth, yield, and soil parameters will be recorded throughout the cropping season. The findings are expected to support sustainable nutrient management strategies and promote the use of organic amendments in crop production systems.

## Thermotolerant *Bacillus* and *Alcaligenes* Improve Physiological and Yield Attributes of Wheat under Heat Stress Conditions

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Wheat (*Triticum aestivum* L.) is a major staple crop worldwide, and its productivity increasingly threatened by terminal heat stress under changing climatic conditions, particularly in Pakistan. This study aimed to evaluate inoculation of thermos-tolerant plant growth-promoting bacteria as a strategy to mitigate heat stress in wheat. The research comprised laboratory screening and field evaluation at the MNS-University of Agriculture Multan. Seventeen thermotolerant bacterial isolates were characterized at 30, 40, and 50°C and assessed for plant growth-promoting and biochemical traits. The isolates belonged to the genera *Bacillus* and *Alcaligenes*. Based on performance, three isolates (TPB4, TPB12, and TPB30) were selected for field evaluation under induced heat shock (42±2.5°C at flowering and 45±3°C at grain filling stages for five days). Heat stress significantly reduced wheat flag leaf photosynthetic pigments, yield components, and grain yield. However, bacterial inoculation alleviated these adverse effects over control. Chlorophyll contents increased by 13.79% and 19.39% when heat stress induced at flowering and grain filling, respectively, compared with respective non-inoculated controls. Inoculation enhanced enzymatic antioxidants, including

superoxide dismutase (19–22.1%), peroxidase (17–28%), and catalase (46–56%), and non-enzymatic antioxidants such as phenolics (30–40%) and anthocyanins (35–87%) as compared to non-inoculated control. Nutrient concentrations in grains were also elevated, with nitrogen, phosphorus, and potassium increasing up to 19%, 33%, and 31%, respectively over control. Consequently, grain yield improved by 12.9% and 5.6% over respective control where heat stress induced at flowering and grain filling stages. These findings demonstrate that thermotolerant bacterial inoculation enhances antioxidant defense, nutrient status, and yield performance, offering a sustainable approach to improving wheat resilience under terminal heat stress.

## Impact of PGPR and Nutrient-Enriched Compost on Growth Parameters of Maize under Pot Trial Conditions

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Maize (*Zea mays* L.) is an important crop globally for its role in nutrition but its productivity is continuously dropping due to deficiencies of nutrients and poor soil fertility. This situation demands sustainable approach to improve growth and yield of maize. To address these problems, we performed a pot trail at wire house Department of Soil Sciences, The Islamia University of Bahawalpur. Experiment involves 6 treatments T1 (Control), T2 (Compost), T3 (P-enriched compost), T4 (PGPR), T5 (PGPR+ Compost) and T6 (PGPR+ P-enriched compost). Each treatment was replicated thrice. Growth parameters like plants height, biomass accumulation and root development were measured. Results showed significant increase in maize growth in treatment with PGPR and P-enriched compost compare to control and other treatments. Inoculation with PGPR improve uptake of nutrients and root development, while P-enriched compost increases availability of phosphorus which significantly enhance plant vigor and production of biomass. Treatment containing both PGPR and P-enriched compost out performed all other treatments showing strong relation between microbes and nutrient enriched organic amendments. Overall studies highlight importance of integrating use of PGPR and P-enriched compost as a sustainable strategy in improving growth and yield of maize and serve as an alternative to conventional fertilizers. These results showed capacity of bio-organic amendments to improve crop productivity, lower dependance on chemical fertilizers and ecofriendly agricultural practices. This implications of this research to extend to field level, where the combined application of PGPR and nutrient enriched compost play important role in increasing soil fertility, improve yield of maize and support sustainable agriculture for food safety in the region.

## Positive Interaction of Soil Bacteria With Exotic Miscanthus × Giganteus in Agro-Climatic Conditions of Multan

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Establishment of exotic plants in new soils under different agro-climatic conditions influence the indigenous microflora interactions. Whereas no research is available on the role of rhizosphere-associated microorganisms in improving early establishment, nutrient acquisition, and biomass production of perennial bioenergy crops such as *Miscanthus × giganteus*. The present study is one of the first systematic investigation of indigenous plant growth-promoting rhizobacteria (PGPR) isolated from recently established *Miscanthus × giganteus* stands in Multan. The objective was to understand their role in enhancing early crop establishment, nutrient acquisition, and ultimately biomass yield. Therefore, fifteen indigenous bacterial isolates (MG1, MG2, .... MG15) were obtained from the rhizosphere soil of healthy *Miscanthus* plants and evaluated during a 60-day growth trial using a completely randomized design with three replications in Lath-house conditions. Overall, PGPR inoculation significantly improved sprouting and early growth compared with the uninoculated control. Germination and establishment efficiency increased by 30–40% in PGPR-treated plants. Plant height increased progressively, resulting in an average growth rate of 0.70–0.75 cm day<sup>-1</sup>, indicating accelerated vegetative development. Leaf number and leaf length were also enhanced, contributing to a 35–45% increase in photosynthetic surface area relative to the control. Physiological performance improved significantly, as reflected by higher chlorophyll content (SPAD values). Nutrient acquisition was also enhanced, with shoot concentrations of nitrogen, phosphorus, and potassium increasing by 25–85%, 30–106%, and 20–75%, respectively, compared with the control. These findings highlighted MG10 and MG13 promising among the isolates due to their ability to produce IAA, P solubilization and root colonization characteristics. Ultimately it can be inferred that the PGPR associated with *Miscanthus* under agro-climatic conditions of Multan, demonstrated their potential for improving crop stand and productivity. However, more trials particularly field experiments are suggested to prove the finding of the study in semi-arid conditions of Multan.

## Accumulation of Arsenic in Tomato in Response to Bacterial Inoculation under Wastewater Irrigation

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Inoculation of plants with rhizobacteria may be considered a cost effective and environmental-friendly technology with a great potential to remove the target compounds induced by waste water irrigation. However bacterial efficiency to alleviate deleterious effects of waste water particularly. in terms of salt ions and heavy metals removal may vary greatly depending on many plants and soil related factors. The present study was conducted with the objective to evaluate the effect of bacterial inoculation and/or farm yard manure (FYM) on growth and yield characteristics of tomato (*Solanum lycopersicum* L.) grown with wastewater. In addition, the impact of these amendments on nutrient and arsenic (As) metal status of plants and soil under wastewater irrigation was investigated. Experimental treatments were consisted of two inoculation levels (un-inoculated and inoculated) and

3 levels of FYM (0, 10 and 20 t ha<sup>-1</sup>) with 5 replications. Results revealed that plant growth characteristics in terms of plant height (52.90 cm), number of fruits per plant (15.10), fruit diameter (38.29 mm), fruit weight (35.65 g), fruit weight per plant (538.31 g), but physiological attributes like total chlorophyll content (1.96 mg g<sup>-1</sup>), photosynthetic rate (14.86  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), GHS (254.6 mg kg<sup>-1</sup> FW), MDA in leaf (10.56  $\mu\text{mol g}^{-1}$  FW), nutrients uptake in shoot and fruit like N (18.56, 21.29 mg g<sup>-1</sup>), P (8.97 and 10.92 mg g<sup>-1</sup>) and K (28.34 and 11.01 mg g<sup>-1</sup>), respectively were significantly ( $p \leq 0.05$ ) affected by bacterial inoculation (*Serratia marcescens* SF3), either alone or in combination with FYM. While in case of MDA and As concentration, results had shown a significant reduction in tomato plant that was 26.85 and 44.83 % less compared control treatment, respectively. It is concluded that amending of wastewater with bacterial inoculation and/or FYM or their integrated use significantly alleviated the deleterious effects of wastewater, and caused a marked increase in plant growth, yield and quality of vegetables namely tomato.

## Optimizing Soil and Crop Health Through the Reclamation of Poor-Quality Irrigation Water Using Bio Amendments

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Soil salinization and the use of poor-quality irrigation water are major problems for sustainable agriculture in arid and semi-arid regions like Pakistan. This study evaluated the effectiveness of two bio-activated organic amendments viz. Black Gold (BG) and Bio-Silica (BS), in mitigating salt-induced stress and improving soil and spinach (*Spinacia oleracea* L.) performance under unfit water irrigation. These amendments were formulated by enriching organic matter with bio-activated sulfur, calcium chloride ( $\text{CaCl}_2$ ), magnesium sulfate ( $\text{MgSO}_4$ ), and beneficial microbes to enhance nutrient availability and reduce salt stress and sodium toxicity. A pot experiment was conducted with ten treatments and three replications arranged using a completely randomized design (CRD). Treatments involved two application methods: W+ (amendment pre-treated water) and S+ (direct soil application), applied under two types of irrigation water categorized as fit or unfit according to standard criteria. Results revealed that the S+BS treatment significantly ( $P < 0.05$ ) improved plant growth parameters, including fresh and dry biomass, root length, and root dry weight, with improvements up to 139.7% over the control under unfit water. Leaf nitrogen, phosphorus, and potassium contents also increased in S+BS-treated plants, indicating enhanced nutrient uptake under saline stress. Post-harvest soil analysis showed significant reductions in soil pH, electrical conductivity, and sodium adsorption ratio, especially under S+BS, demonstrating the superior performance of Bio-Silica in improving soil health. These findings highlighted the potential of Bio-Silica, particularly through direct soil application, as a sustainable strategy for mitigating the adverse effects of poor-quality irrigation water on both crop performance and soil quality.

## Impact of Microbially Enriched Vermicompost in Various Combinations on Growth and Yield of Garlic (*Allium Sativum* L.)

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Microbially enriched organic amendments offer a sustainable approach to improving soil fertility and crop productivity. This study evaluated the effects of rhizobacteria-enriched vermicompost on the growth, yield, and nutrient uptake of garlic (*Allium sativum* L.). A pot experiment was conducted at the Land Resources Research Institute, National Agricultural Research Centre (NARC), Islamabad, during 2019–2020. Vermicompost was inoculated with three locally isolated rhizobacterial strains—*Pseudomonas stutzeri*, *Pseudomonas aeruginosa*, and *Pseudomonas putida*—applied individually or in different combinations prior to soil application. Treatments, including enriched and non-enriched vermicompost, were applied to pots containing 5 kg soil and arranged in a completely randomized design with three replications. Each pot was transplanted with a single 20-day-old garlic seedling and maintained until maturity without the application of chemical fertilizers. Rhizobacteria-enriched vermicompost significantly ( $P \leq 0.05$ ) improved chlorophyll content, plant height, bulb diameter, and dry matter yield compared with non-enriched vermicompost. Among the tested strains, *Pseudomonas putida* exhibited the greatest effect, increasing chlorophyll content, plant height, dry matter yield, and bulb diameter by 23%, 32%, 32%, and 23%, respectively. It also enhanced nitrogen (N), phosphorus (P), and potassium (K) concentrations in garlic shoots by 40%, 63%, and 45%, and in bulbs by 54%, 69%, and 53%, respectively. Post-harvest soil analysis showed a 45% increase in organic matter content, while soil pH remained unaffected. Although combined inoculation of *P. stutzeri* and *P. putida* improved garlic growth relative to non-enriched vermicompost, it was less effective than vermicompost inoculated solely with *P. putida*. These findings highlight the potential of *P. putida*-enriched vermicompost as a sustainable strategy for enhancing garlic productivity and nutrient uptake.

## Mitigation of Heavy Metal Toxicity in Maize Crop by Spent Mushroom Substrate Biochar and Plant Growth Promoting Rhizobia under Contaminated Soil

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Heavy metals toxicity in soil is increasing globally and bioremediation of these contaminants through sustainable and recalcitrant materials has gained attention in recent years. A pot experiment was conducted in glasshouse, Department of Soil and Environmental Sciences, The University of Agriculture Peshawar to study the effect of spent mushroom substrate (SMS) biochar and plant growth promoting rhizobia (PGPR) under contaminated soil. The experiment was laid out in a completely randomized design (CRD) including seven treatments with three replications. Treatments include control, contaminated control Cd and Pb each (20 mg kg<sup>-1</sup> soil), and SMS biochar was added at concentrations of 0.5%, 1%, 1.5%, and 2%. Results showed that the combined application of PGPR with 2% SMS biochar significantly increased plant height (38.7%), shoot dry weight (37.5%) and root dry weight (67.8%) respectively, compared with contaminated control. Cadmium and Pb concentrations in roots, shoots and grains were higher in contaminated soil without biochar. Similarly, PGPR with 2% SMS significantly reduced Cd in roots and shoots by (54% and 73%) and Pb by (62% and 67%) respectively, compared to contaminated control. Moreover, chlorophyll content in maize leaves, increased with or without PGPR and different levels SMS biochar by (05-43%) compared with their contaminated control. Furthermore, soil nutrient content (TOC, N, P, and K) also showed improvement under the combined application of PGPR and biochar. These findings of the study provide a sustainable solution for the bioremediation of Cr in agricultural soil by improving soil microbial and antioxidative activities. Further research is required for the sustainable use of PGPR with SMS biochar to mitigate heavy metals and its mechanism in contaminated soil.

## Inducing Drought Tolerance in Wheat Genotypes through Microbial Biostimulants under Water Deficit Conditions

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Drought tolerant strategies are needed to tackle the escalating issue of water scarcity and to sustain crop productivity under water deficit conditions. There is a gap in identifying the most effective consortium of microbial biostimulants and understanding underlying physiological and antioxidants mechanisms involved in drought resilience of wheat crop. Therefore, experiments were carried out in laboratory, and wire house conditions to identify and optimize the response of drought tolerant microbial biostimulants for wheat genotypes. Three drought tolerant microbial biostimulants: *Bacillus subtilis*, *Bacillus megaterium* and *Trichoderma harzianum* were selected from a laboratory study. The two wheat genotypes: Dilkash-2021 and Bakhar Star (drought tolerant and sensitive, respectively) were selected from a wire house experiment. Afterwards, the response of individual and consortium of selected drought tolerant microbial biostimulants was evaluated in drought tolerant and sensitive wheat genotypes under well-watered and water deficit regimes. Results indicated that seed

inoculation of drought tolerant genotype with microbial consortium of *Bacillus subtilis*, *Bacillus megaterium* and *Trichoderma harzianum*, significantly increased relative water contents (58%), stomatal conductance (39%), sub-stomatal conductance (70%), water use efficiency (38%), and net leaf photosynthetic rate (34%) as compared with un-inoculated control under water deficit. This microbial consortium also led to a significant reduction in malondialdehyde concentration (36%) due to enhanced proline contents (77%), superoxide dismutase (82%) and peroxidase (51%) under water deficit. Therefore, seed inoculation of drought tolerant wheat genotypes with microbial consortium might be considered in formulating the best agricultural practices for alleviating the adverse effects of water deficit on wheat crop.

## Green Synthesis of Carbon Nanotubes Using Rice Stubble-Derived Biochar as a Sustainable Carbon Source

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In more recent years, the synthesis of carbon based Nanotubes is receiving a key consideration from researchers as a fact that carbon Nanotubes can effectively be used for various scientific and industrial purposes due to its unique physico-chemical properties. The challenge for synthesis of carbon Nanotubes lie in its production techniques and available precursors essentially needed for cost effective production. In this research study, Carbon Nanotubes have been synthesized using pyrolysed rice stubble as a precursor source. To synthesize low cost, environmental friendly and renewable biomass CNTs, the rice stubble precursors along with catalyst supports produced through chemical vapor deposition (CVD) technique. Through a successful and reproducible attempt, CNTs were produced through hydrothermally treated rice stubble in the presence of gaseous carbon produced from rice stubble supported by mixed catalyst including (Ni), (Mg) and (NH<sub>4</sub>) in tube furnace with constant flow of N<sub>2</sub> gas. To determine the physico-chemical properties of CNTs, Scanning Electron Microscopy (SEM), Raman Spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR) and X-ray fluorescence (XRF) analyses methods were used to evaluate surface morphology, diameter, alignment, detecting structural defects via the G-band and D-band analysis, identify functional groups and to quantify metal catalyst residues in synthesized CNTs. The graphitization, diameter, thickness and yield of synthesized CNTs showed that pyrolysed rice stubble is a low cost source for synthesizing functionalized CNTs and making it more feasible and realistic approach to convert cheap-bio-available source into highly valuable CNTs.

## Harnessing Soil Microbiome and Nanobiotechnology to Improve Wheat Productivity under Drought Stress

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Soil degradation and water scarcity are major threats to sustainable agricultural production, particularly in semi-arid regions such as Pakistan. Developing strategies that improve soil health while enhancing crop tolerance to environmental stress is therefore essential. Plant growth-promoting rhizobacteria (PGPR) play a significant role in improving soil fertility, nutrient availability, and plant stress tolerance. Recent studies have highlighted their potential to enhance crop performance through physiological and biochemical modulation of plant responses under adverse environmental conditions. In our study, drought-tolerant PGPR strains were isolated from the rhizospheric soils of wheat grown in arid environments. Selected strains exhibited strong plant growth-promoting traits, including phytohormone production such as indole acetic acid, abscisic acid, and cytokinins, along with osmolyte accumulation that supports plant adaptation to water deficit conditions. Their combined application with silicon dioxide nanoparticles demonstrated synergistic effects in improving drought tolerance in wheat by enhancing antioxidant activity, osmolyte production, and nutrient uptake. These microbial–nanoparticle interactions significantly improved plant growth, physiological performance, and yield attributes under water-limited conditions. The findings highlight the importance of soil microbial resources as sustainable tools for improving soil–plant interactions and crop resilience. Integrating PGPR with innovative soil management approaches can contribute to improved soil fertility, enhanced plant stress tolerance, and sustainable crop productivity in drought-prone regions. This approach provides a promising pathway toward climate-resilient agriculture and sustainable soil management for future food security.

## Rhizospheric Colonization and PGP Trait Expression of *Bacillus safensis* Strains: A Pathway to Reduce Chemical Use and environmental impact

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This study characterizes the multifaceted potential of *Bacillus safensis* (strains AF-9) as a high-performance microbial inoculant designed to enhance crop productivity and resilience against biotic and abiotic stressors. Genomic and biochemical analyses revealed robust plant growth-promoting (PGP) traits, including IAA production ( $23.67 \mu\text{g mL}^{-1}$ ), nitrogenase activity ( $32.68 \mu\text{g mL}^{-1}$ ), and phosphorus solubilisation ( $42.4 \mu\text{g mL}^{-1}$ ), the latter of which induced a significant pH reduction from 7.0 to 4.32 through the secretion of oxalic, malic, and gluconic acids. In vitro assays confirmed that AF-9 inoculation exhibited strong antagonistic activity against *Fusarium oxysporum*. Field evaluations across diverse environments demonstrated that inoculation significantly enhanced sunflower growth in hydroponic, sterilized soil, and field conditions along with yield, and oil content over control treatments. While, advanced microscopy—including yfp-labelling (Confocal Laser Scanning Microscope) confirmed successful rhizospheric colonization and biofilm formation authenticating the competency of AF-9. These findings, supported by genomic evidence of stress-alleviation and colonization genes, position *B. safensis* as a potent biofertilizer candidate for sustainable, eco-friendly agricultural intensification.

# Climate Smart Agriculture

## Climate-Resilient Wheat Production through Integrated Nutrient Management Approaches

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Wheat production is adversely affecting by climate variability, declining soil fertility, and low use efficiency of mineral fertilizers. Thus, it is need of the day to develop climate-resilient and sustainable nutrient management strategies. This study was undertaken to evaluate the effects of integrated application of organic amendments and mineral fertilizer on growth, yield and nutrient uptake in wheat. The field experiment was planned by combining the organic amendments [farm manure, sesbania and cluster bean] with different rates of mineral fertilizers [1/3, 1/2, 2/3, and 3/4 of recommended dose of mineral fertilizer (RDMF)] along with RDMF (150-90-60 kg N-P-K ha<sup>-1</sup>) alone and total control at NIA Tandojam during two wheat growing seasons (2021-22 and 2022-23). The treatments repeated thrice were arranged in split plot design. The application of organic amendments and rates of mineral fertilizer significantly affected the grain yield, nutrient uptake and recoveries in wheat variety “Kiran-95”. Among the organic amendments highest grain yield, N, P uptakes and N, P recoveries were noted in farm yard manure during both growing seasons. In case of mineral fertilizer rates, maximum grain yield and N, P uptakes and N, P recoveries were noticed in RDMF. Moreover, the interaction of organic amendments with mineral fertilizer rates were also significant. Integration of farm manure with RDMF produced maximum grain yield. Similarly, highest N and P accumulations and N recovery were noticed in same combination of fertilizers. However, the highest P recovery was recoded in plot, received farm manure and 1/3 of RDMF. The results revealed that integration of farm manure with mineral fertilizer is a climate-smart approach for enhancing wheat productivity and nutrient use efficiency. Adoption of this technique can contribute to agricultural resilience under climatic changing conditions of the regions.

## Performance Evaluation of Indigenously Developed Enhanced Efficiency Fertilizers under Farmer Field Conditions

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Enhanced efficiency fertilizers (EEFs) are designed to improve the availability of nutrients to crops while minimizing losses to the environment. By controlling nutrient release and transformation processes in the soil, these fertilizers enhance nutrient use efficiency and reduce losses through leaching, volatilization, and surface runoff; thereby supporting both higher productivity and more sustainable nutrient management. To evaluate their performance under practical conditions, a total of 81 field trials were conducted on farmers’ fields as well as at government research institutions. Several indigenously developed EEFs were assessed in

comparison with conventional fertilizers (standard DAP and urea). The tested products included boron-fortified DAP (0.1% B), zinc-coated urea (1% Zn), neem oil-coated urea, urease inhibitor-treated urea, LIMUS-coated urea, and dual protection (DP) urea containing both urease and nitrification inhibitors. These trials were conducted across agro-ecological zones on major crops including rice, cotton, and wheat. Among nitrogen-based products, LIMUS-coated urea increased wheat yield by 2.88%, while DP urea showed a 3.38% increase in wheat and a modest 0.68% increase in rice. Neem oil-coated urea also demonstrated positive responses, with yield gains of 2.88% in rice and 3.22% in wheat, whereas urease inhibitor-treated urea did not show a significant improvement in rice. Among phosphatic fertilizers, boron-fortified DAP exhibited the most pronounced impact, significantly increasing yields of rice (11.41%) followed by cotton (8.25%) and wheat (6.25%) compared with standard DAP. These findings highlight that indigenously developed EEFs have strong potential to enhance crop productivity and nutrient use efficiency under local conditions. Their adoption can play a meaningful role in improving fertilizer effectiveness, reducing environmental losses, and advancing sustainable agricultural production systems.

## Potassium-Mediated Stress Tolerance in Crop Plants: A Climate-Smart Nutrient Strategy for Sustainable Agriculture in Pakistan

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Climate change-driven stresses such as drought, heat, salinity, and nutrient imbalances increasingly constrain agricultural productivity in Pakistan. Potassium (K) is a vital macronutrient that regulates key physiological and biochemical processes, enhancing plant tolerance to these environmental stresses. Despite the presence of K-bearing minerals in Pakistani soils, continuous nutrient mining, imbalanced fertilizer use, and low fertilizer use efficiency have led to widespread potassium deficiency and stagnating yields. Evidence from long-term fertilizer experiments and field-based case studies shows that balanced potassium fertilization substantially improves crop growth, yield stability, gas exchange, and produce quality in wheat, maize, and mango under stress conditions. Split and integrated potassium applications, including both soil and foliar methods, enhanced nutrient availability and use efficiency. Moreover, synergistic interactions with nitrogen and other nutrients further strengthened crop resilience. These findings underscore that potassium nutrition should be considered not only as a yield-enhancing input but also as a strategic tool for building climate resilience in cropping systems. Site-specific potassium management combined with integrated nutrient strategies is critical for sustaining soil fertility, improving productivity, and ensuring food security under changing climatic conditions.

## Improving Cereals Yield and Productivity with Boron-Fortified Climate-Smart Urea

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Low nitrogen use efficiency (NUE) in crops is often caused by the high solubility of conventional urea, leading to losses through leaching, surface runoff, denitrification, and ammonia emissions. Additionally, boron-deficient soils, which account for approximately 49% of Punjab, Pakistan, significantly limit crop productivity. To address these challenges, the Soil Chemistry Section at AARI, Faisalabad, developed boron-coated urea (BCU), a climate-smart, slow-release, boron-fortified fertilizer, and evaluated its effects on cereal crop yield and productivity. BCU not only fulfills the boron requirements of crops but also improves NUE in alkaline calcareous soils of Punjab. A series of experiments were conducted to assess nitrogen release from BCU, boron fortification in wheat, and ammonia emissions from standard urea compared to BCU under field conditions. The results demonstrated a 5–8% increase in grain yield and a 30–35% reduction in ammonia emissions. Furthermore, wheat and maize exhibited improved growth, nitrogen use efficiency, and boron uptake. These findings highlight the potential of BCU as a sustainable alternative to conventional urea in wheat-maize cropping systems, contributing to more efficient and environmentally friendly agricultural practices.

## Influence of Cropping Systems on Soil Organic Carbon Fractions, Aggregate-Associated Carbon, and Nutrient Dynamics in Semi-Arid Drylands of Pakistan

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Soil organic carbon (SOC) fractions, aggregate-associated SOC, and nutrient dynamics are essential for maintaining soil fertility and ensuring food security, particularly in dryland environments. However, limited information is available for semi-arid regions of Pakistan. This study evaluated the effects of five cropping systems (barley, chilli, tomato, maize, and alfalfa) across three soil depths (0–15, 15–30, and 30–45 cm) on SOC fractions, aggregate-associated carbon, and nutrient availability. The highest values of water-soluble carbon (251 mg kg<sup>-1</sup>), aggregate-associated carbon (9.34 g kg<sup>-1</sup>), total organic carbon (9.25 g kg<sup>-1</sup>), available nitrogen (0.145 g kg<sup>-1</sup>), available phosphorus (8.91 mg kg<sup>-1</sup>), and

available potassium ( $200 \text{ mg kg}^{-1}$ ) were observed under alfalfa cultivation, followed by maize, in the surface soil (0–15 cm). Aggregate-associated carbon was mainly concentrated in macroaggregates ( $>8 \text{ mm}$ ), with the highest content under alfalfa ( $9.34 \text{ g kg}^{-1}$ ) and the lowest under barley ( $7.11 \text{ g kg}^{-1}$ ). Cropping systems showed inconsistent effects on soil pH and electrical conductivity across depths. Significant relationships were observed between SOC fractions, aggregate stability, and nutrient availability. Long-term cultivation of alfalfa and maize improves SOC fractions, soil structure, and nutrient availability in semi-arid drylands, making these systems suitable for sustainable soil management and productivity enhancement.

## Effect of Different Levels of Nitrogen and Phosphorus on the Growth and Yield of Maize

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An experiment was conducted during 2024–25 at the Agronomy Research Farm, Department of Agronomy, Sindh Agriculture University, Tando Jam, to evaluate the effect of different levels of nitrogen (N) and phosphorus (P) on the growth and yield of maize. The experiment was laid out in a randomized complete block design (RCBD) with three replications and five treatments:  $T_1$  = Control ( $160 \text{ kg N}, 80 \text{ kg P}_2\text{O}_5, 50 \text{ kg K}_2\text{O ha}^{-1}$ ),  $T_2 = 50 \text{ kg N ha}^{-1} + 30 \text{ kg P ha}^{-1}$ ,  $T_3 = 100 \text{ kg N ha}^{-1} + 60 \text{ kg P ha}^{-1}$ ,  $T_4 = 150 \text{ kg N ha}^{-1} + 90 \text{ kg P ha}^{-1}$ , and  $T_5 = 200 \text{ kg N ha}^{-1} + 120 \text{ kg P ha}^{-1}$ . The results indicated that the highest growth and yield parameters were recorded in treatment  $T_5$  ( $200 \text{ kg N ha}^{-1} + 120 \text{ kg P ha}^{-1}$ ), which produced a maximum plant height of 212 cm, stem girth of 4 cm, 2 tillers plant<sup>-1</sup>, spike length of 19 cm, and biological yield of  $74 \text{ kg plot}^{-1}$ . Treatment  $T_4$  ( $150 \text{ kg N ha}^{-1} + 90 \text{ kg P ha}^{-1}$ ) also showed significant improvement, recording 202 cm plant height, 4 cm stem girth, 1 tiller plant<sup>-1</sup>, 18 cm spike length, and  $68 \text{ kg plot}^{-1}$  biological yield. The control treatment ( $160 \text{ kg N}, 80 \text{ kg P}_2\text{O}_5, 50 \text{ kg K}_2\text{O ha}^{-1}$ ) resulted in 197 cm plant height, 4 cm stem girth, 1 tiller plant<sup>-1</sup>, 17 cm spike length, and  $61 \text{ kg plot}^{-1}$  biological yield. Lower fertilizer levels, particularly  $T_3$  ( $100 \text{ kg N ha}^{-1} + 60 \text{ kg P ha}^{-1}$ ) and  $T_2$  ( $50 \text{ kg N ha}^{-1} + 30 \text{ kg P ha}^{-1}$ ), produced comparatively reduced growth and yield attributes. It is concluded that the application of nitrogen and phosphorus, particularly at  $200 \text{ kg N ha}^{-1}$  and  $120 \text{ kg P ha}^{-1}$ , significantly enhances the growth and yield of maize under the given experimental conditions.

## Zinc Extraction from Recycling of Alkaline and Zinc-Carbon Batteries for Agricultural and Environmental Sustainability

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Improper disposal of used alkaline batteries poses significant environmental hazards while wasting valuable metals. Zinc (Zn), an essential micronutrient and industrial material, is in growing demand, yet global reserves could be depleted within a few decades. Alkaline batteries, in particular, contain substantial amounts of Zn (~24%) and manganese (~40%), making them a promising secondary resource. This study explores the hydrometallurgical recovery of Zn from used AA alkaline batteries. Laboratory experiments employed sulfuric acid leaching under controlled solid-to-liquid ratios, acid concentrations, and leaching durations. Atomic absorption spectrophotometry was used to quantify Zn recovery, with maximum dissolution achieved at 0.7% acid over 120 minutes. The study aimed to optimize leaching conditions to maximize Zn extraction while minimizing impurities and to assess the recovered Zn's potential as a fertilizer. Results demonstrated Zn extraction efficiencies of up to 87%, with solution concentrations reaching 17.4 g/L under optimized conditions. Laboratory-based plant growth trials showed no significant difference between conventional Zn fertilizers and the recovered Zn. The study concludes that hydrometallurgical recycling of alkaline batteries is a viable approach to reducing hazardous waste, recovering valuable minerals such as Zn, and supporting sustainable agriculture.

## Effect of Foliar-Applied Nano-Hydroxyapatite on Growth and Phosphorus Use Efficiency of Maize under Alkaline Soil Conditions

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Sustainable soil management is essential for ensuring long-term agricultural productivity and environmental stability. Conventional fertilizers often exhibit low nutrient use efficiency due to losses through fixation, leaching, and volatilization, particularly in alkaline soils where phosphorus (P) availability is severely limited. Such inefficiencies reduce crop productivity and contribute to soil degradation and environmental concerns. Nano-fertilizer technology has recently emerged as a promising approach to enhance nutrient availability, improve uptake efficiency, and support resilient agricultural systems. Nano-hydroxyapatite (nHAP), a nano-scale phosphorus source, offers controlled nutrient release and improved phosphorus use efficiency compared to conventional fertilizers. A field experiment was conducted at the Soil Fertility Research Institute, ARC Tandojam, using a Randomized Complete Block Design (RCBD) with three replications and four treatments to evaluate the effect of foliar-applied nano-hydroxyapatite on maize (*Zea mays* L., cv. Akbar). The treatments included T<sub>1</sub> (control), T<sub>2</sub> (recommended NPK: 160–80–50 kg ha<sup>-1</sup>), T<sub>3</sub> (0.5 g L<sup>-1</sup> nHAP), and T<sub>4</sub> (1 g L<sup>-1</sup> nHAP). Growth parameters, including plant height and leaf height, were recorded at maturity. The results revealed significant differences among treatments. Nano-hydroxyapatite application, particularly at 1 g L<sup>-1</sup>, produced the highest plant height (approximately 140–150 cm) compared to the control (110–125 cm). Leaf height was also significantly enhanced under nHAP treatments, indicating improved vegetative growth and phosphorus utilization. The improved growth performance suggests enhanced phosphorus availability and nutrient uptake efficiency under nano-fertilizer application. In conclusion, foliar application of nano-hydroxyapatite, especially at 1 g L<sup>-1</sup>, effectively improved maize growth under alkaline soil conditions. Nano-fertilizer technology therefore represents a promising and sustainable phosphorus management strategy for enhancing nutrient use efficiency and supporting maize productivity in phosphorus-deficient soils.

## Envisaging Spatial and Temporal Changes In Soil Physico-Chemical Properties of Research Farm of The University of Agriculture, Peshawar

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Soil is a heterogeneous medium that varies across time and space. In the present study, variations in soil properties were associated with cropping patterns, standing crops at the time of sampling, growth stages, and fertilizer application timing. The study was designed to assess spatial and temporal changes over a five-year period in the physico-chemical properties of soils at the Research Farm of the University of Agriculture, Peshawar. A total of 151 surface soil samples (0–20 cm) were collected from 6–7 spots per location within a 5–10 m radius, using the same coordinates as in a previous study (Abid, 2015) and a global positioning system (GPS). Samples were analyzed for soil pH, electrical conductivity (EC), organic matter (OM), lime, mineral nitrogen (N), AB-DTPA extractable phosphorus (P), potassium (K), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), and soil texture. Soil properties showed moderate variability, with the highest coefficient of variation observed for AB-DTPA extractable Mn (57.02%) and the lowest for soil pH (3.28%). Overall, N, P, and Zn were deficient in 60%, 75%, and 95% of the area, respectively, whereas K, Cu, Mn, and Fe were sufficient in 90% of the farm. Over the five-year period, OM, Zn, and sand content decreased, while lime, N, P, K, Mn, Cu, Fe, EC, and pH showed no significant change. Phosphorus remained deficient, whereas K was sufficient. All parameters were interpolated using ordinary kriging. Data from 2015 and 2020 were compared using ArcGIS (“Minus” spatial analyst tool), and separate maps for each parameter were prepared, illustrating changes in soil fertility over the five-year period. Semi-variogram analysis applied the best-fit models (Exponential, Spherical, and Gaussian) for all properties. The nugget-to-sill ratio indicated strong spatial dependency for pH, EC, OM, and Zn in both 2015 and 2020, weak spatial dependency for K and Fe, and moderate dependency for the remaining properties. The soils were alkaline, with silt loam to loam texture and no salinity detected. Overall, the fertility status was medium to low, with P and Zn being the most deficient nutrients. The generated maps provide a valuable tool for optimized soil management, helping to prevent over- or under-fertilization at the Research Farm.

## Influence of Eucalyptus and Hemp Plant Residues on Nitrification Inhibition and Wheat (*Triticum aestivum* L.) Yield

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The judicious use of nitrogen (N) is essential for improving crop productivity while sustaining soil and environmental health. This study investigated the effect of urea-treated soil on the nitrification process and wheat growth by incorporating native plant residues (Eucalyptus and Hemp) in comparison with the synthetic nitrification inhibitor dicyandiamide (DCD). During the experiment, nitrogen transformations were studied by amending soil with DCD, Eucalyptus leaf powder (UR), and hemp plant residue (HR) at 1% and 20% of the applied urea N (200 mg/kg), respectively. The treatments were: T1 control (soil with no amendment), T2 urea N 200 mg/kg, T3 urea N 200 + 4 mg/kg DCD, T4 urea N 200 + 80 mg/kg UR, T5 urea N 200 + 80 mg/kg HR, and T6 urea N 200 + 40 mg/kg urea R + 40 mg/kg HR. Soil amended with these treatments was incubated for 60 days, with sampling at 5, 10, 15, 20, 25, 35, 45, and 60 days. The same treatments were also applied to soil in pots arranged in a completely randomized design (CRD) to grow wheat plants under greenhouse conditions. Soil samples collected during incubation and after harvest were analyzed for  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  to assess nitrogen fate and cycling through nitrification. The addition of DCD during incubation resulted in the highest total mineral nitrogen (TMN) value (185 mg/kg) and improved TMN recovery to 81%, compared to 79% in treatments without DCD. Similarly, plant residues, particularly UR, showed strong potential to inhibit nitrification, enhancing N uptake and applied N recovery. In the greenhouse experiment, UR increased N recovery and agronomic efficiency by approximately 22% and 29%, respectively. The study concludes that selected plant residues, especially Eucalyptus, have significant potential as organic nitrification inhibitors and can be used to improve wheat growth and nitrogen use efficiency.

## Enhancing Zinc and Phosphorus Use Efficiency through Biochar for Wheat Crop in Calcareous Soil

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Biochar amendment enhances zinc and phosphorus use efficiency by improving nutrient availability and soil fertility in calcareous soils. To assess the influence of biochar along with Zinc (Zn) and Phosphorus ( $\text{P}_2\text{O}_5$ ) levels on wheat crop and soil quality, a field experiment was conducted in calcareous soil of Dera Ismail Khan (D.I. Khan). Before the establishment of experiment, composite soil samples were collected for the analysis of physico-chemical properties. The experiment was laid out in a Randomized Complete Block Design (RCBD) with a split-plot arrangement and three replications. Each subplot measured 3.5 m  $\times$  4.5 m and was sown with wheat cultivar Hasham-2008. Nine treatment combinations consisting of Zn applied at 0, 5, and 10 kg  $\text{ha}^{-1}$  through  $\text{ZnSO}_4$  and  $\text{P}_2\text{O}_5$  applied at 0, 60, and 90 kg  $\text{ha}^{-1}$  through single super phosphate (SSP) were allocated to subplots, whereas main plots were treated with and without biochar. A basal dose of nitrogen (N) and potassium (K) at 120–60 kg  $\text{ha}^{-1}$  was applied. Half of the nitrogen and the full dose of potassium, in the form of urea and  $\text{K}_2\text{SO}_4$  respectively, were applied at sowing, while the remaining half of nitrogen was applied at the booting stage. Results revealed that significantly ( $P < 0.05$ ) higher biological yield (11,298 kg  $\text{ha}^{-1}$ ), grain yield (3,540 kg  $\text{ha}^{-1}$ ), and straw yield (7,758 kg  $\text{ha}^{-1}$ ) were obtained in biochar-treated plots

receiving Zn at 10 kg ha<sup>-1</sup> and P<sub>2</sub>O<sub>5</sub> at 90 kg ha<sup>-1</sup>. The same treatment significantly increased phosphorus concentration in grain (0.35%) and straw (0.23%), phosphorus uptake by straw (17.84 kg ha<sup>-1</sup>), and total phosphorus uptake (30.23 kg ha<sup>-1</sup>), while grain P uptake (12.39 kg ha<sup>-1</sup>) remained statistically non-significant. The combined application of biochar (20 t ha<sup>-1</sup>), Zn (5 kg ha<sup>-1</sup>), and P<sub>2</sub>O<sub>5</sub> (90 kg ha<sup>-1</sup>) significantly enhanced Zn concentration in grain (24.5 mg kg<sup>-1</sup>) and straw (14.4 mg kg<sup>-1</sup>), Zn uptake by grain (86.69 g ha<sup>-1</sup>) and straw (111.36 g ha<sup>-1</sup>), and total Zn uptake (198 g ha<sup>-1</sup>) compared with other treatments applied alone or in combination. Regarding post-harvest soil properties, significantly higher AB-DTPA extractable P (9.61 mg kg<sup>-1</sup>), Zn (1.17 mg kg<sup>-1</sup>), and K (160 mg kg<sup>-1</sup>) were observed in plots treated with biochar at 20 t ha<sup>-1</sup> along with 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 10 kg Zn ha<sup>-1</sup>. Maximum soil organic matter content (0.85%) was recorded in biochar-amended plots receiving 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. Soil pH and EC were not significantly affected by biochar, Zn, or P treatments; however, relatively lower soil pH was observed in biochar-treated plots irrespective of Zn and P levels. The maximum P use efficiency (PUE) (13.57 %) was recorded in plot received integrated application of biochar, P and Zn @ 20 ton, 90 and 10 kg ha<sup>-1</sup> per hectare respectively. Maximum Zn use efficiency (ZUE) (1.83 %) was observed in biochar treated plots along with application of P<sub>2</sub>O<sub>5</sub> @ 90 kg ha<sup>-1</sup> and Zn @ 5 kg per hectare followed by a value of (1.07 %) in B x Zn x P @ (20 ton, 10 and 90 Kg per hectare) respectively. It was concluded that the application of biochar at 20 t ha<sup>-1</sup> combined with Zn and P<sub>2</sub>O<sub>5</sub> at 10 and 90 kg ha<sup>-1</sup>, respectively, significantly improved wheat yield, nutrient uptake, and nutrient use efficiency, and is therefore recommended for calcareous soils of D.I. Khan.

## Integrated Effect of Sugarcane Bagasse Biochar and Vermicompost on Soil Properties and Growth of Maize

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Declining soil fertility and reduced organic matter content are major constraints to sustainable crop production. Organic amendments, such as biochar and vermicompost, are increasingly recognized for their potential to enhance soil physicochemical properties and improve crop performance. This study evaluated the integrated effect of sugarcane bagasse biochar and vermicompost on soil properties and the growth of maize (*Zea mays* L.). A pot experiment was conducted under a Completely Randomized Design (CRD) with five treatments and three replications, including control, sole biochar, sole vermicompost, and combined applications at varying ratios. Growth parameters, including plant height, leaf area, root length, biomass accumulation, and yield attributes, were recorded. Post-harvest soil analyses were conducted to assess changes in pH, organic matter content, nutrient availability, and bulk density. The results revealed that combined application of biochar and vermicompost significantly enhanced soil organic matter, improved nutrient availability, and promoted superior plant growth compared to individual amendments and the control. The synergistic interaction between the two amendments led to increased biomass production and improved yield-related traits. These findings indicate that integrating sugarcane bagasse biochar with vermicompost is an environmentally sustainable approach to improving soil health and maize productivity, reducing reliance on synthetic fertilizers, and supporting long-term soil sustainability.

## Enhancing Soil Nitrogen through Soybean Cultivation to Improve Soil Health for Sustainable Agriculture

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Leguminous crops are fundamental to sustainable agriculture due to their capacity to enhance soil fertility and increase crop productivity through symbiotic biological nitrogen fixation. This study evaluates the impact of different nitrogen fertilizer doses (0, 75, 37.5, and 18.5 kg ha<sup>-1</sup>) combined with a fixed phosphorus application (50 kg ha<sup>-1</sup>) on soybean growth, yield, and soil health. A Randomized Complete Block Design (RCBD) was used to assess key parameters, including plant height, number of pods per plant, and average yield (kg ha<sup>-1</sup>). The results showed that nitrogen application significantly influenced plant growth and yield. The highest plant height (50.95 cm), maximum number of pods (25), and highest average yield (1100 kg ha<sup>-1</sup>) were recorded in T-4 (18.5 kg N ha<sup>-1</sup>). In contrast, the control treatment (T-1, 0 kg N ha<sup>-1</sup>) exhibited the lowest values, with a plant height of 27.375 cm, an average of 8 pods per plant, and the lowest yield of 580 kg ha<sup>-1</sup>. These findings suggest that moderate nitrogen application optimizes plant development and yield, while excessive nitrogen may not provide additional benefits. The study highlights the importance of legumes in improving soil nitrogen levels, organic matter, and overall soil health. Future research should explore long-term nitrogen application strategies, microbial interactions, and their role in enhancing soil sustainability and productivity.

## Comparative Effects of Pressmud and Conventional Chemical Fertilizers on Wheat (*Triticum aestivum* L.) Production and Soil Physico-Chemical Characteristics under Field Conditions

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There are concerns regarding the long-term sustainability of wheat production due to declining soil fertility and excessive use of chemical fertilizers. Pressmud, a by-product of the sugar industry, is rich in organic matter and essential nutrients and has gained attention as a potential alternative nutrient source. Therefore, this study is planned to evaluate the comparative effects of pressmud and inorganic nitrogen, phosphorus, and potassium (NPK) fertilizers on wheat production and soil properties under field conditions during 2024-2025. The experiment was arranged in a Randomized Complete Block Design (RCBD) with six treatments and three replications. Treatments comprised: control (T1), recommended NPK (120–90–60 kg ha<sup>-1</sup>) (T2), pressmud at 5 t ha<sup>-1</sup> (T3), pressmud at 10 t ha<sup>-1</sup> (T4), pressmud (5 t ha<sup>-1</sup>) + 50% recommended NPK (T5), and pressmud (10 t ha<sup>-1</sup>) + 50% recommended NPK

(T6). Integrated treatments (T5 and T6) significantly enhanced growth attributes and yield components compared to sole applications. The combination of pressmud at 10 t ha<sup>-1</sup> with 50% recommended NPK (T6) produced the highest grain and biological yields ( $p < 0.05$ ), demonstrating improved nutrient use efficiency. Sole pressmud application significantly increased soil organic matter and improved nutrient availability, while integrated treatments maintained balanced soil pH and electrical conductivity. Compared to full recommended NPK, integrated treatments achieved remarkable yield. The results revealed that integrating pressmud with reduced chemical fertilizer rates can sustain wheat productivity, enhance soil health, and reduce dependency on synthetic fertilizers. Pressmud also increased water holding capacity and reduced soil bulk density creating a good soil condition for enhanced crop growth. Therefore, integrated nutrient management involving pressmud represents a viable and environmentally sustainable strategy for wheat cultivation.

## Synergistic Effects of N-Fertilization on Crop Productivity and Soil Quality in Wheat-Pea Intercropping system

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Optimizing nitrogen fertilization in wheat–pea intercropping systems is essential for improving crop productivity and soil quality. Wheat–pea intercropping is a promising strategy for sustainable agriculture, as it enhances nitrogen-use efficiency and overall system performance. This study evaluated the effects of different recommended nitrogen fertilization (RNF) rates on crop productivity and soil quality parameters. The experiment followed a two-factor design, where Factor A included cropping systems (sole wheat, sole pea, and wheat–pea intercropping), and Factor B comprised nitrogen levels ( $N_0$ ,  $N_1$ ,  $N_2$ , and  $N_3$ ). Nitrogen was applied to wheat at rates of 0, 100, 135, and 170 kg N ha<sup>-1</sup>, and to pea at rates of 0, 55, 85, and 115 kg N ha<sup>-1</sup>. The wheat–pea intercropping system exhibited a land equivalent ratio (LER) of 1.88, indicating an 88% advantage in land-use efficiency over sole cropping. Intercropped wheat produced approximately 86% of the biomass yield of sole wheat, while intercropped pea slightly exceeded the biomass yield of sole pea by about 2%. Soil properties, including pH, electrical conductivity (EC), moisture content, total organic carbon (TOC), water-soluble carbon, microbial biomass, extractable nitrate and ammonium-N, available phosphorus, and enzyme activities, were analyzed. Results demonstrated that optimized nitrogen application improved both crop performance and soil quality. Overall, the findings support the development of integrated nutrient management strategies aligned with sustainable intensification in cereal–legume intercropping systems.

## Tillage and Intercropping Interventions Altered Soil

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Tillage and legume based intercropping interventions are recognized to enhance soil organic carbon (SOC) and associated carbon fractions particularly in fragile rain-fed agro-ecosystems. Therefore, a two years’ field study was conducted to evaluate the effects of tillage (no-tillage, NT vs conventional tillage CT) and cropping systems (monoculture vs. legume-based intercropping) on SOC, permanganate oxidizable carbon (POXC) and particulate organic carbon (POC) of an inceptisol in the lesser Himalayas of District Poonch, Azad Jammu & Kashmir. Soil samples were collected from three soil depths (0-10 cm, 10-20 cm and 20-30cm). Results indicated that NT improved SOC by 7-12 % compared to CT in 0-10 cm soil depth, with cumulative annual increase of 2-3%. Intercropping of maize with soybean and vetch with wheat further enhanced SOC by 4-8% compared to their monoculture. The labile carbon pool i.e. POXC is sensitive to management practices has recorded 8-15% increase under NT and 5-10% under intercropping. The temporal increase of 7-9% in POXC from 2017-2018 indicated its responsiveness to tillage and legume based intercropping interventions. Similarly, 8-12% increase under NT and 5-8% under legume intercropping in POC indicated improved aggregation and carbon stabilization. The carbon fractions showed strong stratification, which declined with depth while NT consistently moderated this reduction. The combined application of NT and legume intercropping demonstrated synergistic effects on carbon accumulation across soil depths. These findings underscore the potential of conservation agriculture to enhance soil fertility, structural stability, and carbon sequestration in erosion-prone rain-fed systems of lesser Himalayas. Adoption of these practices can provide both immediate benefits to soil health and long-term contributions to climate change mitigation.

# Climate Change, Soil and Water Conservation

## Synergistic Effects of Biochar and Biostimulants on Soil Water Retention and Plant Drought Resistance Across Soil Textures

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Climate change is causing droughts to occur more frequently, which has significant implications for crop yields. In this review, analyzed articles published between 2015 and 2024 to assess the effects of biochar and plant biostimulants (applied individually or in combination) on soil water behavior and plant responses to drought across different soil types. Peer-reviewed studies, field trials, and database surveys were examined, in which soils were categorized as coarse (sand–sandy loam) or fine (clay–silt), and biochar was classified based on their feedstock and production methods. Biochar increased both the amount of water available to plants and the field water-holding capacity, with average increases of 28.5% and 20.4%, respectively; the largest gains were observed in coarse soils. Both microbial and non-microbial biostimulants promoted improved growth, osmotic adjustment in roots, and enhanced antioxidant defenses, although their effectiveness was strongly influenced by soil texture, delivery method, and adsorption capacity. When biochar and biostimulants were combined, additional benefits were observed often synergistic rather than merely additive including enhanced root development, microbial survival, nutrient release, and water uptake, particularly in coarse soils with low organic matter. In fine-textured soils, the primary advantages were improved nutrient dynamics and soil structure. This review identified several important research gaps. For example, there is no standardized methodology for evaluating the effects of biochar on the hydraulic properties of soils with different textures. Long-term field experiments remain limited, and optimal strategies for combining biochar and biostimulants have yet to be established. By translating these findings into precise, texture-guided management practices, it may be possible to make substantial contributions toward improving drought resilience in diverse farming systems.

## Strategies for Enhancing Agricultural and Water Productivity for Ensuring Food and water Security in Middle East Region

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The world population is to reach 9.3 billion in 2050, the population explosion will affect mainly the world food demand, researchers predict that the demand for food will rise by 60%. Demand for food, directly affects the necessity of increasing agricultural output, as agriculture is the main food producer

and the driving force of most countries' economy. But to produce food, one requires water, and our region (MENA) and the world are already today facing water scarcity, in the coming years the increase in demographics will boost the demand for water even more. MENA is one of the most water scarce regions of the world and despite that, its average daily water consumption per capita is one of the highest in the world, due mainly to its agricultural irrigation needs (60-70% of its daily water usage). Governments need to ensure water sustainability rapidly, ground water is depleting, desalination is a costly and non-ecological process and treated sewage water availability is limited. The Private Office of HH Ruler of Dubai – Al Nakhli in on a mission to help UAE agriculture become more sustainable by not only supporting the UAE Water Security Strategy 2036 but also saving water by improving water and food security, and reduction in methane gas emission. Through artificial intelligence this had the added benefit of increasing the water holding capacity of the soil. to save up to a trillion litres of water per year in UAE only – that's the same consumption as 5 million people or half the population of the UAE. Arid and semiarid regions are highly prone to salinization due to low rainfall and improper water management practices. These accounts for almost 40-45% of the Earth's total land surface, Salinity and drought, two very closely associated abiotic stressors, negatively affect crop productivity (Gamalero et al.2020). Almost 20% of the total irrigated land has been degraded due to excess soil salinity (FAO, 2020). The overall impact has demonstrated that sustainable production is possible in the UAE, with huge water savings. This helps support the conclusion that domestic production in the UAE can be both sustainable and economically feasible.

## Influence of Surface Residue Cover on Soil Erosion Dynamics in a Maize Wheat Cropping System: Field Measurements versus RUSLE-Based Estimates

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Accelerated soil erosion threatens agricultural sustainability in high-rainfall environments, particularly in the sub-mountainous regions of Pakistan. This study examined how varying crop residue cover affects soil erosion in a maize–wheat rotation and evaluated the accuracy of the Revised Universal Soil Loss Equation (RUSLE) under local field conditions. A field investigation was conducted over two consecutive years (2016–2018) at the University of Poonch, Rawalakot, Azad Jammu and Kashmir. The experiment was carried out on a uniform 4% slope using 18 bounded runoff plots measuring 6 m × 1.5 m. Treatments included maize and wheat residues applied at three surface cover levels (0, 4, and 6 Mg ha<sup>-1</sup>), with each crop grown in its respective season. Soil erosion quantified from runoff plots was compared with erosion estimates generated by RUSLE. The findings revealed consistent over prediction of soil loss by RUSLE across all treatments, with the greatest discrepancies observed under residue-free conditions. In maize plots without residue cover, measured soil loss averaged 3.86 t ha<sup>-1</sup> yr<sup>-1</sup>, whereas RUSLE estimated losses of 20.76 t ha<sup>-1</sup> yr<sup>-1</sup>. A similar pattern was observed in wheat, where actual erosion rates of 3.52 t ha<sup>-1</sup> yr<sup>-1</sup> contrasted sharply with model predictions of 21.85 t ha<sup>-1</sup> yr<sup>-1</sup>. Overall, RUSLE estimates exceeded observed values by approximately 5.4 to 7.9 times. These results demonstrate the limitations of applying generalized erosion models without local calibration

and confirm the critical role of crop residue retention in controlling soil erosion in maize–wheat production systems.

## Improved Production Technologies for Oil Palm in Coastal Sindh and Baluchistan to Enhance Soil Resilience and Support Edible Oil Self-Sufficiency

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Oil palm (*Elaeis guineensis* jacq) is a high-value oil tree with significant potential to support sustainable agriculture and economic development in the coastal regions of Pakistan. Research in this area has focused on developing and promoting science-based production technologies to enhance oil palm productivity while maintaining soil health, improving nutrient efficiency, and building resilience to environmental stress. The approach integrated sequential pre-nursery, post-nursery, and field-level experiments to evaluate elite oil palm germplasm for growth performance, nutrient uptake efficiency, and drought tolerance under water-limited coastal conditions. Nursery studies identified poly bags with peat moss as the most effective pre-nursery system, ensuring healthy and uniform seedlings. Post-nursery trials confirmed that integrated nutrient management, combining 75% NPKMg with 25% poultry manure, significantly enhanced seedling growth, improved physiological traits such as chlorophyll content and promoted better nutrient uptake, establishing a strong foundation for field performance. Drought tolerance assessments showed that, while moisture stress reduced growth and physiological activity, the Deli × La Mé variety consistently performed well, demonstrating its adaptability to challenging coastal environments. Multi-location field experiments optimized planting density and fertilizer regimes for immature palms, generating location-specific recommendations to support sustainable establishment and growth while minimizing nutrient losses and environmental impact. Together, these interventions demonstrate that combining elite genotypes, optimized nutrient management, and climate-resilient practices not only enhances oil palm growth but also strengthens soil-crop systems, builds resilience against environmental stress, and promotes long-term sustainability. The outcomes of the studies contribute to local edible oil self-sufficiency and align with the broader sustainable development agenda. This work highlights the critical role of soil resilience in sustainable agriculture, showing that informed management strategies can transform coastal agro-ecosystems into productive, resilient, and environmentally sustainable systems.

## Canal Irrigation System Management: Global Lessons for Improving Efficiency and Equity

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The canal irrigation system, crucial for global food security, faces significant challenges due to increasing water scarcity, rising external demands, and persistent management inefficiencies. Conventional supply-oriented management approaches have often resulted in low water-use efficiency, unreliable service delivery, and inequitable water distribution, particularly disadvantaging farmers located at the tail ends of canal networks. This review integrates global experiences and advanced frameworks to propose a comprehensive transformation in canal system management, focusing on improving both efficiency and equity. The analysis highlights that efficiency must be evaluated beyond field-level metrics by adopting a river basin perspective, utilizing water accounting to distinguish actual water savings from non-recoverable losses. Modernization requires transitioning from rigid supply systems to demand-driven networks through automation and downstream control mechanisms. Institutional reforms are essential for sustainable improvements. The Japanese model of “state-reinforced self-governance” demonstrates the effectiveness of empowering local water user groups while maintaining state oversight for accountability. Policies must also address the “efficiency paradox” by enforcing monitoring-based caps on water use to prevent resource depletion. A balanced approach involves hybrid allocation mechanisms that integrate water rights protection with market-based reallocation to enhance efficiency and productivity. Overall, the integration of strong governance, transparent economic incentives, and problem-oriented strategies provides a pathway toward resilient, efficient, and equitable canal irrigation systems.

## Assessing the Impact of Darawat Dam on Vegetation, Land Use/Land Cover, and Soil Fertility: A Temporal Analysis of the Command Area

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This study evaluates the impact of the Darawat Dam on vegetation cover, land use/land cover (LULC), and soil fertility within its command area. The area, located near Janghri village (near Hyderabad, Pakistan), was analyzed using ArcGIS and Sentinel-2 satellite imagery from 2018 to 2024. Changes in LULC and vegetation health were assessed using the Normalized Difference Vegetation Index (NDVI). In addition, 50 soil samples were collected from 25 locations at two depths (0–15 cm and 15–30 cm) to determine key physicochemical properties, including soil texture, electrical conductivity (EC), pH, sodium adsorption ratio (SAR), organic matter, available phosphorus, and extractable potassium. The results indicate substantial land cover changes, with cropland expanding from 9% in 2018 to 45% in 2024, while rangeland declined from 89% to 54%. NDVI analysis showed a 30% reduction in rangeland (from 88% to 58%) but also revealed improved vegetation density and health, particularly in cultivated areas. Soil analysis showed low salinity (mean EC: 0.203 dS m<sup>-1</sup>) and neutral to slightly alkaline pH (7.0–8.0), with SAR values (1.6–4.6) indicating no sodicity risk. Organic matter content was low, averaging 0.85% in the surface soil and 0.69% in the subsurface. Extractable potassium was within adequate ranges, whereas available phosphorus was low to marginal across both depths. Overall, the findings suggest that the Darawat Dam has enhanced water availability, promoted cropland expansion, and improved vegetation conditions. However, improving soil fertility through phosphorus fertilization and organic matter addition is essential to sustain agricultural productivity in the area.

# Synergistic Effects of Reduced Tillage and Leguminous Green Manure on Soil Carbon Fractions, Nutrient Content and Crop Yield under Semi-Arid Conditions

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Land degradation caused by intensive plowing and erosion is a growing challenge to sustainable agriculture, particularly in arid and semi-arid regions, as it deteriorates soil structure and fertility. A two-year field experiment was conducted to evaluate the combined effects of conservation tillage systems, namely reduced tillage (RT) and minimum tillage (MT), along with leguminous green manure (mung bean). The treatment effects were measured on soil sediment loss, nutrient retention, and wheat productivity, compared to conventional intensive tillage practices using a mouldboard plough (MP) and tine cultivator (TC). Results showed that MT and RT combined with green manure significantly reduced surface runoff and sediment yield by 64.7% and 26.2%, respectively, compared to MP. These conservation practices also improved soil carbon fractions, including particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and microbial biomass carbon (MBC). Additionally, RT+GM notably reduced losses of total nitrogen (N), potassium (K), zinc (Zn), and iron (Fe) by 34%, 40.8%, 39.6%, and 41%, respectively, compared to MP+summer fallow (SF). Principal component analysis (PCA) and ANOVA confirmed that conservation tillage with green manure significantly ( $p<0.05$ ) enhanced soil health indicators relative to conventional intensive plowing. Overall, integrating conservation tillage with leguminous green manure effectively reduces soil runoff and sediment loss while improving carbon retention and nutrient conservation in arid and semi-arid agroecosystems.

## Field Experiments to Estimate Hydraulic Soil Erosion in Pothwar

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Soil erosion is one of the main agents that degrade soils. Pakistan’s nearly 76% of land suffers with soil erosion that covers about16 million hectares of land. Pothwar plateau and the surrounding areas are the most water eroded areas in the country, where average annual soil loss reaches 2500–5000 t km–2 a–1. The water erosion is degrading soil by washing away organic matter, nutrients, and precious water needed for rainfed crop production. However, this continued downward spiral of soil quality decline remains un-noticed due to lack of field data. Our research group has conducted a series of field experiments to estimate the losses caused by soil erosion and to find out ways to reduce these losses. The data-based evidences of severe soil losses alongwith loss of macro and micro nutrients,

organic matter, and crop productivity will be presented while suggesting the countermeasures for erosion control in the agricultural lands.

## Evaluating the Impact of Managed Aquifer Recharge on Groundwater Quality in Semi-Arid Climate

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Global water scarcity, exacerbated by climate change and rapid urbanization, necessitates innovative strategies to safeguard dwindling groundwater resources. In regions where geological factors naturally render the aquifer saline, excessive extraction further risks salinity intrusion and water quality deterioration. To address these challenges, this study evaluated the implementation of Managed Aquifer Recharge (MAR) as a dual-purpose intervention designed to conserve harvested rainwater and improve local groundwater quality over the time. Initial sites characterization was conducted using SCARP strata charts and Electrical Resistivity Meter (ERM) surveys. The methodology involved the site-specific installation of three recharge wells, each equipped with settling and filtration chambers to treat runoff collected from paved areas. Fortnightly data collection monitored depth-to-water tables alongside chemical parameters. The results revealed significant improvements in water quality when comparing pre-recharge baseline conditions to post-recharge recovery. Specifically, baseline Total Dissolved Solids (TDS) concentrations across the three sites decreased substantially from 1080 mg/L, 1055 mg/L, and 1020 mg/L to post-recharge means of 260 mg/L, 170 mg/L, and 210 mg/L, respectively. This remarkable decline in TDS values indicates the formation of freshwater lenses and an effective dilution mechanism, demonstrating a pronounced hydro-chemical improvement within the saline aquifer system. Ultimately, these recharge interventions are closely aligned with UN Sustainable Development Goals (SDGs 6, 11, and 13), offering a scalable water security solution for semi-arid regions facing saline groundwater constraints.

## Improving Soil Health through Regenerative Agriculture Approaches in Cotton-Wheat Cropping System

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The cotton-wheat cropping system is a predominant agricultural practice in South Punjab of Pakistan including some areas of Sindh and Blochistan, but it often leads to soil degradation due to continuous growing of exhaustive crops and conventional tillage practices. Regenerative agriculture and crop diversification has been proposed as a sustainable strategy to mitigate soil health issues and improve overall agricultural productivity. The present field study was conducted at MNS-University of Agriculture Multan with the aim to evaluate the impact of regenerative agricultural approaches on soil health in cotton-wheat cropping system. Specifically, we investigated the effects of intercropping of

different leguminous crops and tillage systems into the rotation on soil fertility, structure, and microbial population. This study was comprised of RCBD split split plot design with three replications. The intercropping of legumes (mungbean, mashbean and soybean) was done in cotton crop under different tillage systems (conventional and zero) with different levels of nitrogen (recommended dose and 15% reduced dose of the recommended). Soil samples were collected to assess the changes in soil health indicators, including organic matter content, bulk density, available nitrogen, microbial population and system productivity. Results showed that soil properties and system productivity were improved under zero tillage as compared to conventional tillage in 2nd year of the study. Results regarding soil health, organic matter was improved by 30-35% in zero tillage and soil bulk density was reduced by 9-15% after 2nd year experiment. It was due to inclusion of leguminous crops and permanent zero tillage plots. Moreover, nitrogen load was reduced up to 15% for the succeeding crop (wheat) because of intercropping of leguminous crops in cotton crop. While regarding system productivity, it was noted with the passage of time that cotton and wheat yields were increased in zero tillage plots over conventional practices. Benefit-cost ratio (BCR) of conventional tillage system was recorded as 1.46 and 1.81 for year 1 and 2, respectively where 15% reduced dose of nitrogen was applied. While, BCR of zero tillage system was 1.33 and 1.72 for year 1 and 2, respectively where 15% reduced dose of nitrogen was applied. Conclusively, initial two years study of zero-till with legume intercropping improved soil organic matter, microbial population, and overall soil health in the cotton-wheat system. This allowed a 15% reduction in nitrogen use, reduced production costs, and enhanced economic returns. These positive trends suggest that long term zero-till and legume-based diversification could lead to even more stable, sustainable, and resilient outcomes in the cotton-wheat system. Therefore, extended long-term studies are strongly recommended to validate and further quantify these benefits on a permanent and consistent basis.

## Effect of Phosphorus Fertilization on Micronutrients Availability and Uptake in Maize Grown in Alkaline-Calcareous Soil

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Excessive phosphorus (P) fertilization can alter micronutrient availability in soils and may induce nutrient imbalances in plants. This study evaluated the effect of graded P application on micronutrient dynamics in soil and their uptake by maize (*Zea mays* L.). Pot and incubation experiments were conducted concurrently in the greenhouse and laboratory of the Department of Soil and Environmental Sciences, The University of Agriculture, Peshawar, Pakistan, during 2009. Six phosphorus levels (0, 30, 60, 90, 120 and 150 kg P ha<sup>-1</sup>) were applied as single superphosphate along with recommended micronutrient doses of Zn (10), Cu (2), Fe (5), Mn (5) and B (0.5 kg ha<sup>-1</sup>) supplied as their respective sulphate salts and boric acid. Basal fertilizers of 120 kg N and 60 kg K<sub>2</sub>O ha<sup>-1</sup> were applied as urea and potassium sulphate. Spring maize (cv. Jalal) was used as the test crop in a randomized complete block design with four replications. Plant growth responded positively to P fertilization up to 90 kg P ha<sup>-1</sup>, resulting in a 53% increase in biomass compared with the control, after which growth declined with further P additions. Relative yield showed a strong relationship with

applied P ( $R^2 = 0.83$ ). Increasing P supply reduced plant concentrations of B, Zn and Cu, while Fe and Mn concentrations increased, indicating differential micronutrient responses to P fertilization. However, micronutrient uptake generally followed plant growth and P uptake trends, suggesting that uptake provides a more reliable indicator than tissue concentration for interpreting micronutrient behavior. Ratios of P with B, Zn, Cu and Mn increased linearly with rising P concentration, whereas the P/Fe ratio showed an inconsistent pattern. Incubation results confirmed negative interactions of P with B, Zn and Cu, and positive interactions with Fe and Mn. Increasing P application also slightly reduced soil pH ( $R^2 = 0.83$ ). Overall, the results demonstrate that phosphorus fertilization can significantly influence micronutrient availability in soil and their uptake by maize under the experimental conditions.

## Assessment of Eddy Covariance Technique for Measuring Evapotranspiration at Different Time Scales in South Punjab

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Exchanges of energy, water vapor, and carbon dioxide between land surface ecosystems and the atmosphere are routinely quantified using eddy covariance (EC) flux towers. These systems provide critical information on evapotranspiration (ET) dynamics, particularly in water-scarce agricultural regions such as South Punjab, where precise monitoring of crop water use is essential for sustainable resource management. Although EC is widely deployed globally, its reliability across multiple time scales (hourly to seasonal) in semi-arid climates remains insufficiently characterized. Moreover, the application of EC to optimize irrigation scheduling in cotton-based cropping systems of South Punjab has yet to be validated under field conditions. This study aimed to: (1) evaluate EC performance for ET estimation across multiple time scales, and (2) assess its utility as a real-time tool for deficit-based irrigation scheduling. Continuous ET measurements were conducted using an EC flux tower installed at Jalalpur Pirwala during the 2024 Kharif growing season. Hourly fluxes were quality-controlled (including removal of anomalous negative nocturnal values) and gap-filled using linear interpolation. Daily and seasonal ET totals were integrated with rainfall records to compute crop water deficits. Distinct diurnal and seasonal ET patterns were observed (daytime peaks of  $0.8\text{--}1.2\text{ mm h}^{-1}$ ; daily totals of  $6\text{--}10\text{ mm d}^{-1}$  during peak growth stages). Irrigation scheduling analysis identified critical water-stress periods (e.g., a cumulative deficit of  $-60\text{ mm}$  in August). Energy balance closure achieved was 85%; operational challenges included dust deposition on sensors and data gaps associated with intense monsoon rainfall events. This study validates EC as a reliable method for measuring ET in semi-arid agroecosystems and demonstrates its practical utility for deficit-based irrigation management. Integration of hybrid approaches is recommended to complement EC measurements with hydrological modelling for improved spatial scalability. These findings contribute to the advancement of sustainable water management in South Punjab and comparable semi-arid agricultural regions.

## Effects of Irrigation Water Quality on Soil Properties, Nutrient Uptake, and Wheat (*Triticum aestivum* L.) Productivity Under Semi-Arid Conditions in South Punjab, Pakistan

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Salinity is a major abiotic constraint to wheat (*Triticum aestivum* L.) productivity in arid and semi-arid regions, primarily arising from the progressive accumulation of soluble salts via irrigation with poor-quality water. This study investigated the effects of irrigation water quality on soil chemical properties, physiological processes, nutrient uptake, and yield performance of wheat at MNS-University of Agriculture, Multan, Pakistan. A randomized complete block design (RCBD) was employed with three irrigation water treatments: canal water (T<sub>1</sub>), brackish water (T<sub>2</sub>), and a mixture of canal and brackish water (T<sub>3</sub>), each replicated three times using the wheat variety Urooj-22. Soil chemical properties exhibited progressive deterioration under brackish water irrigation. Soil pH increased progressively under T<sub>2</sub> (8.1–8.5), and electrical conductivity (EC) rose from 2.48 to 3.82 dS/m by the fourth irrigation, indicating severe salinity buildup. The Sodium Adsorption Ratio (SAR) increased sharply under T<sub>2</sub> from 6.8 to 11.2, surpassing the critical sodicity threshold (SAR ≥ 10), while Cation Exchange Capacity (CEC) declined from 14.2 to 12.8 cmol<sub>n</sub>/kg, reflecting soil structural degradation due to sodium-induced clay dispersion. In contrast, T<sub>1</sub> maintained favourable soil conditions with lower pH (7.7–7.9), EC (1.75–1.96 dS/m), safe SAR levels (2.9–3.5), and stable CEC (14.1–14.8 cmol<sub>n</sub>/kg). T<sub>3</sub> showed intermediate soil responses, indicating moderate yet progressive salt accumulation. Soil moisture retention, monitored across four irrigation stages, was highest in T<sub>1</sub> and lowest in T<sub>2</sub>, attributed to osmotic stress under elevated soil salinity. Chlorophyll content (SPAD units) was highest in T<sub>1</sub> (38.77) and lowest in T<sub>2</sub> (31.00), indicating significantly impaired photosynthetic activity under saline stress. Nutrient uptake was significantly affected by irrigation water quality; T<sub>1</sub> recorded maximum nitrogen (2.85%), phosphorus (0.35%), and potassium (2.60%) contents, while T<sub>2</sub> showed minimum uptake (N: 2.10%, P: 0.25%, K: 1.90%) due to ionic competition and reduced nutrient availability. Yield attributes exhibited a consistent pattern, with T<sub>1</sub> significantly outperforming T<sub>2</sub>, and T<sub>3</sub> demonstrating partial alleviation of salinity-induced yield losses. Overall, it is concluded that canal water irrigation sustains soil fertility, nutrient dynamics, and wheat productivity, while brackish water significantly deteriorates soil physicochemical health through increased SAR and reduced CEC, ultimately suppressing crop yield. Mixed water provides a temporary compromise but contributes to gradual soil degradation. Efficient water quality management is therefore essential for sustainable wheat production in salt-affected regions.

## Wind Manipulation Effects on the Growth and Nutrients Availability in Maize

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Wind speed is considered a serious threat for crop production. High wind velocity can create drought in soil ultimately effect on nutrient mobility and availability. Wind also affects biomass allocation, root growth, nutrient uptake. In view of significance of wind treatment, pot experiment was conducted to evaluate the effect of wind on maize under different compost applications. Study involved two factorial- completely randomized design included: Factor A: Wind treatment- WT (3): WT1: Ambient wind, WT2: Enhanced wind, WT3: Controlled wind and Factor B: Compost treatments (3): C1: No compost, C2: 12.5 tons ha<sup>-1</sup>, C3: 25 tons ha<sup>-1</sup> 2.5 kilograms soil from arable land of drought affected areas of Badin was used in pot experiment involving local maize variety “Hybrid maize”. The compost was applied before sowing maize. The results indicated that enhanced wind velocity, reduced most of growth parameters (plant height, fresh and dry weights of plant, number of leaves, stem girth, leaf area). The addition of compost to soil enhances its organic matter content, which is essential for preserving soil fertility and reducing nutrient loss. In the case of nutrients (N P K) concentrations followed a similar trend as of growth parameters. However, N P K concentrations were found in adequate range at 25 tons/ha in controlled wind velocity plant tissue of maize. It is concluded that in the controlled wind velocity with application of selected compost could help to mitigate effect of wind on maize plant, reduce the nutrient loss and improve the growth of root biomass.

## Economic Evaluation of Natural Vegetation of Kheri Murat National Park, Tehsil Fateh Jung, District Attock

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Pakistan possesses diverse climatic and soil conditions that support a wide range of forest ecosystems. Among these, scrub forests are widely distributed across the country, particularly in the foothills of the Himalayas. Kherimurat National Park and its surrounding areas represent a significant scrub forest ecosystem located within the Pothowar region. These forests commonly occur below the subtropical chir pine forests at elevations ranging from 460 to 920 m, particularly in regions such as the Murree foothills, Margalla Hills (Islamabad), Pothowar Plateau, Kalachitta Hills (Attock), Salt Range (Jhelum), and Suleiman Mountain Range. Vegetation analysis plays a crucial role in understanding ecosystem structure, species composition, and biodiversity, providing valuable information for sustainable forest management and ecological conservation. The present study aims to evaluate the natural vegetation of Kherimurat National Park through both quantitative and qualitative assessments. Field surveys will be conducted to collect vegetation data, and structured questionnaires will be administered to local communities and residents to obtain traditional ecological knowledge regarding plant distribution and forest utilization. The findings of this study will contribute to a better understanding of the vegetation structure and species composition of Kherimurat scrub forests, providing baseline information for future ecological research and sustainable forest management strategies in the region.

# Assessment of Climatic Parameter Variation and Its Impact on Sustainable Agriculture in Dir Upper Pakistan with Mitigation and Adaptation Strategies

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Climate change poses a significant threat to agricultural sustainability, particularly in vulnerable mountainous regions such as Upper Dir, Pakistan. This study analyzed variations in key climatic parameters and their implications for sustainable agriculture in the region. The study evaluated historical climate trends (2002–2023) and projected future scenarios using the high-emission Representative Concentration Pathway (RCP 8.5). Meteorological data obtained from the Pakistan Meteorological Department were analyzed using Mann–Kendall trend analysis, return period analysis, and regression forecasting. The analysis focused on key agro-climatic parameters including temperature, rainfall, humidity, wind speed, and aridity. Results indicated that the annual mean temperature increased by approximately 2°C between 1980 and 2023, while rainfall declined by about 2%. Soil moisture decreased by approximately 6%, contributing to increasing aridity and hydrological stress in the region. Wind speed showed minor seasonal fluctuations, whereas humidity increased, particularly during monsoon periods. Future climate projections under the RCP 8.5 scenario indicate substantial warming throughout the 21st century. Between 2011 and 2040, temperatures are projected to increase by 1.5–3.5°C (median 2.5°C). During 2041–2070, warming is expected to accelerate, with increases ranging from 4 to 7°C (median 5.5°C). By the end of the century (2071–2100), temperatures could rise by 5–12°C, with a median increase of approximately 8.5°C. To mitigate these impacts, climate-resilient crops such as tamarillo, olive, avocado, and dragon fruit were introduced, and more than 30,000 tamarillo plants were distributed across the region. Additional adaptation strategies included tunnel farming, agroforestry, construction of small dams, and improved irrigation systems. The findings highlight the urgent need for climate-smart agriculture, afforestation programs, and integrated water resource management to sustain agricultural productivity and rural livelihoods under changing climatic conditions.

## Evaluating Cotton Genotypes for Heat Stress Tolerance Through Physiological and Yield Metrics

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Reinstating cotton production requires synchronized and well-planned interventions. Among these, the development and adoption of heat-tolerant varieties is crucial to sustain and enhance productivity, particularly under high temperatures associated with climate change. This study was conducted at the experimental field of the Central Cotton Research Institute, Sakrand, to evaluate the heat stress tolerance of newly developed cotton genotypes. Two sets of genotypes were assessed: non-Bt cotton (CRIS-694, CRIS-797, CRIS-698, with CRIS-613 as the standard) and Bt cotton (Bt.CRIS-714, Bt.CRIS-716, Bt.CRIS-723, with Bt.CRIS-508 as the standard). These genotypes were sown on four different dates (1st April, 15th April, 1st May, and 15th May) in a split-plot design with three replications to induce varying levels of heat stress. Statistical analysis revealed significant ( $p < 0.05$ ) differences among sowing dates, genotypes, and their interactions. Among non-Bt genotypes, CRIS-694 consistently outperformed others across sowing dates, followed by CRIS-698, exceeding the performance of the standard variety CRIS-613. Within the Bt group, Bt.CRIS-723 recorded the highest yield under heat stress, followed by Bt.CRIS-714 and Bt.CRIS-716, compared to the standard Bt.CRIS-508. Heat stress significantly increased shedding per plant across all genotypes, with higher percentages of squares, flowers, and small bolls under elevated temperatures, highlighting the adverse impact of heat on cotton reproductive development. The findings underscore the potential of the selected cotton genotypes as heat-tolerant cultivars and provide valuable insights into cotton performance under high-temperature environments.

## Impact of Climate Change on Soil Microbial Diversity under Organic Farming Systems

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Climate change is significantly altering soil ecosystems through rising temperatures, irregular precipitation patterns, and increased frequency of extreme weather events. Soil microbial communities play a fundamental role in nutrient cycling, soil fertility maintenance, and carbon sequestration, particularly under organic farming systems where biological processes are central to productivity. This study investigates the impact of climate variability on soil microbial diversity and activity within organically managed agricultural fields. Soil samples were collected from certified organic farms across varying climatic gradients, and parameters including microbial biomass carbon, soil respiration, enzymatic activity, and bacterial and fungal diversity were analyzed using standard microbiological and molecular techniques. Preliminary findings indicate that moderate increases in temperature enhance microbial activity in organically amended soils due to higher organic matter availability; however, prolonged heat stress and moisture deficits significantly reduce microbial diversity and functional stability. Organic systems showed greater resilience compared to conventional systems due to improved soil structure, higher organic carbon content, and enhanced moisture retention capacity. The results highlight the critical role of organic farming practices in buffering soil microbial communities against climatic stress. Strengthening organic matter management and promoting climate-resilient organic practices can sustain soil biological health under

changing environmental conditions. This research contributes to understanding the ecological mechanisms through which organic farming enhances soil adaptation to climate change.

## Effect of Different Nitrogenous Forms During Crop Residue Management on Soil Microbial Activities and GHG Emissions

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Crop residue management methods influence soil organic carbon (SOC) and nitrogen (N) dynamics due to microbial access. The various forms of N directly or indirectly affect the activities of soil microbial communities and greenhouse gas (GHG) emissions. It was hypothesized that residue mulching would have the lowest GHG emissions and N losses under the combined  $\text{NH}_4\text{NO}_3$  source. For this, an incubation study was carried out using three nitrogenous sources  $(\text{NH}_2)_2\text{CO}$  as ammonium,  $\text{Ca}(\text{NO}_3)_2$  as nitrate, and  $\text{NH}_4\text{NO}_3$  as both ammonium and nitrate forms, and no N as a control, along with maize residues ( $10 \text{ g kg}^{-1}$  of soil) as mulching or incorporation. The results revealed that total GHG emissions were reduced by 64.6%, 38%, and 45.8% with urea, calcium nitrate, and ammonium nitrate, respectively, under maize residue mulching; however, emissions increased by 38.03% with  $\text{NH}_4\text{NO}_3$  under residue incorporation. The N losses were significantly reduced by all N forms under residue mulching, whereas losses increased by 50.32% and 43.25% with  $(\text{NH}_2)_2\text{CO}$  and  $\text{NH}_4\text{NO}_3$  under residue incorporation. The maximum MBC content ( $331 \text{ mg C kg}^{-1}$  soil) was in combined  $\text{NH}_4\text{NO}_3$  form under incorporation, and the minimum ( $195 \text{ mg C kg}^{-1}$  soil) was in urea under residue mulching. The  $\beta$ -glucosidase activity was significantly increased across all N forms, with maximum values ( $126.30$  and  $126.23 \text{ nMol g}^{-1} \text{ soil hr}^{-1}$ ) in urea under incorporation and mulching, respectively. The maximum leucine aminopeptidase activity ( $13519.12 \text{ nMol g}^{-1} \text{ soil hr}^{-1}$ ) was obtained with ammonium nitrate in residue incorporation. The study concluded that applying separate ammoniacal N and combined ammonium nitrate N sources, with residue mulching, reduced microbial activity and significantly decreased GHG emissions and N losses relative to residue addition alone.

## Biodiversity Conservation and Sustainable Utilization of Wild Rubus Species in the Himalayan Region of Pakistan

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A constant increase in world’s population, novel economic and political pressures, competition for land and water and the double burden of malnutrition i.e., under-nutrition and over-nutrition are

serious challenges to be addressed. Lack of dietary diversity and dependency on only few crops for food and feed purposes is a great challenge too. The changing climatic scenarios are also seriously affecting the sustainable food supply systems. Moreover, problems with production and distribution of food are also causing serious postharvest physical and nutritional losses along the chain. Though there could be many solutions to address these acute problems. However, the use of underutilized fruit species could be the sensible approach if their potential is exploited through breeding, production, agro-processing and marketing. Numerous underutilized fruit species worldwide have been reported to be rich in vitamins, minerals and other micronutrients, suggesting that they have the potential to play a role in addressing the major problem of malnutrition. Using indigenous underutilized fruit species to address these acute problems could be the cheapest and sustainable solution for local as well as global communities. However, to unlock the full potential of these naturally grown underutilized fruit species, many barriers exist. These barriers include non-availability of nutritional information and non-existence of proper supply chain systems. To achieve that, a demand-led research across the whole value chain is needed. Further efforts are also required to establish certified nurseries, small scale value addition units and a proper supply chain system for these fruit species.

## Growth Response of *Ziziphus Mauritiana* as Impacted by Water Stress

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Drought has become one of the important limitations to agricultural development, especially in regions that are water deficit. Plants undergo water stress either when the supply of water to their roots is limited or when rate of transpiration is high. Water stress is mainly due to water shortage e.g. dry spell or excessive saline soil. Each year, water stress on agronomic plants in various regions throughout the world reduces agricultural yields and affects food supply with the ultimate result – drought. Therefore, the capacity to tolerate such stress is of huge economic significance. Plants try to modify to the stress situations by arrangement of bio-chemical and physio-logical interventions. In the present scenario, drought resistance has become an important topic of debate in agricultural research. But for in forestry studies, it is still given less attention. This study emphasis the positive effects of water use efficiency on the growth behavior of the chosen plants. The major focus of that research was to observe the growth response of *Ziziphus mauritiana* at daily, average and extreme levels of water application. The research trial for this purpose was planned in the nursery area of the department of Forestry and Range Management, University of Agriculture Faisalabad. The seedling plants of chosen tree species were obtained from the nursery of the department of Forestry and Range Management. Beside control level, there were four treatments. Randomized Complete Block Design

was used for conducting the experiment. The germination response of the selected tree species was noticed in response to water use efficiency at initial developmental phases. Seedlings were raised in pots by irrigating at various levels i.e. Daily (T0), 4 days (T1), 8 days (T2), 12 days (T3), and 16 days (T4) to observe the germination ratio and key morphological features at various levels of water application. Data about different morphological features exhibited variations in their performance after analysis. The effect of all the treatments on the height of plants was significant. It was obvious that the growth behavior of *Z. mauritiana* was better by enhancing the water use efficiency.

## Enhancing Crop Productivity through Climate-Resilient Approach using Salicylic Acid under Water Deficit Conditions

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It is well stated that Pakistan is facing impacts of climate change very severely in addition to water scarcity. Biotic and abiotic stresses pose serious threats to agricultural productivity worldwide. Among these stresses, drought stress is one of the most critical constraint, limiting crop productivity and causing more than 50% loss in crop yield. Salicylic acid (SA) is a natural phenolic phytohormone and plant growth regulator that acts as a biostimulant to enhance plant immunity and stress tolerance. It improves crop productivity by mediating resistance to biotic threats (fungi, bacteria, viruses) and abiotic stresses (drought, salinity, heavy metals) while regulating growth, photosynthesis, and nutrient uptake. To assess its effects on crop and stress mitigation, this study was conducted during 2023 to 2026. Field experiments were conducted at Soil Chemistry Section regarding exogenous application of SA where different levels of SA including 0, 0.5, 1 and 1.5 mM were tested under normal and water deficit conditions. Salicylic acid was tested by foliar and seed priming by using wheat as test crop. The results showed that exogenous application of SA not only improved plant growth and yield but also nutritional quality of produce. Although the exogenous application of SA under normal conditions gave better results comparing to control. But, its application under water deficit conditions showed more promising and significant results with improved crop yield and efficient utilization of mineral. The grain yield of wheat increased over control by 12% under normal irrigation regimes and 27% under limited water supply conditions with the application of salicylic acid. This study concluded that exogenous application of salicylic acid is very useful for enhancing crop productivity and it proved climate resilient approach for improving crop productivity and nutritional quality of produce under limited water conditions.

## Evaluation of Biochar-Coated Urea for Improving Nitrogen Efficiency and Wheat Yield

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Low nitrogen use efficiency of conventional urea due to losses of volatilization and leaching remains a major constraint in crop production. This study evaluated the effectiveness of biochar-coated urea, prepared from fruit and vegetable waste-derived biochar, on wheat yield and nitrogen use efficiency. A trial was conducted at the field area of Soil Chemistry Section, Ayub Agricultural Research Institute (AARI). The experiment comprised eight treatments: T1 (Control), T2 (NPK), T3 (1% biochar-coated urea + PK), T4 (2% biochar-coated urea + PK), T5 [ $\frac{1}{2}$  N (1% coated) +  $\frac{1}{2}$  N (uncoated) + PK], T6 [ $\frac{1}{2}$  N (2% coated) +  $\frac{1}{2}$  N (uncoated) + PK], T7 [ $\frac{1}{2}$  N (1% coated) +  $\frac{1}{2}$  N (2% coated) + PK], and OT8 [ $\frac{1}{3}$  N (uncoated) +  $\frac{1}{3}$  N (1% coated) +  $\frac{1}{3}$  N (2% coated) + PK]. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Results showed Biochar-coated urea treatments significantly improved the parameter compared to NPK alone. The highest yield value (5.20 t/ha) was recorded in T8, which was significantly superior to all other treatments. This was followed by T5 (4.91 t/ha). The lowest value (2.16 t/ha) was observed in the control treatment. Post-harvest soil analysis revealed that biochar-coated urea treatments significantly improved soil organic matter, available nitrogen, phosphorus, and potassium compared to control and conventional NPK. The highest improvement in soil fertility parameters was observed in T8, indicating the positive role of biochar coating in nutrient retention and soil health. This study clearly demonstrated that integrated use of biochar coated and uncoated urea is an effective strategy for improving crop yield.

## Impact of Management Practices on Available Phosphorus and Potassium in Lasbela

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Phosphorus (P) and potassium (K) are most critical nutrients to manage in crop production after nitrogen. A survey study was conducted in surroundings of Tehsil Uthal, District Lasbela to evaluate the effect of management practices on available P and K. 25 samples were collected from five management practices: i) Bare soil, ii) crop land, Forest, iv) Grass land, v) Orchard land. All collected samples were air dried, grinded and sieved through 2 mm mesh size. The data collected on available P and K were analyzed with R statistical software using a linear model. pH values for all soil collected were above 8 with highest values of 8.24 from soil collected from Forest Land while minimum pH was recorded in crop land. Available P was minimum in orchard land while highest was found in Forest Land (16 mg kg<sup>-1</sup>). Available K was highest in crop land (143 mg kg<sup>-1</sup>) while minimum was in forest

land (93 mg kg<sup>-1</sup>). Hence, it can be concluded that soils with forests can have more available P and crop land due to regular cultivation and soil disturbance release more available K in soil nutrients pool.

## Can Compost Buffer Wind Stress? Impacts of Wind Velocity on Growth and NPK Uptake in Maize (*Zea mays* L.)

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Wind velocity is an important but often overlooked abiotic stress affecting crop production. High wind velocity accelerates soil moisture loss, induces physiological drought, and consequently alters nutrient availability and uptake. In view of its agronomic significance, a pot experiment was conducted to evaluate the effect of wind stress on maize under different compost application rates. The study was arranged in a two-factor completely randomized design. Factor A consisted of three wind treatments: WT1 (ambient wind), WT2 (enhanced wind), and WT3 (controlled wind). Factor B included three compost levels: C1 (no compost), C2 (12.5 t ha<sup>-1</sup>), and C3 (25 t ha<sup>-1</sup>). Each pot contained 2.5 kg of soil collected from drought-affected arable land in Badin. A local hybrid maize variety was sown, and compost was incorporated into the soil prior to planting. Enhanced wind velocity significantly reduced growth parameters, including plant height, number of leaves, stem girth, leaf area, and fresh and dry biomass. Wind stress likely increased transportational demand and reduced soil moisture availability, thereby limiting nutrient uptake and assimilate partitioning. In contrast, compost application improved soil organic matter content, enhanced moisture retention, and reduced nutrient losses. Nitrogen, phosphorus, and potassium concentrations in plant tissues followed trends similar to growth responses. These findings indicate that compost amendment can partially mitigate the adverse effects of wind stress by improving soil physical and nutritional status. Under controlled wind velocity, higher compost application enhanced root biomass development, reduced nutrient depletion, and improved overall maize growth performance.

## Maize Cultivation and Consumption Practices in Azad Jammu and Kashmir: Insights from Farmers

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Maize (*Zea mays* L.) has historically been a cornerstone of agriculture in Azad Jammu and Kashmir (AJK), serving as a primary food source and essential livestock feed. This study investigates current farming practices and consumption patterns of maize across AJK's major maize-growing regions. A

three-stage stratified random sampling method was employed to select a sample of 175 respondents, and descriptive statistics were used for data analysis. The findings reveal that traditional maize varieties continue to dominate cultivation practices, with 59% of farmers opting for these varieties. On average, farmers use 3.41 kg of seed per kanal, and the application of chemical fertilizers remains minimal, while pesticide use was reported as nonexistent. Despite these traditional methods, an average yield of 401 kg per acre was recorded, although lodging remains a significant challenge hindering higher productivity. Regarding consumption patterns, approximately 82% of the maize crop is consumed domestically, highlighting its continued importance in local diets. A smaller proportion, 6%, is used for seed, and only 10% is sold to other farmers or in markets. These findings underscore the enduring significance of maize as a staple food and its integral role in agricultural livelihoods in AJK. This study provides insights into the current state of maize farming in AJK, emphasizing the need for sustainable agricultural practices to address productivity challenges and ensure food security. It also suggests avenues for future research and policy interventions aimed at enhancing maize cultivation techniques and promoting economic resilience among farming communities in the region.

## Climate-Resilient Nursery Techniques Improve Establishment and Productivity of Rice Varieties

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Climate-resilient nursery management is critical for sustaining rice productivity under drought conditions. A field experiment was conducted to evaluate the performance of selected rice varieties under different climate resilient nursery raising methods. The study was arranged in a factorial randomized complete block design (RCBD) with three replications. Treatments included three nursery raising methods—wet bed, dry bed, and parachute method—and three rice varieties: Shua (OP), Red rice (indigenous), and Guard LP18 (hybrid). Key growth and yield parameters including seedling vigor, plant height, tiller number, panicle length, and grain yield were recorded to assess varietal response to different nursery techniques. Results indicated that nursery raising methods and varietal differences significantly influenced seedling establishment and crop performance. The parachute method produced more vigorous seedlings, higher tiller density, and better transplant establishment compared with the wet and dry bed methods. Among the tested varieties, the hybrid Guard LP18 showed superior growth and yield potential, whereas the indigenous Red rice displayed moderate adaptability across nursery systems. Shua (OP) exhibited relatively lower yield but stable establishment under all methods. The interaction between nursery method and variety suggested that Guard LP18 under the parachute nursery system achieved the highest grain yield. These findings indicate that appropriate nursery management combined with suitable varietal selection can enhance rice productivity under climate-variable conditions.

## Remote SensingBased Evaluation of Wheat Cultivars and Nitrogen Management Using Normalized Difference Vegetation Index

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Spectral reflectance and remote sensing technique provide rapid, non-destructive methods for evaluating crop growth and productivity under various nutrient conditions. This study evaluated the potential use of vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), for estimating biomass, leaf area index (LAI), and grain yield of wheat under different nitrogen application regimes. Even for estimation of grain yield in wheat NDVI is considered a potential screening tool. Both field experiments were conducted to scrutinize the response of NDVI to the yield behavior of different wheat cultivars and nitrogen fertilization at the agronomic research area, University of Agriculture, Faisalabad-Pakistan. Spectral reflectance was measured using a GreenSeeker Hand Held optical sensor, and NDVI, total dry matter (TDM), and grain yield were recorded at key growth stages from tillering to maturity. Split plot design was used as experimental model in, keeping four nitrogen rates (N1=0 kg ha<sup>-1</sup>, N2 =55 kg ha<sup>-1</sup>, N3 = 110 kg ha<sup>-1</sup>, and N4 = 220 kg ha<sup>-1</sup>) in main plots and ten wheat cultivars (Bakkhar-2001, Chakwal-50, Chakwal-97, Faisalabad-2008, GA-2002, Inqlab-91, Lasani-2008, Miraj-2008, Sahar-2006, and Shafaq-2006) in subplots with four replications. The impact of nitrogen and the difference between cultivars were forecasted through NDVI. Results revealed significant genotypic variation in NDVI across nitrogen levels. NDVI showed strong correlations with grain yield at later growth stages, explaining 6477% of yield variation under nitrogen stress, while NDVI accounted for 7090% of biomass variation. Positive relationships were also observed between NDVI and LAI, particularly at booting and grain filling stages. The results suggested that nitrogen treatment N4 (220 kg ha<sup>-1</sup>) and cultivar Faisalabad-2008 gave the maximum NDVI value (0.85) at the grain filling stage among all treatments. The correlation among NDVI at booting, grain filling, and maturity stages with grain yield was positive ( $R^2 = 0.90$ ;  $R^2 = 0.90$ ;  $R^2 = 0.95$ ), respectively. So, booting, grain filling, and maturity can be good depictive stages during mid and later growth stages of wheat crop under agro-climatic conditions of Faisalabad and under similar other wheat growing environments in the country.

## Morpho-Physiological Responses of Cotton through Supplemental foliar applied Potassium Silicate under Deficit irrigation in Hyper-Arid Region

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Water scarcity and drought stress are major constraints limiting crop productivity in arid regions, particularly in Xinjiang, China, a key global cotton-producing area. Enhancing drought tolerance in cotton is critical for sustaining yield and improving resource-use efficiency under water-limited conditions. This study evaluated the role of foliar-applied potassium silicate ( $K_2SiO_3$ ) in improving morpho-physiological, biochemical, and yield responses of cotton under deficit irrigation. Pot and field experiments were conducted using four cotton varieties, from which Zhong Mian-113 (drought-tolerant) and Xin Nong-525 (drought-sensitive) were selected for detailed field trials during 2023–2024. Treatments included three irrigation regimes (85%, 65%, and 40% field capacity) and potassium silicate levels (0, 220, and 440 mg L<sup>-1</sup>), applied at flowering and boll initiation stages. Severe drought (40–45% FC) significantly reduced chlorophyll content, photosynthetic rate, relative water content, and stomatal conductance, with greater sensitivity observed in Xin Nong-525. However, potassium silicate application, particularly at 440 mg L<sup>-1</sup>, markedly improved physiological performance, antioxidant enzyme activities (CAT, SOD), osmolyte accumulation (proline), and water relations in both varieties. It also reduced oxidative stress indicators such as H<sub>2</sub>O<sub>2</sub> and MDA. Notably, Zhong Mian-113 showed superior drought tolerance, with potassium silicate enhancing photosynthesis, PSII efficiency, and water-use efficiency, resulting in yield increases of up to 18–20% over two growing seasons. These improvements were associated with enhanced osmotic adjustment, chlorophyll stabilization, and activation of antioxidant defense systems. Overall, foliar application of potassium silicate emerges as an effective and sustainable strategy to mitigate drought stress, improve cotton productivity, and enhance climate resilience in hyper-arid regions.

## Soil, Water and Environmental Chemistry

### Emerging Pollutants and Soil Resilience: Challenges for Sustainable Development in Pakistan

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Emerging pollutants like pharmaceuticals, personal care products, endocrine disrupting chemicals, microplastics and industrial products are causing serious environmental issues. Especially their presence in soil risks our food security. Especially in Pakistan rapid urbanization, population growth, industrialization and expanded agricultural activities increased contamination of emerging pollutants. Most of the industry in Pakistan is located on the banks of natural drains and their wastewater is directly released into these drains without treatment. So, this water can contaminate both fresh water and soil. In Peri urban areas of major industrial cities, this water is used for irrigation purposes. Presence of these pollutants in soil can affect the microbial community, nutrient cycling and can pose serious health issues. This can overall affect agricultural productivity, ecosystem stability, and long-term sustainability. The Pakistan's soils vulnerability is further enhanced due to other challenges like climatic stresses, water scarcity and temperature extremes. Addressing emerging pollutants and enhancing soil resilience presents a complex challenge for the to cope with the sustainable development goals, including food security, public health protection, and environmental conservation. So, treatment of wastewater before release into natural system and adoption of sustainable agricultural practices could be effective tools to tackle these issues. Furthermore, enhancing scientific research and capacity building will be critical for understanding pollutant behavior in diverse soil types and developing remediation strategies.

### Assessing the Effects of Bioinoculant and Herbicide Applications on Rhizospheric Soil Bacterial Communities

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Soil microbial communities in the rhizosphere are integral to maintaining crop productivity, nutrient cycling, and overall soil health. Agricultural inputs may influence the structure and function of soil microbial communities. Therefore, two complementary studies were conducted to evaluate how contrasting management strategies affect rhizospheric bacterial communities. The first examined the introduction of a symbiotic fungus, *Trichoderma asperellum* SL2, in rice cultivation systems. The second assessed the impact of commonly used herbicides, glufosinate-ammonium and metsulfuron-methyl applied at recommended field rates (495 g a.i./ha and 15 g a.i./ha, respectively) in oil palm plantations. Changes in soil bacterial community composition and diversity were analysed using 16S rRNA gene high-throughput sequencing. In the rice plots, 16 L of *T. asperellum* SL2 spore suspension was uniformly applied to field plots using a spraying drone. One month after application, treated plots exhibited bacterial community profiles comparable to controls, suggesting that the introduction of the fungus did not disrupt the native rhizospheric microbiota. In the oil palm plantation, herbicides were applied to the rhizosphere and monitored over nine months. Analyses of alpha and beta diversity indicated only minimal shifts in microbial community structure over time. Importantly, the relative abundance of beneficial and functionally relevant bacterial taxa remained stable. Overall, the findings indicate that the application of *T. asperellum* SL2 as a bioinoculant did not exert any negative impact on the native soil bacterial population, as evidenced by the comparable microbial profiles observed between treated and control plots. Similarly, the use of glufosinate-ammonium and metsulfuron-methyl at recommended field rates did not adversely affect the diversity, composition, or potential functions of soil bacterial communities in oil palm plantations. These results suggest that both the biological amendment and the evaluated herbicide practices are compatible with the maintenance of rhizospheric microbial stability, supporting their use within sustainable crop management systems.

## Wastewater Reuse in Agriculture: Effects on Soil Health and Spinach Growth

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The reuse of wastewater for crop irrigation is increasingly important due to declining freshwater availability. In peri-urban agriculture, untreated wastewater is often used because it supplies nutrients and organic matter, but it may also introduce salts and heavy metals that threaten soil health and food safety. This study evaluated the effects of wastewater irrigation on soil properties and the growth of spinach (*Spinacia oleracea* L.). Four treatments were tested: tap water (control), untreated textile wastewater, a 1:1 mixture of tap water and wastewater, and alternate application of tap water and wastewater. Results indicated that spinach growth parameters were highest under alternate irrigation, producing maximum plant height (12.83 cm), leaf area (29.67 cm<sup>2</sup>), fresh biomass (120 g pot<sup>-1</sup>), and dry biomass (19 g pot<sup>-1</sup>). The highest chlorophyll content (54.50 SPAD value) was observed with the 1:1 water mixture. Plant metal concentrations ranged from 8.35–12.92 mg kg<sup>-1</sup> for Cu, 0.38–1.06 mg kg<sup>-1</sup> for Cd, and 8.06 mg kg<sup>-1</sup> for Pb, with greater accumulation under wastewater treatments. Post-harvest soil analysis showed an increase in EC from 0.46 to 0.69 dS m<sup>-1</sup>, whereas soil pH remained stable (7.07–7.27). Soil metal concentrations also increased after harvest: Cu (15.83–19.77 mg kg<sup>-1</sup>),

Cd ( $0.34\text{--}0.56\text{ mg kg}^{-1}$ ), and Pb ( $0.12\text{--}1.34\text{ mg kg}^{-1}$ ) under wastewater irrigation. Overall, alternating wastewater with tap water improved spinach growth while reducing excessive salinity and heavy metal accumulation compared to continuous wastewater use. Proper treatment, controlled application, and regular monitoring are essential for sustainable wastewater irrigation.

## Foliar Applied Biostimulants and Micronutrients and Physiological and Growth Responses of Maize under Drought Stress

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Maize (*Zea mays* L.) is a vital crop for global food security and agro-based economies, contributing nearly 97% of Pakistan's total crop production. However, its production is frequently constrained by abiotic stresses, particularly drought, which is becoming more severe and widespread due to climate change. Biostimulants are compounds containing plant growth regulators, amino acids, and peptides that enhance natural plant processes and have shown promise in improving plant growth and stress tolerance. When combined with micronutrients such as zinc, copper, iron, manganese, and boron, biostimulants may provide synergistic benefits under drought-stressed environments, as these micronutrients play important roles in enzymatic activity, membrane stability, photosynthesis, and reproductive development. The primary objective of this study was to evaluate the physiological and agronomic responses of maize hybrids to foliar applications of biostimulants combined with micronutrients under drought stress. A pot experiment was conducted using a Completely Randomized Design (CRD) with five treatment combinations of biostimulants and micronutrients (Zn, Fe, B, Cu, and Mn). Data on morphological, physiological, biochemical, and yield parameters were recorded under drought stress conditions. Maximum shoot length ( $87.33\text{ cm}$ ), moisture content ( $17.53\%$ ), and fresh and dry seedling biomass ( $34\text{ g}$  and  $20\text{ g}$ , respectively) were recorded under normal irrigation conditions, whereas the lowest values were observed under drought stress. Under normal irrigation, foliar application of biostimulants combined with boron resulted in the highest increase in photosynthetic rate ( $11.67\text{ }\mu\text{mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$ ) compared to the control. Under drought stress conditions, foliar application of biostimulants combined with iron resulted in the highest increase in transpiration rate ( $3.53\text{ mmol H}_2\text{O m}^{-2}\text{ s}^{-1}$ ). Foliar application of biostimulants combined with zinc showed the greatest reduction in stomatal conductance under both normal ( $180\text{ mmol H}_2\text{O m}^{-2}\text{ s}^{-1}$ ) and drought stress conditions ( $100.67\text{ mmol H}_2\text{O m}^{-2}\text{ s}^{-1}$ ). Overall, foliar application of micronutrients in combination with biostimulants improved drought tolerance and water use efficiency, thereby enhancing maize growth, physiological performance, and yield.

## UAV-Based Soil Moisture Estimation for Precision Agriculture: Advanced Remote Sensing Approach Using TOTRAM Method

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Accurate soil moisture estimation is essential for optimizing irrigation scheduling and improving water use efficiency in precision agriculture. However, achieving high spatial resolution, frequent temporal monitoring, and cost efficiency simultaneously remains challenging. This study presents a UAV-based approach for high-resolution soil moisture mapping using multispectral and thermal imagery integrated with the Thermal–Optical Trapezoid Model (TOTRAM). Field experiments were conducted during the monsoon season (July 2025) at agricultural research sites in Lahore University of Management Sciences (LUMS) and Okara, Pakistan. Five UAV flights were conducted using a six-band multispectral camera capturing blue, green, red, red-edge, near-infrared, and thermal wavelengths. Ground-truth soil moisture measurements were collected using capacitance-based sensors installed at multiple depths and calibrated using a site-specific equation ( $\text{Soil Moisture} = 0.25 \times \text{raw values} - 31.4$ ). The TOTRAM approach combines the Normalized Difference Vegetation Index (NDVI) derived from multispectral imagery with land surface temperature obtained from thermal bands to estimate soil moisture conditions within a trapezoidal feature space. The model identifies warm and cold edges through pixel-based statistical analysis to determine soil water deficit parameters across varying atmospheric conditions. Compared with optical-only approaches such as OPTRAM, TOTRAM was selected due to its improved ability to capture evapotranspiration processes through thermal data integration. Model validation was conducted using multiple datasets. UAV-ground truth comparisons yielded  $R^2$  values between 0.15 and 0.43 with mean absolute errors ranging from 0.105 to 0.120. Integration with multi-temporal Landsat imagery across eight acquisition dates significantly improved performance for topsoil moisture estimation, achieving  $R^2$  values up to 0.892 and mean absolute error of 0.023. Cross-platform UAV–Landsat fusion further demonstrated strong methodological robustness across different sensor platforms and spatial resolutions. The results indicate that the method performs best for surface soil moisture estimation compared with deeper root-zone moisture predictions, with performance influenced by vegetation density, surface heterogeneity, and temporal moisture variability. Overall, the study demonstrates that UAV-based TOTRAM provides an effective solution for real-time, field-scale soil moisture monitoring, enabling improved irrigation management and reducing dependence on extensive ground sensor networks.

## Evaluating The Impact of Biochar on Spinach Growth under Lead (Pb) Stress

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Lead (Pb) contamination, particularly in the soils of Punjab, Pakistan, has negatively impacted spinach (*Spinacia oleracea*) production. It reduces germination, stunts plant growth, and leads to the accumulation of toxic heavy metals in edible plant parts, posing serious risks to human health and

food safety. Biochar, as a soil amendment, binds heavy metals and reduces their bioavailability. This study was conducted to evaluate the effect of biochar on spinach grown under Pb stress. Parameters measured included germination rate, plant growth, biomass, Pb concentration in edible parts, and antioxidant production. The experiment was carried out in a wirehouse at the Department of Soil Science, The Islamia University of Bahawalpur. A completely randomized design (CRD) was used with 5 kg of soil per pot. Three treatments were applied with three replications each. Two levels of Pb stress were imposed. The treatments included T<sub>0</sub> (control), T<sub>1</sub> (biochar at 1%), and T<sub>2</sub> (biochar at 2%). Results showed improved germination, growth, and biomass in biochar-treated plants compared to the control. Biochar application also reduced Pb bioavailability in plants. Overall, biochar application provides a sustainable and eco-friendly approach to enhancing crop yield and mitigating heavy metal pollution. Further field trials are recommended to validate these findings under diverse environmental conditions.

## Wheat Growth, Yield and Postharvest Nutrient Status in relation to Phosphorus and Sulphur in Alkaline-Calcareous Soils

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Phosphorus (P) and sulfur (S) are essential plant nutrients that play significant roles in enhancing early growth, development, and yield of wheat. Phosphorus is vital for various physiological processes during both vegetative and reproductive stages, while sulfur, an essential secondary macronutrient, improves soil chemistry and nutrient availability, particularly in problematic soils. Sulfur can reduce salinity, improve soil health, lower soil pH, and enhance nutrient uptake. A field experiment was conducted during the Rabi season of 2023–24 at the Soil and Environment Research Institute, Tandojam, to evaluate the effects of different rates of phosphorus and sulfur on wheat growth, yield, and post-harvest soil nutrient status. The experiment was laid out in a randomized complete block design (RCBD) with three replications. Phosphorus was applied at rates of 60, 90, and 120 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> (as DAP), integrated with sulfur at 20, 40, and 60 kg S ha<sup>-1</sup> (as sulfur bentonite), along with a control and an N and K basal treatment. Results showed that the combined application of 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 60 kg S ha<sup>-1</sup> produced the highest growth and yield, with a 21% increase (3306 kg ha<sup>-1</sup>) compared to the control. Increasing sulfur rates improved soil structure, nutrient uptake, and root development, particularly under alkaline calcareous conditions. The study suggests that the combined application of 90 kg P<sub>2</sub>O<sub>5</sub> and 60 kg S ha<sup>-1</sup> is an effective strategy for enhancing wheat growth, yield, and soil fertility. Further research is recommended to evaluate long-term sustainability.

## Phosphorus Supply from Rock Phosphate in Poultry Litter Compost Mediated by Microbes for Sustainable and Resilient Soil Fertility

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The rising cost of chemical fertilizers, particularly phosphorus (P) fertilizers, has created economic challenges for farmers and highlighted the need for sustainable alternatives to maintain soil fertility. While compost and manures are eco-friendly amendments, their limited nutrient content and slow decomposition often discourage adoption. This study investigated the formulation of value-added compost enriched with poultry litter (PL), low-grade rock phosphate (RP), partially acidulated rock phosphate (PARP), and two microbial inoculants [phosphorus-solubilizing bacteria (S1) and decomposer bacteria (S2)]. Rock phosphate was incorporated at 5% P (dry-weight basis), and composting was conducted in field pits (3.13 m<sup>3</sup>) for 120 days. Nutrient dynamics, including available P<sub>2</sub>O<sub>5</sub>, total nitrogen (N), organic carbon (OC), C:N ratio, and pH, were monitored at 0, 45, and 120 days. Results showed that phosphorus availability (P<sub>2</sub>O<sub>5</sub>) increased substantially in treatments combining PL with RP or PARP, especially when inoculated with microbial strains. The PL+PARP+S2 treatment achieved the highest available P<sub>2</sub>O<sub>5</sub> (0.14% to 2.28%), while PL+PARP+S1 also showed significant improvement (0.14% to 1.97%). Organic carbon declined across all treatments, and PARP-based composts exhibited the lowest C:N ratios, indicating enhanced decomposition and maturity. Nitrogen levels remained relatively stable, and pH stayed within neutral to slightly alkaline ranges, ensuring nutrient stability. This study demonstrates that integrating RP/PARP with microbial inoculants into composting systems can significantly enhance phosphorus availability, improve compost quality, and reduce dependence on costly chemical fertilizers. Such value-added composts strengthen soil resilience, promote sustainable nutrient cycling, and support eco-friendly agricultural development in phosphorus-deficient regions.

## Characterization of Designed Biochar for Stabilization of Heavy Metals in Agriculture Soil

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A series of experiments were conducted to evaluate the role of biochar derived from different feedstocks and produced at varying pyrolysis temperatures on the bioavailability of heavy metals in contaminated soils. Bulk soil samples were collected from a coal mine tailing site at Dara Adam Khel (33.6945° N, 71.4959° E). For comparison, an agricultural soil sample (0–20 cm depth) was collected from an agricultural research farm (34.0206° N, 71.4815° E) and artificially spiked with Cd, Pb, Cu, and Cr at rates of 50, 10, 50, and 100 mg kg<sup>-1</sup>, respectively. Three types of biochars were produced from agricultural residues—rice straw, maize straw, and sugarcane bagasse using pyrolysis temperatures of 300°C, 500°C, and 700°C. The physicochemical properties of all biochars were characterized and subsequently evaluated through Batch sorption experiments, soil incubation studies, and greenhouse pot experiments. Lettuce (*Lactuca sativa* L.) and brassica (*Brassica napus* L.) were grown in amended

soils for 105 days. Results showed that both feedstock type and pyrolysis temperature strongly influenced biochar properties. Biochar pH, electrical conductivity, and ash content increased with rising pyrolysis temperature, whereas nitrogen, hydrogen, and oxygen contents declined. Carbon content increased with temperature and varied by feedstock, reaching maximum values at 700°C (rice straw: 84%, maize straw: 71%, sugarcane bagasse: 76%). Ash content was highest in rice straw biochar produced at elevated temperatures. Surface area and cation exchange capacity peaked at 500°C, with rice straw biochar exhibiting the highest values (24.03 m<sup>2</sup> g<sup>-1</sup> and 19.27 cmol kg<sup>-1</sup>, respectively). FTIR analysis confirmed that surface functional groups were most abundant at 500°C and diminished at 700°C. Batch sorption results indicated that biochars produced at 500°C exhibited superior heavy metal sorption compared to those produced at 300°C and 700°C, with rice straw biochar showing the greatest sorption capacity. Based on these findings, incubation studies were conducted using biochar application rates of 0, 0.5, 1, and 2% for 90 days. Weekly analysis revealed a progressive reduction in AB-DTPA-extractable Cd, Pb, Cu, and Cr, with concentrations remaining below WHO permissible limits. Greenhouse experiments demonstrated that biochar application, particularly at 2%, significantly enhanced crop yield, plant growth parameters, and soil physicochemical properties, including pH, organic matter, and nutrient availability (N, P, and K). Heavy metal uptake by lettuce and brassica was significantly reduced, with the greatest improvement observed in rice straw biochar amended soils. It is concluded that biochars derived from crop residues, particularly rice straw produced at 500°C, are effective soil amendments for immobilizing heavy metals. Application at 2% (equivalent to 40 t ha<sup>-1</sup>) proved most effective, offering a sustainable remediation strategy for contaminated soils and safer crop production.

## Untreated Contaminated Irrigation Water as A Critical Point-Source Hazard: Heavy Metal Bioaccumulation and Carcinogenic Health Risks in the Soil-Plant Continuum of Khyber Pakhtunkhwa, Pakistan

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The pervasive use of contaminated irrigation water represents a major environmental hazard, introducing toxic heavy metals into the food chain and posing severe public health risks. This study provides a comprehensive, multi-medium risk assessment, investigating the accumulation and transfer of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) in the contaminated irrigation water-soil-vegetable continuum across six agriculturally critical districts of Khyber Pakhtunkhwa, Pakistan. Results reveal severe contamination: irrigation water was most polluted in Peshawar, with Cd and Pb predominating. Subsequent soil analysis showed significant enrichment, particularly of Zn and Cu. Alarming, vegetable contamination was widespread, with 100% of samples in Peshawar exceeding safe limits for Cd and Ni. Bioconcentration factors (BCFs) were notably high (up to 39.6 for Pb), confirming efficient soil-to-plant transfer. Correlation analysis established the irrigation water as the primary contamination source. The estimated weekly intake for several metals exceeded permissible limits, indicating a tangible carcinogenic and non-carcinogenic health hazard for consumers. This work unequivocally identifies untreated contaminated irrigation

water as a critical point-source hazard, demanding immediate regulatory intervention and sustainable remediation strategies to safeguard food security and public health.

## Geographic Distribution of Iodine in Soil, Water and Grains and its relation to Goiter Prevalence in District Poonch of Azad Jammu and Kashmir

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The soils of the Himalayan Hindukush region, including District Poonch, Azad Jammu and Kashmir, are inherently deficient in iodine due to continuous leaching caused by snowmelt and heavy rainfall. This environmental depletion lowers iodine concentrations in crops and livestock, contributing to iodine deficiency disorders (IDDs), particularly goiter. Poor socioeconomic conditions and limited access to iodine-rich foods further intensify the problem. This study investigated the spatial variability of iodine in soils, drinking water, and maize grains, and examined its association with goiter prevalence across the subdivisions of Abbaspur, Hajira, and Rawalakot. A systematic, georeferenced survey was conducted, enrolling 130 goiter patients of different age groups. Demographic, dietary, and clinical information was collected using structured questionnaires, and urinary iodine concentration (UIC) was measured to assess iodine status. Soil samples were collected from 78 sites at three depths (0–15, 16–30, and 31–45 cm), generating 1,170 samples that were composited depth-wise for analysis. Drinking water and locally grown maize grain samples were also collected from each site for iodine determination. Survey results showed that only 5–10% of households consumed a balanced diet, while the majority belonged to low-income families with limited nutritional awareness. Among patients, 59.3% were severely iodine-deficient based on UIC values. The highest deficiency was observed in Rawalakot (81.1%), followed by Hajira (60%) and Abbaspur (47%). Soil iodine concentrations declined with depth, averaging 1.31, 1.17, and 0.96 mg kg<sup>-1</sup>, respectively. Total soil iodine exhibited strong positive correlations with altitude ( $R^2 = 0.858$ ) and organic matter ( $R^2 = 0.943$ ), and negative correlations with soil pH and sand content. Grain iodine content strongly correlated with total soil iodine ( $R^2 = 0.954$ ). High-altitude soils and maize grains from Rawalakot contained substantially higher iodine levels than those from lower-altitude areas. This study provides baseline evidence of widespread environmental iodine deficiency and demonstrates a clear linkage between environmental iodine status and goiter prevalence. The findings highlight the urgent need for improved iodine nutrition strategies to reduce IDDs in vulnerable populations of the Himalayan region.

## Influence of Thermal and Acid Activation on the Adsorptive Performance and Mechanism of Bentonite for Azithromycin Removal

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The widespread occurrence of azithromycin (AZM) in aquatic environments has become a growing concern due to its persistence and its role in accelerating antimicrobial resistance. In regions where wastewater treatment infrastructure is limited, cost-effective and locally available materials are urgently needed for antibiotic removal. This study evaluates the potential of locally sourced bentonite from Khyber Pakhtunkhwa, Pakistan, in raw and modified forms, for the adsorption of AZM from aqueous solutions. The clay was subjected to thermal treatment (500 °C) and acid activation (0.5 M HCl) to enhance its physicochemical properties. Mineralogical, structural, and morphological characteristics were examined using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy coupled with energy-dispersive X-ray analysis (SEM–EDS). Batch adsorption experiments were performed to assess the influence of pH, contact time, adsorbent dose, and initial AZM concentration. Adsorption was strongly influenced by solution pH, with maximum removal achieved under acidic conditions, highlighting the importance of electrostatic interactions between protonated surfaces and AZM molecules. Rapid uptake occurred during the first 60 minutes, after which equilibrium was reached. Increasing adsorbent dose improved removal efficiency until site saturation was approached. Among the tested materials, acid-activated bentonite exhibited the highest adsorption performance, achieving removal efficiencies exceeding 95% under optimized conditions. Surface modification enhanced adsorption capacity by increasing available active sites and improving surface reactivity. Isotherm modeling indicated that the Freundlich model best described the adsorption process, suggesting multilayer adsorption on heterogeneous surfaces. Dubinin–Radushkevich and Temkin analyses supported the presence of strong adsorbate–adsorbent interactions. Kinetic data were better represented by the pseudo-second-order model, indicating that chemisorption likely governs the rate-controlling step. Characterization results confirmed structural modifications following treatment, including changes in surface morphology and elemental distribution. The improved adsorption performance of modified bentonite is attributed to increased surface area, enhanced porosity, and greater availability of reactive functional groups. The findings demonstrate that acid-activated bentonite derived from local deposits can serve as an efficient, economical, and environmentally sustainable adsorbent for the removal of azithromycin from contaminated water. This approach offers practical relevance for developing decentralized and low-cost water treatment strategies in antibiotic-impacted regions.

## Potassium Adsorption and Desorption Characteristics of Some Selected Soil Series

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To investigate the potassium adsorption and desorption characteristic of five soil a study was carried out at Department of Soil Science, Faculty of Agriculture, Gomal University Dera Ismail Khan. Five oil

series namely Ramak, Gishkori, Saggu, Zindani and Tikken were collected from different locations. All the soil series varied in term of their physico – chemical characteristics. The adsorption and desorption isotherm were developed for each of the soil series. Comparing the adsorption and desorption isotherm it was found that all the curve obtained were different from each other. The maximum adsorption was measured and it was found that 266 mg kg<sup>-1</sup> in Zindani soil series, it was followed by Gishkori, Saggu and Tikken soil series. The least adsorption was recorded 227.5 mg kg<sup>-1</sup> in the Ramak soil series. Three adsorption models were used i.e. Langmuir, Freundlich and Temkin. It was found that data better fitted the Freundlich, Langmuir and Temkin equations respectively. The Co-efficient of determination was highest (0.99) recorded for Freundlich equation in Tikken soil series. Contrary to the actual adsorption data the Langmuir adsorption maximum was found the highest in Tikken soil with vale of 416.6 mg kg<sup>-1</sup>. The bonding energy was highest 0.0272 (L (mg P)<sup>-1</sup>) recorded in Zindani soil series. Hence, it may be concluded that the adsorption and desorption curves of potassium showed differences in the isotherms due changes in soil properties.

## Synergistic Role of Wheat-Safflower Intercropping and Copper Nanoparticles in Mitigating Cadmium Toxicity

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Cadmium (Cd) is recognized as a hazardous, non-essential transition metal that adversely impacts plant growth and human health. Copper nanoparticles (CuNPs) have emerged as a promising nano-amendment, capable of alleviating Cd toxicity through their ability to immobilize Cd in soil, stimulate antioxidant defense mechanism, support physiological functions, and reduce Cd accumulation in plant tissues. Intercropping strategies, such as the introduction of safflower (*Carthamus tinctorius* L.) alongside major crops, further improves soil health, metal immobilization, and plant tolerance against Cd stress. A pot study was conducted to investigate the combined effect of CuNPs and safflower intercropping on reversing the adverse effects of Cd toxicity on growth and yield of wheat. Soil was artificially spiked with Cd @ 25 mg kg<sup>-1</sup> and treated with two levels of CuNPs (50 and 100 ppm). Intercropping with safflower was maintained alongside the wheat to evaluate its role in improving plant growth and yield responses. The results revealed that combined application of CuNPs (100 ppm) with safflower intercropping produced the highest biomass of wheat roots, shoots, and grains. Intercropping with safflower in the presence of CuNPs (100 ppm) significantly increased the plant height, shoot and root fresh weight, shoot and root dry weight and root length by 83.49%, 47.10%, 98.70%, 50.66%, 152.78% and 193.94%, respectively, compared to untreated stressed control. Additionally, yield-related attributes including number of tillers (58.33%), number of spikes (54.61%), spike length (43.41%), spike weight (42.88%) and 100-grain weight (53.79%) were also increased compared with untreated control. Overall, these findings suggest that integrating safflower intercropping with CuNPs application can effectively mitigate Cd-induced stress and enhance growth and yield performance of wheat, highlighting its potential as sustainable strategy for managing Cd-contaminated soils.

## Synergistic Role of Zinc Oxide and Hydroxyapatite Nanoparticles in Mitigating Cadmium Stress in Wheat (*Triticum aestivum*)

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Cadmium (Cd) is among the most hazardous heavy metals, posing substantial risks to agricultural productivity and food security. Nanomaterial based soil amendments, particularly, zinc oxide nanoparticles (ZnO-NPs) and nano-hydroxyapatite (n-HAP), have demonstrated significant potential in increasing crops resilience by reducing Cd bioavailability in soil. This study evaluated the comparative and combined effects of ZnO-NPs and n-HAP, applied individually and in combination, on the growth and yield performance of wheat under Cd stress condition. A pot experiment was conducted using Cd spiked soil (20 mg kg<sup>-1</sup> Cd). The experiment comprised of twelve treatments: an uncontaminated control, a Cd-contaminated control, two individual application rates of ZnO-NPs (15 and 30 ppm) and n-HAP (50 and 100 ppm), and two combined treatments applied at a ratio 3:10, along with equivalent doses of corresponding precursors (zinc acetate and phosphoric acid). Data were recorded regarding different growth and yield attributes. The combined application of ZnO-NPs and n-HAP significantly improved all measured growth and yield parameters of wheat relative to Cd-contaminated control. The synergistic treatment (ZnO-NPs @15 ppm + n-HAP @ 50 ppm) resulted in the highest increases in plant height (12.43%), root fresh weight (36.58%), shoot fresh weight (36.58%) and shoot dry weight (229.04%) relative to the untreated Cd-contaminated control. Moreover, significant increases were observed in number of tillers (38.09%), spike length (23.47%), 100-grain weight (28.26%) and husk weight (55.80%). These findings demonstrate that the combined application of ZnO-NPs and n-HAP offers a superior strategy for alleviating the adverse effects of Cd stress on wheat growth and productivity, highlighting their potential as an effective nanotechnology-based amendment for sustainable soil remediation and safe crop production.

## Residual Impacts of Nano-Hydroxyapatite and Iron Nanoparticles on Maize (*Zea mays*) Growth and Yield under Cadmium Stress

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Cadmium (Cd) contamination in agricultural soils poses a persistent threat to crop productivity, soil health and food safety. Cadmium toxicity not only impairs the growth of the current crop but can have lingering effects on subsequent crops due to its high toxicity and persistent nature. Understanding how nano-based amendments influence soil Cd bioavailability and the performance of following crops is critical for sustainable crop production and long term soil health. This study focused on evaluating

the residual effects of nano-hydroxyapatite (nHAP) and iron nanoparticles (FeNPs) on maize growth and yield, following the harvest of a previous crop grown on Cd- contaminated soil (@ 20 mg kg<sup>-1</sup>). A pot experiment was conducted with twelve treatments: an uncontaminated control, Cd-contaminated control, nHAP precursor (50 and 100 ppm), nHAP (50 and 100 ppm), FeNPs precursor (10 and 20 ppm), FeNPs (10 and 20 ppm) and hybrid nanoparticles (nHAP:FeNPs at @ 50:5 ppm and 50:10 ppm, each replicated thrice. During the experiment, agronomic traits like plant height, root length, fresh and dry weight of root and shoot, and total grain weight were recorded at harvest. Results indicated that FeNPs and their precursor showed superior residual effects in improving maize growth parameters compared to the other treatments including nano-hybrid combinations. Application of the FeNP precursor significantly increased the shoot fresh weight (5.81%), shoot dry weight (15.93%) and SPAD value (18.29%) relative to the Cd-stressed control. Iron nanoparticles imparted notable residual benefits to root growth, with 26.47% increase in root fresh weight. In contrast, maximum number of cobs per pot and cob weight was recorded in nano-hybrid treated pots, indicating a measureable residual benefit of combined FeNP and nHAP treatment on maize yield. Overall, the study confirms that nano-based soil amendments particularly FeNPs and nHAP imparts residual effects, improving growth and yield of maize in Cd-contaminated soils.

## Response of Maize to Varying Levels of Cadmium at Seedling Stage

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Soil contamination by heavy metals has become one of the greatest limitations to sustainable crop production and environmental safety in the world. Cadmium (Cd) is considered to be one of the most dangerous pollutants among the toxic trace elements, as it has high mobility in the soil-water system, high bioavailability, and great accumulation in plant tissues. This study evaluates the effect of cadmium stress of different concentrations (0, 5, 10, 20, and 40 mg L<sup>-1</sup>) on seed germination behavior of four maize varieties (Top Pak-7022, DK-6321, KWS, and DK-702) and identifies varietal differences in tolerance. Twenty surface-sterilized seeds were placed on filter paper in Petri plates under controlled laboratory conditions, and each treatment was replicated three times. Cadmium solutions of the respective concentrations were applied, and germination percentage, root and shoot length, germination energy, germination index, vigor index, and mean germination time were recorded and statistically analyzed. Significant varietal differences were observed in germination response under Cd stress. The maize variety (DK6321) showed the highest tolerance, maintaining relatively higher germination performance at 20 and 40 mg Cd L<sup>-1</sup>. Dekalb-7024 showed intermediate tolerance, with stability at lower Cd levels but reduction in higher concentrations. Root and shoot length were significantly reduced at 20 mg L<sup>-1</sup> in all cultivars. Germination energy, germination index, and vigor index showed variable responses, with higher values recorded at 40 mg L<sup>-1</sup> in some cultivars; overall, increasing Cd concentration caused a decline in germination efficiency in all varieties. Maize varieties (DK-6321 of Bayer and DK-7024 of Monsanto) proved to be the most Cd-tolerant, whereas KWS was the most sensitive. Results revealed the importance of varietal screening for selecting maize varieties suitable for cultivation in Cd-contaminated environments.

# Phosphate Sorption and Desorption Dynamics: A Comparative Study of Soil Series and Biochar

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To investigate the phosphate sorption and desorption characteristics of soil series i.e. Sodhra (Typic Torrifluents) and Ramak (Chromic Haplotorrets) and wooden biochar a study was carried out after collecting the soil samples and preparation of wooden biochar (from Prosopis Juliflora). The physio – chemical characteristics of soil series showed that the both soils were alkaline in nature with texture sandy clay loam. Both the soil were non saline soils under cultivation for long time. Status of organic matter in both the soil series was low i.e. less than 1% while in biochar sample the organic matter content was found higher i.e. 1.83%. The time for adsorption study was 24 hours and for that of desorption was 48 hours. The adsorption and desorption isotherms were developed for all the three samples. The maximum values of adsorption in soil series Sodhra and Ramak were 114.004 and 221.945 mg kg<sup>-1</sup>, while the maximum value of adsorption in biochar sample was 374.2379 mg kg<sup>-1</sup>. Three different adsorption models namely Langmuir, Freundlich and Temkin were used for adsorption data. After applying the equations, the Freundlich model stood better fit for the Sodhra soil series with value of R<sup>2</sup> = 0.984, while the Langmuir model showed better fit for Ramak soil series and biochar sample with value of R<sup>2</sup> = 0.9989 and R<sup>2</sup> = 0.9963 respectively. The Temkin model remained unfit for the adsorption data.

## Combined Effect of Organic Amendments and Subsurface Water Retention Technology (Swrt) on Soil Hydraulic Properties and Health

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In Pakistan, water shortage is a major threat to sustainable agricultural production. Crop production is being constantly decline due to changing climate, erratic rainfall patterns, and depleting freshwater supplies. Low soil organic matter and conventional irrigation techniques result in significant water loss through runoff and deep percolation, which lowers water use efficiency. In this regard, cutting-edge water management techniques like Subsurface Water Retention Technology (SWRT) combined with organic amendments offer a workable plan to improve crop production and soil moisture conservation. SWRT functions by restricting excessive downward water movement below the root

zone, ensuring greater moisture retention within the active root region. Integrating SWRT with organic amendments offers a sustainable, resource-efficient, and climate-resilient approach to addressing water scarcity challenges and promoting long-term agricultural productivity. The present research work was conducted to evaluate eight pea plant genotypes using Randomized Complete Block Design (RCBD) with three replication. Soil physical properties and crop parameters were measured before treatment application and after harvest. Results showed that the combined application of SWRT with organic amendments (+ banana leaves @ 4 t ha<sup>-1</sup> + poultry manure @ 4 t ha<sup>-1</sup>) significantly improved soil organic matter (58%), infiltration rate (51%), water holding capacity (68%), and reduced bulk density (12.1%). The maximum pod yield (92 pods plant<sup>-1</sup>), and plant weight (300 g plant<sup>-1</sup>) were recorded under SWRT + banana leaves @ 4 t ha<sup>-1</sup> + poultry manure @ 4 t ha<sup>-1</sup>. The study concludes that integrating SWRT with organic amendments resulted improved soil moisture content and other physical properties as well as pea's crop productivity, providing a sustainable soil and water management strategy.

## Synergistic Effects of Copper Nanoparticles and Biochar on Cadmium Immobilization in Cd-Contaminated Soil

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Cadmium (Cd) contamination in agricultural soils is a growing environmental concern due to its high toxicity and persistence. Cadmium (Cd), due to its high mobility and bioavailability in soil, can be readily taken up by plants and transferred into the food chain, posing serious risks to human health. Biochar is recognized for its ability to immobilize heavy metals, while the synergistic effects of copper nanoparticles (CuNPs) and rice husk biochar to mitigate Cd stress in wheat remain largely unexplored. A pot experiment was conducted to evaluate the efficacy of individual and combined effects of CuNPs and rice husk biochar on Cd bioaccumulation in wheat plants. Results showed that the combined application of CuNPs and rice husk biochar at 100 mg kg<sup>-1</sup> and 0.2%, most significantly decreased bioavailable Cd in soil by 67.08% and also reduced the Cd concentration in roots by 86.89%, in shoots by 73.72%, and in grains by 91.02% compared to the contaminated control. CuNPs and rice husk biochar reduced the grain Cd concentration below the threshold level of 0.2 mg kg<sup>-1</sup>. These findings determined that the synergistic application of copper nanoparticles and rice husk biochar effectively immobilized the cadmium in soil and significantly reduced its translocation to wheat grains. Immobilization of Cd in soils and reduction in its uptake further enhanced the wheat growth and physiological performance, highlighting nano-biochar application as a promising remediation strategy for Cd-contaminated soils.

## Charge Transfer Engineering in Pd based nano Aerogels for Enhanced Electro-Oxidative Degradation of Recalcitrant Di-butyl Phthalate

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In this work, Pd-based aerogels were modified with transition metals Ag-Fe for the degradation and electrochemical oxidation of di-butyl phthalates (DBP) in water. The newly synthesized PdAgFe aerogel showed a uniform dispersion with a practical size of 4-9 nm, and achieved a dense interconnected network revealed by transmission electron microscopy. The PdAgFe-assisted electrochemical oxidation of DBP achieved 97% removal at pollutant concentrations of 90 mg/L, surpassing that with binary aerogels, i.e. PdFe (86.3%) and PdAg (70.6%). The oxygen evolution potential of PdAgFe increased progressively from 1.61 to 1.97 V with maximum applied DBP concentration. This reflects the enhanced catalytic selectivity and activity of PdAgFe under optimum operating scan rate ( $5 \text{ mV s}^{-1}$ ) in 1 M KOH with 8 h of process duration. Kinetic modeling confirmed that DBP degradation followed a pseudo-first-order rate law, with PdAgFe showing the highest apparent rate constant ( $k = 0.36 \text{ h}^{-1}$ ,  $R^2 = 0.99$ ) at 90 mg/L. This enhanced electrochemical potential of PdAgFe is associated with its strong structural and electronic characteristics. For instance, XPS analysis revealed  $\text{Fe}^{3+}$  oxidation states and a positive shift in Pd 3d binding energy to 334.32 eV, indicative of strong electronic coupling within the trimetallic framework. Our findings proposed valuable insights into the cost-effective Pd-engineered aerogels with transition metals to enhance catalytic removal of DBP.

## Evaluation and Treatment Strategies for Emerging Micropollutants in Wastewater

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Emerging micropollutants (EMPs), including pharmaceuticals, personal care products, endocrine-disrupting compounds, and industrial chemicals, have become a significant environmental concern due to their persistence, bioaccumulation potential, and adverse ecological and human health effects even at trace concentrations. Conventional wastewater treatment processes are often inefficient in completely removing these contaminants, leading to their continuous release into aquatic and terrestrial ecosystems. This has driven increasing interest in advanced degradation techniques. This abstract reviews the major pathways and technologies for the degradation of EMPs, focusing on physicochemical, biological, and hybrid treatment methods. Advanced oxidation processes (AOPs), such as ozonation, photocatalysis, and Fenton-based reactions, have shown high efficiency in degrading a wide range of micropollutants through the generation of reactive oxygen species. Similarly, biological approaches, including microbial degradation and enzymatic transformation, offer eco-friendly and cost-effective alternatives, though they may be slower and compound-specific. Emerging strategies, such as nanomaterial-assisted degradation and electrochemical methods,

provide promising avenues for enhancing removal efficiency and selectivity. Despite significant progress, challenges remain in achieving complete mineralization, avoiding the formation of toxic transformation products, and scaling up these technologies for real-world applications. Future research should emphasize integrated treatment systems, real-time monitoring, and risk assessment to ensure sustainable management of emerging micropollutants.

## Bioremediation of Rawal Lake Water Using Indigenous Microalgae: Physicochemical Characterization and Biomass Valorization Potential

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Urban water remediation coupled with carbon-neutral fuel production represents a sustainable strategy to address critical environmental and energy challenges. In this study, water samples were collected from Rawal Dam and its tributaries and analyzed for physicochemical parameters. The pH of the reservoir water ranged from 6.0 to 8.3, while phosphate-phosphorus concentrations varied between 0.48 and 2.78 mg/L across the sampling sites. Total Kjeldahl Nitrogen (TKN), ammonium-nitrogen, chemical oxygen demand (COD), and several heavy metals were found to exceed permissible limits, reflecting the high pollution burden in the reservoir vicinity. To address this concern, efficient algal strains were isolated using modified BBM, showing strong potential for growth in nutrient-rich reservoir water. Their cultivation offers the dual benefit of pollutant reduction and biomass accumulation, with subsequent transesterification of harvested biomass confirming the feasibility of biofuel production. This integrated approach highlights the promise of algal systems for sustainable water remediation while generating renewable energy, contributing to circular and low-carbon urban water management strategies.

## Soil Salinity and Biosaline Agriculture

### Advanced Remote Sensing Surveillance for Sustainable Soil and Water Management

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In the field of Soil and water management, remote sensing offers a tremendous source of information, which help greatly for better decision of maximizing use efficiency of those precious resources. Advancements in remote sensing (RS) for soil and water management, thoroughly achieved by AI and machine learning, lead to a transition leap from passive monitoring to predictive, real-time analytics. Furthermore, the integration of drone-based hyperspectral data and IoT ground sensors into cloud-based platforms (e.g., Google Earth Engine) facilitates localized precision agriculture, enabling early detection of soil degradation and optimizing agricultural inputs. The spatial information that can be inferred from the combinations of different remote sensing sources is extremely huge nowadays,

furthermore, the integration between land surface characteristics measurements and atmospheric remote sensing monitoring and prediction can give a whole real view of different Geo-biophysical parameters. Utilizing and deploying all of this information for soil and water management in the right way require qualified researcher gather multidiscipline in agriculture, soil, water, spatial information, sensors, AI, etc. the integration of this disciplines allows us to harness the vast amounts of data collected with space and terrestrial sensors and enhances our ability to understand soil properties, dynamics, and functions and to address soil-water related challenges.

## Management Strategies for the Efficient Use of Salt Affected Soils and Poor Quality Water for Meeting Food Security in Semiarid Climates

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In the face of growing population, urbanization, and water scarcity, efficient management of salt-affected soils and poor quality water is vital to meet food security in semiarid climates. It requires an integrated, multi-faceted approach combining proper soil, water, and crop management. The key management strategies may include the use of organic and inorganic amendments, adequate crop nutrition, bacterial inoculation, organic matter incorporation into soil, and cyclic and blended use of fresh water and poor quality water. A series of experiments comprising of different soil and water salinity levels, and application of organic and chemical substances were conducted to evaluate the efficiency of these substances for improving soil health and crop yield. In the first study, sunflower was grown with saline-sodic water having EC 5.56 dS m<sup>-1</sup>, SAR 17.3 mmol L<sup>-1</sup>, and RSC 5.24 meq L<sup>-1</sup> by adding K and FYM. Integrated application of 100 mg kg<sup>-1</sup> K<sub>2</sub>O and 5% FYM decreased soil EC by 54%, SAR 43% while increased organic matter by 166% under saline sodic water irrigation compared to saline sodic water without K and FYM. In another study, cotton and sugarcane were grown at 10 dS m<sup>-1</sup> EC by supplying K. Addition of 100 mg kg<sup>-1</sup> K<sub>2</sub>O efficiently reduced Na<sup>+</sup> while increased K<sup>+</sup>, K<sup>+</sup>: Na<sup>+</sup> ratio, Ca<sup>2+</sup>, Mg<sup>2+</sup> with an improvement of 60.5% in cotton lint yield, and 56% in cane yield of sugarcane at 10 dS m<sup>-1</sup> salinity compared to same salinity level without K. Wheat was grown on saline sodic soil having EC 13 dS m<sup>-1</sup>, SAR 23.3 (mmol L<sup>-1</sup>)<sup>1/2</sup> and pH 8.6 by supplying K, Si and press mud. Integrated application of Si, K and press mud reversed the deleterious effects of salts, and improved grain yield by 40-156% in salt tolerant while 46-206% in salt sensitive cultivars compared to salt stressed environment without amending substances. Cyclic and blended use of poor quality and fresh water could significantly improve the fruit yield of tomato compared to sole application of poor quality water. Silicon, FYM and PGPR could significantly ameliorate the deleterious effects of soil and water salinity by maintaining ionic homeostasis, physiological dynamics, and enzymatic activities. Integrated application of Si, FYM and PGPR showed superiority over their sole application, and increased relative water content by 64.25%, membrane stability index 44.5%, photosynthesis 42.82%, chlorophyll content by 47.64%, and grain yield of wheat by 55.76% at 10 dS m<sup>-1</sup> compared to same salinity level without amending substances.

## Biochar Application Enhances Chemical Properties and Nutrient Availability in Saline-Alkali Soils: A Meta-Analysis

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Saline-alkali soils are a major global challenge. They degrade soil chemistry, reduce nutrient availability, and limit crop productivity. Biochar amendment has emerged as a promising organic approach for mitigating soil degradation and enhancing soil quality in salt-affected environments. We conducted a meta-analysis of 113 peer-reviewed publications and 714 paired comparisons (2014–2025) to evaluate the effectiveness of biochar application on soil chemical properties under saline-alkali conditions. Biochar significantly ( $p < 0.05$ ) increased soil organic carbon (90.4%), available nitrogen (47.9%), available phosphorus (51.1%), available potassium (101.8%), and cation exchange capacity (34.1%) compared to the control. Biochar also reduced soil pH (1.5%), electrical conductivity (7.7%), and exchangeable sodium percentage (32.7%). It decreased soluble sodium (3.2%) and chloride (41.7%), while increasing soluble calcium (41.8%) and magnesium (24.0%). Furthermore, stalk-derived biochar applied at high rates ( $\geq 3\%$ ) showed the best performance, increasing SOC by 123.0%. Stalk- and wood-derived biochar feedstock gave the largest improvements in AK (165.9%), AP (66.1%), and AN (54.2%). Correlation analysis revealed that SOC was positively correlated with  $\text{Ca}^{2+}$  ( $r = 0.038$ ),  $\text{Mg}^{2+}$  ( $r = 0.298$ ), and AP ( $r = 0.061$ ), while negatively correlated with AN ( $r = -0.034$ ). In summary, medium-temperature pyrolyzed biochar derived from stalk and wood feedstock, applied at higher rates, represents an effective and sustainable strategy for improving chemical properties and nutrient status in saline-alkali soils. These findings provide valuable insights for developing evidence-based biochar application protocols and formulating ecological restoration strategies for large-scale saline-alkali soil remediation.

## Comparative Physiological Evaluation of Two Tomato (*Solanum lycopersicum* L.) Cultivars Screened from In Vitro and Their Performance on Salt Tolerance in Pot Experiment

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Tomato is an important vegetable crop worldwide but is moderately sensitive to salinity, which limits its production in South Asian regions facing salt stress and water scarcity. The study focused on salt tolerance of fourteen tomato cultivars collected from the local market of Mianyang, China, for screening in vitro culture, followed by a pot experiment on two distinct cultivars. Under in vitro culture, seed germination, mean germination time, shoot length, and root length were assessed at 1.5 g L<sup>-1</sup> NaCl. Seed germination significantly increased in Yellow Pearl (73.33%) but declined in Pink Jade cultivars, indicating strong cultivar-dependent responses. Overall, NaCl stress markedly affected vegetative growth, with Yellow Pearl and Red Jade performing relatively better under in vitro conditions. Based on screening results, Red Jade and Yellow Pearl were selected for a pot experiment to assess morphological responses under irrigation with 0, 10, 20, and 40 mg L<sup>-1</sup> NaCl. Parameters including seed germination, survival rate, shoot height, root length, leaf number, leaf area, and fresh biomass were measured. Increasing salinity levels adversely affected most growth traits in both cultivars; however, Red Jade showed greater tolerance than Yellow Pearl. The application of 10 mg L<sup>-1</sup> NaCl resulted in better overall growth and biomass accumulation, while leaf area was highest at 40 mg L<sup>-1</sup> NaCl. In conclusion, high salinity negatively impacts tomato growth, but tolerant cultivars such as Red Jade and Yellow Pearl may be suitable for cultivation in salt-affected areas to improve productivity.

## Operational Soil Salinity Monitoring in Monsoon-Irrigated Basins: Open-Source SAR-Optical Fusion Workflow for Drought Resilience and Yield Forecasting Rechna Doab, Punjab Case Study (2015-2025)

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Soil salinization is a major threat to agricultural sustainability in the irrigated regions of Punjab, Pakistan. In the tail-end areas of the Rechna Doab irrigation system, salinity is expanding at approximately 3,200 ha year<sup>-1</sup>, currently affecting nearly 687,000 ha across the districts of Sahiwal, Okara, and Pakpattan. Crop yield losses in moderate-to-severe salinity zones (electrical conductivity > 4 dS m<sup>-1</sup>) range between 15% and 40%. Conventional optical remote sensing approaches often fail to capture salinity dynamics during monsoon and irrigation periods due to persistent cloud cover and vegetation masking. This study developed an operational and open-source workflow integrating Sentinel-1 synthetic aperture radar (SAR) and Landsat optical data to monitor salinity and waterlogging dynamics from 2015–2025. Data processing was conducted using QGIS, GDAL, and Google Earth Engine. The methodology combined the Sentinel-1 Radar Vegetation Index (RVI) at 10 m resolution with Landsat-derived salinity indicators, including the Normalized Difference Salinity Index (NDSI) and Salinity Index-4, calculated during the rabi cropping season at 30 m resolution. A Random Forest machine learning classifier was trained using 120–150 field-sampled soil electrical conductivity profiles representing the full salinity gradient. Additional covariates, including Soil Grids v2.0 soil

properties, CHIRPS precipitation data, and SRTM elevation, were incorporated to capture environmental drivers of salinization. The binary salinity classification for  $EC > 4 \text{ dS m}^{-1}$  achieved 82–88% accuracy, while quantitative EC estimation produced a root mean square error of  $\sim 1.5 \text{ dS m}^{-1}$ . Temporal validation using ten-year NDVI trends showed strong negative correlations with salinity ( $r = -0.65$  to  $-0.76$ ), confirming vegetation–salinity interactions. Spatial coincidence analysis identified approximately 200,000 ha experiencing both root-zone saturation ( $>30\%$ ) and severe salinity ( $>6 \text{ dS m}^{-1}$ ), indicating areas requiring urgent drainage intervention. Seasonal analysis revealed linked to subsurface salt redistribution and irrigation delays, potentially causing 12–35% wheat yield losses by 2026 if current management practices persist. The proposed workflow provides a transparent, low-cost monitoring framework for basin-scale salinity assessment and can be applied to other monsoon-influenced irrigation systems where cloud cover limits conventional remote sensing.

## Harnessing Salt-Tolerant Rhizobacteria to Improve Salinity Tolerance in Canola (*Brassica napus*)

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Soil salinization is a major abiotic stress that severely limits canola (*Brassica napus* L.) productivity by disrupting plant physiological, biochemical, and soil processes. Although salt-tolerant plant growth-promoting rhizobacteria (PGPR) have been extensively studied worldwide, there is limited information on the effectiveness of indigenous salt-tolerant PGPR from Pakistan, particularly for enhancing canola's salinity tolerance. This study aimed to evaluate the potential of indigenous salt-tolerant PGPR, isolated from saline soils of Pindi Bhattiyan, Pakistan, to improve salinity tolerance, physiological performance, and soil health in canola. A controlled pot experiment was conducted at the Land Resources Research Institute, National Agricultural Research Centre (NARC), Islamabad. Canola plants were inoculated with pre-characterized indigenous PGPR strains [*Agrobacterium tumefaciens* (B1), *Bacillus subtilis* (B2), and a bacterial consortium] under saline conditions and compared with a non-inoculated control. Physiological, biochemical, antioxidant, and soil parameters were measured to assess PGPR effectiveness under salinity stress. Among the treatments, *Agrobacterium tumefaciens* (B1) showed superior performance, significantly enhancing antioxidant enzyme activities (catalase, peroxidase, and superoxide dismutase) by up to 335%, while maintaining higher chlorophyll a, chlorophyll b, and carotenoid contents. Both B1 and B2 improved osmotic adjustment by increasing sucrose and total sugar accumulation. Additionally, B1 and the consortium enhanced soil properties by reducing soil electrical conductivity by 26.3% and lowering soil pH by over 13% under saline conditions. In conclusion, indigenous salt-tolerant PGPR, particularly *Agrobacterium tumefaciens* (B1), can effectively enhance salinity tolerance in canola through improvements in physiological, biochemical, antioxidant, and soil-related mechanisms. These findings highlight the potential of locally adapted PGPR as a sustainable bio-inoculant strategy for salt-affected soils in Pakistan. Future studies should focus on long-term field trials across diverse agro-climatic conditions and explore soil microbial interactions to support large-scale biofertilizer development.

## Salicylic Acid Enhances Growth and Yield of Pea (*Pisum sativum* L.) Under Saline Conditions

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Salicylic acid is widely recognized for its role in mitigating the adverse effects of abiotic stresses, including salinity, in plants. This study evaluated the effectiveness of foliar-applied salicylic acid in enhancing the growth and yield of pea (*Pisum sativum* L.) under increasing soil salinity. The experiment was conducted in 2019 at the ornamental nursery of the Department of Agriculture, University of Swabi, using a randomized complete block design (RCBD) with two factors and three replications. Pea plants were grown from seed and, 30 days after germination, were exposed to different salinity levels (0, 25, 50, and 75 mM NaCl) combined with foliar applications of salicylic acid at concentrations of 0, 1, 2, and 3 mM. Salinity stress significantly reduced vine length, stem diameter, fresh pod weight, pod width, pod length, number of seeds per pod, and total yield. However, foliar application of salicylic acid at 2 mM effectively alleviated these negative effects by improving growth attributes and yield, while also promoting earlier flowering and pod development. These findings highlight the potential of salicylic acid as a cost-effective and environmentally friendly approach to improving pea production under saline conditions. Further research is recommended to assess its broader applicability across different crops and field conditions, supporting the development of sustainable salinity management strategies to enhance agricultural productivity.

## Biochar Improves Soil Properties and Wheat Growth Under Saline Conditions: A Growth Chamber Study

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The application of biochar to agricultural soils has emerged as a promising strategy for sustainable soil management. To evaluate its effects, a pot experiment was conducted using a completely randomized design (CRD) to assess the influence of biochar particle sizes (B1 = 0.002 mm, B2 = 0.05 mm, B3 = 2 mm) applied at 40 t ha<sup>-1</sup> on soil properties and wheat growth under non-saline (S0) and saline conditions (S1 = 0.1%, S2 = 0.2%, S3 = 0.3% NaCl). Biochar particle size significantly affected soil electrical conductivity (EC), pH, water-holding capacity, days to emergence, germination percentage, shoot and root biomass, root-to-shoot ratio, and chlorophyll content. The finest biochar (0.002 mm) resulted in the highest values for days to emergence (7.75 days), shoot biomass (2.74 g), root biomass (0.84 g), and chlorophyll content (55.67 CCI). In contrast, the coarsest biochar (2 mm) significantly increased the root-to-shoot ratio (0.33), enhanced germination (80%), and reduced soil pH (7.12) and EC (0.59 dS m<sup>-1</sup>). Salinity negatively affected plant growth, with the highest pH (7.49), days to emergence (8.22 days), and EC (0.71 dS m<sup>-1</sup>) observed at 0.3% NaCl. The best plant performance was recorded under non-saline conditions, with maximum germination (92%), shoot biomass (3.05 g), root

biomass (1.03 g), root-to-shoot ratio (1.03), and chlorophyll content (59.44 CCI), followed by the 0.1% NaCl treatment. These findings suggest that biochar applied at 40 t ha<sup>-1</sup> with particle sizes of 0.002–0.05 mm can improve soil health and wheat productivity under non-saline to mildly saline conditions (0–0.1% NaCl).

## Salicylic Acid as a Potential Growth Regulator Under Salinity Stress in Pea (*Pisum sativum* L.) Plants

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Salicylic acid (SA) is well recognized for its role in mitigating the adverse effects of abiotic stresses, including salinity, in plants. The present study evaluated the effectiveness of foliar-applied SA in enhancing the growth and yield of pea (*Pisum sativum* L.) under increasing soil salinity in agricultural areas. The experiment was conducted in 2019 at the ornamental nursery of the Department of Agriculture, University of Swabi, using a randomized complete block design (RCBD) with two factors and three replications. Pea plants were raised from seed and, 30 days after germination, subjected to different salinity levels (0, 25, 50, and 75 mM NaCl) combined with foliar applications of SA at concentrations of 0, 1, 2, and 3 mM. Salinity stress significantly reduced vine length, stem diameter, fresh pod weight, pod width, pod length, number of seeds per pod, and total yield. However, foliar application of SA at 2 mM markedly alleviated these negative effects by improving growth attributes and yield, in addition to promoting earlier flowering and pod development. These findings highlight the potential of SA as a cost-effective and environmentally friendly strategy for improving pea production under saline conditions. Further research is recommended to explore its broader applicability across different crops and field environments to develop sustainable salinity management practices that enhance agricultural productivity.

## Response of Various Exotic and Local Wheat Lines/Varieties to Natural Field Salinity under Diverse Agro-Climatic Conditions

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This study evaluated the response of six wheat varieties, including exotic and locally adapted lines, to salinity stress under natural field conditions at two locations: Kohat (Khyber Pakhtunkhwa) and Multan (Punjab), with soil electrical conductivity (EC) ranging from 4 to 8 dS m<sup>-1</sup>. Experiments were arranged in a randomized complete block design (RCBD) with four replications per site. Soils at Kohat had an EC of 4.28 dS m<sup>-1</sup>, whereas Multan soils were saltier (EC 8.11 dS m<sup>-1</sup>). Soil pH ranged from 7.72 to 7.75,

Na<sup>+</sup> from 36.8 to 41.4 meq L<sup>-1</sup>, K<sup>+</sup> from 0.27 to 0.51 meq L<sup>-1</sup>, Ca<sup>2+</sup>+Mg<sup>2+</sup> from 5.94 to 30.54 meq L<sup>-1</sup>, and organic matter from 0.64 to 0.71%, representing intermediate to high salinity stress. Multan also exhibited higher sodium adsorption ratio (SAR 21.9), chloride (23.8 meq L<sup>-1</sup>), sulfate (43.1 meq L<sup>-1</sup>), bicarbonate (9.68 meq L<sup>-1</sup>), and lime content (17.56%) compared to Kohat. Salinity affected wheat growth and yield, with Kohat showing higher average plant height (79.1 cm) and plant population (100.7 plants m<sup>-2</sup>) than Multan (69.1 cm; 86.9 plants m<sup>-2</sup>). Among the varieties, EX11 exhibited the highest plant population (119.6 plants m<sup>-2</sup> at Kohat; 106.0 plants m<sup>-2</sup> at Multan), grain yield (2,663.9 kg ha<sup>-1</sup> at Kohat; 2,418.2 kg ha<sup>-1</sup> at Multan), and total biomass (8,174.9 kg ha<sup>-1</sup> at Kohat; 7,848.1 kg ha<sup>-1</sup> at Multan). EX22 performed well in plant height (84.1 cm at Kohat) and thousand-grain weight (45.4 g at Kohat; 42.4 g at Multan). Harvest index was higher at Kohat (32.8%) than Multan (27.9%). Ionic regulation strongly influenced performance. EX11 and KT-17 had the lowest sodium accumulation (0.13–0.14), while PS-19 and Tanda-23 accumulated more (0.22). Nitrogen (2.16–2.54%), carbon (29.9–32.9%), and C:N ratios (lowest in EX11 and EX22: 12.52–12.66) indicated better nutrient balance under stress. Phosphorus ranged from 0.20 to 0.24%, with highest levels in Tanda-23 and EX33. Overall, EX11 and EX22 were the most productive varieties, demonstrating superior establishment, biomass, grain yield, and ionic balance under salinity stress, suggesting their suitability for cultivation in salt-affected regions with proper soil and water management.

## Exploring The Potential of Quinoa as a Food Security Crop for Salt-Affected and Dry Land Farming Systems

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Climate change is resulting in severe decline in crop yields around the world due to enhanced soil salinity, heat and drought stress. Quinoa (*Chenopodium quinoa* Willd) has been regarded as an important crop for food security under the changing climatic conditions. The combined effects of soil salinity, drought and heat stress on two genotypes of quinoa (Titicaca, Puno) were explored during a field experiment conducted on salt affected soil under dryland conditions. The joint stress of salinity, high-temperature and drought was more detrimental for plant growth and grain yield in contrast to individual stresses. The combined stresses caused 36, 41%, and 35 and 43% decline in plant biomass and grain yield Puno and Titicaca, respectively. Likewise, relative water contents and stomatal conductance in both genotypes also declined in the same way. Plants accumulated the highest K and lowest Na in the shoot when heat and drought stress were imposed along with salt stress. The mineral contents in grains such as Zn, Ca, Fe, Mg, K, Mn and Cu) also reduced more under the combined stresses of salinity, drought and heat. The contents of carbohydrates, proteins and lipids in grain were not affected by salinity alone but declined when salinity was combined with heat and drought. Plant growth, grain yield and quality was better in case of Puno compared to Titicaca. Henceforth, Puno genotype should be cultivated on salt affected soils under dry land farming systems prone to heat stress.

## Soil and Maize Resilience Enhancement for sustainable development by Osmolytes to Mitigate Salt Stress in Changing Climate

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Osmolytes play a significant role in enhancing crop resilience and sustainable soil health particularly in stress conditions imposed by climate changing. They improves the soil quality, enhance the crop productivity in various real-world scenarios. Understanding osmolytes applications and mechanisms for salt tolerance is crucial for optimizing maize growth in salt-stressed soils which are going to increase by climate change . This approach offer sustainable and environmental friendly solutions to address agricultural challenges. So the study was conducted with the objective of mitigation salt stress and improvement in Maize attributes by accompanying the osmolytes. Two osmolytes Proline and Glycine betaine was applied with concentrations 20mM, 40mM, and 60mM against 2dSm<sup>-1</sup>, Threshold level 5dSm and high salinity 10dSm<sup>-1</sup>. Different crop and chemical attributes were recorded. The results reveal that salt stress induced reduction in maize growth which can be alleviated by using osmolytes. Among osmolytes the application of Proline 60mM and Glycine betaine 60mM performed significantly better not only for improvement of maize growth characteristics but also improved the internal concentrations of these compounds in maize plants. In salt-affected soils, which are predicted to become more common as a result of the effects of climate change, this study emphasizes the potential of osmolytes as a sustainable, climate-resilient strategy for boosting Soil health, increasing crop productivity, and ensuring the long-term sustainability of agricultural systems.

## Role of Halopriming in Improving Physiological Responses and Yield of Wheat under Salt Stress

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Soil salinity is a major constraint to wheat production in Pakistan. The use of salt-tolerant varieties and seed priming are practical approaches to mitigate salinity stress. This study evaluated the effect of halopriming (30 mM NaCl) compared with dry seed under different salinity levels (0, 4, 6, and 8 dS m<sup>-1</sup>) on growth and physiological traits of two wheat varieties (Bakhtawar and Auqab). Salinity significantly reduced all measured traits, with 8 dS m<sup>-1</sup> decreasing grain yield per plant by 68%, biological yield by 56%, harvest index by 29%, and shoot K<sup>+</sup>/Na<sup>+</sup> ratio by 60%. Seed priming improved most traits, increasing grain yield (12%), biological yield (24%), harvest index (12%), and K<sup>+</sup>/Na<sup>+</sup> ratio (12%), though its effect on grains per spike was non-significant. Bakhtawar outperformed Auqab across all parameters. Overall, salinity adversely affected wheat performance, while NaCl seed priming effectively alleviated salt-induced damage and improved productivity.

# Role of Compost for the Conservation of Water to Evaluate Ecological Intensification and Yield Forecasting of Wheat under Changing Climate Scenarios

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Climate change and abiotic environmental stresses are among the most critical global challenges affecting plant growth and crop production. Wheat is one of the most strategically important crops for human consumption. Minimizing the impact of both biotic and abiotic stresses on plant growth is essential. Compost as an organic amendment improves plant growth and productivity, potentially leading to improved physicochemical properties of soil and climatic conditions under stress conditions. A two-year field experiment was conducted to evaluate the response of two wheat varieties towards compost application under three water stress levels (i.e. water stress (W.S.), W.S. + compost Level, 2 (10, 20 tons ha<sup>-1</sup>) in natural saline conditions. Four irrigation levels were applied under field conditions using a randomized complete block design (RCBD) in a split-plot arrangement. Different crop growth (i.e. plant height, shoot length, shoot fresh and dry weight, root length, root fresh and dry weight), physiological (SPAD value, RWC and MSI), elemental analysis (Na<sup>+</sup>, K<sup>+</sup>, N, P and Ca<sup>+</sup>) and antioxidant activity (SOD, POD and CAT) were analyzed in this experiment. W.S. significantly reduced all measured parameters. However, the application of compost at 20 tons ha<sup>-1</sup> significantly improved these values in plant height 65, 57cm, SPAD value, RWC, and MSI improved from 50% to 81%, 66% to 68%, and 79% to 43%, maximum uptakes of K<sup>+</sup>, N, and P were 0.0235%, 0.0118%, and 0.039%, and POD and CAT activities were also enhanced, from 245 to 453 and 195.67 to 398.67 Unit/g FW, respectively, in the cultivars Faisalabad-2008 and Sehar-2006. It was concluded that W.S. conditions pose the greatest threat to wheat yields, but applied, compost applied @ 20 tons ha<sup>-1</sup> helps conserve water and mitigate heat stress, ecological intensification, and sustain wheat yields under moderate climate change scenarios.

## Selection and Characterization of Advanced Wheat Mutants for Yield Improvement in Saline Environment

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Salinity is one of the most severe abiotic stress restricting wheat productivity in arid and semi-arid regions where marginal lands are prevalent. The current study aimed to identify salt-tolerant advanced wheat mutant lines developed through Gamma rays, EMS and in combination for high-yielding potential under saline condition. Thirty advanced wheat mutant lines and twenty seven high yielding varieties were initially screened in passive hydroponic conditions at four salinity levels 0, 100,

150 and 200 mM of NaCl. Selected fifteen mutant lines were further evaluated in pots under saline soil for growth, physiological and ionic traits. Finally, fifteen promising lines/varieties were tested under naturally saline field conditions at Bio-saline Research Station, Pakka Anna to assess yield and yield-related traits. Significant genetic variability was observed among mutant lines across all experimental systems. Results revealed that selected mutants SE4/12-4, SE5/12-7, SG3/12-23, SG3/12-25, SG2/12-26 and Fsd-2008 maintained high tolerance as compared to standard check LU-26-S, with higher biomass, enhanced antioxidant capacity, higher chlorophyll retention and reduced ionic imbalance and high grain yield (20% increased). KCT7/12-44, SCT6/12-9, Sarsabz, Subhani, NIA Sussai and NIA Sunhari exhibited moderate tolerance demonstrating enhanced salt tolerance and stable yield performance. The integration of controlled and field-based screening proved effective for identifying wheat genotypes, induced defense response in order to maintain food security in salt-affected regions.

## Evaluation of Maize (*Zea mays* L.) Genotypes for Salinity Tolerance by Using Line × Tester Analysis

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Salt stress is the second major a biotic stress after drought which abruptly effects the maize production. In present study 50 maize inbred lines were evaluated under control ( $T_1 = 0.89 \text{ dS m}^{-1}$ ), and three salt treatments ( $T_2 = 8 \text{ dS m}^{-1}$ ,  $T_3 = 10 \text{ dS m}^{-1}$  and  $T_4 = 12 \text{ dS m}^{-1}$ ) based on different morpho-physiological traits. Ten salt tolerant high yielding inbreds were selected as lines and four salt susceptible inbreds were selected as tester to generate 40 F1 crosses. F1 crosses along with parents (lines and testers) and one commercial hybrid (NK-8441) were evaluated under same salinity levels as reported above. Results showed the existence of significant in studied F1 crosses for all studied plant traits. Genetic component of variance showed the prevalence of dominance gene action over additive gene action and non-additive type of gene action was observed for most of the studied traits. The maize lines DDR-15, ILYL-34 and ILYL-38 showed significant and positive general combining abilities for desirable traits i.e. biomass production at seedling stage, cell membrane stability, relative water content, and potassium contents in leaf sap and grain yield. Cross combinations ILYL-17 × ILYL-38, ILYL-7 × ILYL-38 and PEIL-20 × ILYL-38 showed significant and positive specific combing abilities for yield and other desirable traits at under all four treatments while ILYL-34 × ILYL-23, PEIL-6 × ILYL- 38 and DDR-15 × ILYL-38 displayed significant and positive SCA even at high salinity level i.e.12dSm-1 recommending for salt affected areas. F1 crosses ILYL-17 × ILYL-38, DDR-15 × ILYL- 38 ILYL-7 × ILYL-38 and PEIL-20 × ILYL-38 performed better than commercial check under high salinity level in term of desirable traits and grain yield suggesting their further utilization under saline regime of Punjab in farmer's field to observe full yield potential of the crosses. Study concluded that developed F1 crosses could be categorized into two major groups i.e. one group having F1 crosses which performed better in term of yield under normal and stress condition suggesting them for general cultivation while other group contains F1 crosses performing better under high salt stress condition (12dSm-1) that could be cultivated in salt affected areas.

# Genetic Evaluation of Quantitative Traits in Segregating Generations of Okra Under Salt Stress

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Okra (*Abelmoschus esculentus* L) is a very nutritious vegetable growing in different parts of the world. Salinity is a worldwide problem and affects the yield of Okra globally especially in Pakistan. The present study was conducted for genetic evaluation of segregating populations of okra under salt stress. 10 parents and their F<sub>2</sub> population obtained after 45 crosses of parents were selected for this study. 3 replicates of each parent were grown in pots and 6.5 ds/m EC level was applied. Screening was performed based on the number of different parameters, such as days to emergence, days of flowering, plant height at first flowering, no. of pods, pod length, pod weight, pod width, leaf surface area, electrolyte leakage, Na<sup>+</sup> and K<sup>+</sup>. On the basis of these parameters 65 progenies were selected and evaluated in F<sub>3</sub> generation under salinity. The experiment was conducted under completely randomized design. Correlation analysis, bi plot analysis, principal component analysis and cluster analysis were performed to check the association between different traits. Results showed that genetic diversity in OKRA F<sub>2</sub> progenies under salt stress had significant effect on selected traits of okra. Furthermore, cluster analysis showed that genotypes in cluster 1 are salt tolerant as compared to genotypes in cluster 5. This study helped us in identifying salt tolerant genotypes of OKRA.

## Others

### Soil as a Pathway to Sustainable Development: A Qur’anic Ethical Perspective

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Living things depend on soil as it is a foundational resource for life, food security, and ecological balance. However, due to soil degradation and unsustainable land use, our lives are under existential threats. It reminds us to use the soil sustainably. Against this backdrop, this paper examines soil as a means of sustainable development from a Qur’anic perspective. The objective of the paper is to highlight how the Qur’an frames soil (ṭīn, turāb, arḍ) as both a life-giving resource and a moral trust entrusted to humanity. Through an analytical reading of selected Qur’anic verses, the study explores key concepts such as stewardship (khilāfah), balance (mīzān), ethical utilization of the earth, and the

prohibition of corruption (fasād) on land. The paper argues that the Qur’anic worldview advances principles aligned with contemporary sustainability discourse, including conservation, moderation (wasatiyyah), and intergenerational responsibility (hifz al-nasl). By linking these ethical foundations with modern sustainable development goals (SDGs)-particularly food security, environmental protection, and climate resilience-the study demonstrates the relevance of Qur’anic teachings in addressing present-day environmental challenges related to soil. The paper recommends that it is important to incorporate Qur’anic ethical insights into sustainability discussions, which may enrich value-based approaches to soil conservation and sustainable development.

## Microplastics in Soils: Emerging Threats to Soil Resilience and Sustainable Development

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Microplastic pollution has traditionally been framed as a marine environmental issue. However, growing evidence indicates that soils may act as major sinks for microplastics, often accumulating higher concentrations than aquatic systems. Agricultural intensification, plastic mulching, sewage sludge application, compost amendments, irrigation with contaminated water, atmospheric deposition, and urban runoff are now recognized as significant pathways introducing microplastics into terrestrial ecosystems. Despite this, the implications of microplastic contamination for soil resilience remain insufficiently understood. Soil resilience, which is the capacity of soil systems to resist, adapt, and recover from disturbances, is fundamental to sustainable development, food security, and climate adaptation. Emerging research suggests that microplastics can alter soil physical structure including bulk density, porosity, and aggregation, influence water retention and infiltration dynamics, and interfere with nutrient cycling processes. Interactions with soil biota, including microbes and invertebrates, may disrupt enzymatic activities, carbon sequestration pathways, and overall soil ecosystem functioning. In tropical regions, where intense rainfall, high temperatures, and rapid urbanization intersect, microplastic dynamics in soils may differ significantly from temperate systems, raising additional research and policy concerns. This paper synthesizes current global evidence on the occurrence, transport pathways, and ecological impacts of microplastics in soils, highlighting critical knowledge gaps, particularly in developing and rapidly urbanizing regions. It further examines how microplastic contamination challenges soil resilience frameworks and discusses the implications for sustainable land management, circular economy strategies, and environmental governance. Addressing microplastics in soils is no longer optional, but crucial to safeguard soil health, sustain agricultural productivity, and ensure long term environmental sustainability in a changing climate.

## Design and Synergistic Engineering of Biomass-Derived Carbon/Metal Oxide Composites for Durable Supercapacitor Applications

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The conversion of agricultural waste into high-value functional materials presents a sustainable pathway toward green energy technologies. In this study, pineapple peel (PP) agro-waste was valorized into porous carbon-based composite electrodes for supercapacitor applications. A series of porous carbon/ZnMn<sub>2</sub>O<sub>4</sub> composites were successfully synthesized via low-temperature combustion at 500°C using ZnCl<sub>2</sub> activated pineapple peel and MnCO<sub>3</sub> as precursors. The incorporation of MnCO<sub>3</sub> played a crucial role in tailoring pore morphology and size distribution, resulting in enhanced electrochemical performance through the synergistic interaction between conductive carbon and ZnMn<sub>2</sub>O<sub>4</sub>. The optimized composite achieved a high specific surface area of 976.12 m<sup>2</sup> g<sup>-1</sup>. Electrochemical evaluation revealed that the PPZn-Mn1 electrode delivered a specific capacitance of 104.89 F g<sup>-1</sup> at a current density of 300 mA g<sup>-1</sup>, while pristine PPZn exhibited 119.03 F g<sup>-1</sup> under similar conditions. Notably, PPZn-Mn1 demonstrated superior rate capability and cycling stability, retaining 97.06% of its capacitance after 5000 charge–discharge cycles, significantly outperforming PPZn (79.52%). The corresponding symmetrical cell retained 83.89% capacitance after 5000 cycles, confirming its durability. Additionally, ZnSnO<sub>3</sub>/mesoporous carbon (PP-ZTO) and porous carbon (PP-C) composites were synthesized using a similar combustion approach. The PP-ZTO composite exhibited a high surface area of 896.39 m<sup>2</sup> g<sup>-1</sup>, with well-defined crystalline peaks corresponding to ZnSnO<sub>3</sub>. Morphological analysis confirmed a highly porous architecture with ZnSnO<sub>3</sub> uniformly distributed on the carbon surface. The composite delivered a specific capacitance of 94 F g<sup>-1</sup> at 0.3 A g<sup>-1</sup> and demonstrated excellent electrochemical stability with approximately 80% capacitance retention after 3000 cycles. Overall, the incorporation of metal oxide phases (ZnMn<sub>2</sub>O<sub>4</sub> and ZnSnO<sub>3</sub>) into biomass derived porous carbon significantly enhanced rate capability, cycle stability, and structural durability. These findings highlight the potential of pineapple peel-derived carbon/metal oxide composites as sustainable, low-cost, and high-performance electrode materials for next-generation supercapacitor applications, contributing to circular economy strategies and environmentally responsible energy storage solutions.

## Geo-Spatial Characterization of Potentially Toxic Lead, Zinc, and Copper Contaminated Soils along a Highway

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The contamination of urban roadside soils has been a major issue in recent years because they act as a sink for contaminants such as heavy metals. These contaminants are emitted from various sources and can have a direct influence on soil and human health. These substances are toxic to living organisms when their concentrations exceed the threshold limits of the environment and the human body. A study was conducted to evaluate the geo-spatial distribution of potentially toxic elements (PTEs) contamination along the Faisalabad–Sheikhupura highway. A total of 11 sites were selected, and from each site, six soil, plant, and water samples were collected from the right side and six samples from the left side of the highway. Soil samples were analyzed for PTEs (Pb, Zn, and Cu). Different ecological risk indicators were calculated, i.e., contamination factor (CF), geo-accumulation index (I<sub>geo</sub>), pollution load index (PLI), translocation factor (TF), and ecological risk index (ERI). It was noted

that the concentrations of Pb, Cu, and Zn at 0–15 cm soil depth ranged from 0.003–0.923, 0.001–3.739, and 0.004–1.889 mg kg<sup>-1</sup>, respectively, and from 0.001–0.532, 0.001–1.983, and 0.003–0.952 mg kg<sup>-1</sup>, respectively, at 15–30 cm soil depth. The concentrations of Pb, Cu, and Zn in water samples ranged from 0.012–1.654, 0.034–0.721, and 0.004–1.889 mg L<sup>-1</sup>, respectively, while the concentrations of Pb, Zn, and Cu in plant samples ranged from 0.034–0.532, 0.004–1.539, and 0.002–1.983 mg kg<sup>-1</sup>. Based on the soil, water, and plant quality indices, it was concluded that the study area is moderately to highly contaminated due to excessive emissions and contamination from nearby industries.

## Utilization of Benzophenone Contaminated Wastewater as Substrate for Microlagae to Produce Biolipids

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Benzophenone (BP) derivatives from household, paint, food, cosmetics, and synthetic industries are carcinogenic, persistent, bio-accumulative, and endocrine-disrupting. Wastewater containing BPs must be treated before discharge. This study evaluated algae for BP degradation and lipid accumulation for biodiesel production. Algae were collected from freshwater lakes, treatment plants, and Nullah Leh. Screening at 50 ppm BP identified three potent strains. Optimized conditions (pH 7, 25°C, 50 ppm substrate, NH<sub>4</sub>Cl/NH<sub>4</sub>NO<sub>3</sub> as nitrogen source) enhanced degradation and lipid accumulation. GC-MS analysis revealed major lipid compounds suitable for biodiesel. Results indicate algae can efficiently degrade BPs and produce biofuel, addressing water pollution and fossil fuel dependence.

## Assessing Land Degradation and Soil Moisture Dynamics Using Remote Sensing Indicators for Sustainable Land Management in the Thal Desert, Punjab, Pakistan

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Land degradation threatens soil resilience in arid and semi-arid regions, reducing agricultural productivity and ecosystem sustainability. The Thal Desert, spanning Bhakkar, Layyah, Muzaffargarh, and Khushab districts of Punjab, Pakistan, is a fragile ecosystem increasingly affected by anthropogenic pressures and climate variability. This study evaluated land degradation patterns and soil moisture dynamics from 2001 to 2023 using multi-source remote sensing datasets. The analysis integrated Landsat 5, 7, and 8, Sentinel-2 imagery, MODIS Land Surface Temperature (MOD11A2), MODIS NDVI time series (MOD13Q1), and Sentinel-1 SAR data for soil moisture through Google Earth Engine. Terrain characteristics were derived from the SRTM Digital Elevation Model, while CHIRPS

precipitation and ERA5-Land climate variables supported environmental analysis. Land degradation was assessed using vegetation and moisture indices, including NDVI, SAVI, NDMI, and surface albedo to compute the Modified Soil Degradation Index (MSDI). A Random Forest machine learning model was used to classify degradation severity and identify vulnerable zones. Results showed that approximately 38% of the Thal Desert exhibits significant land degradation, with severe degradation concentrated in southwestern Bhakkar and northern Layyah. NDVI indicated a declining vegetation trend of 0.008 units year<sup>-1</sup>, strongly correlated with reduced soil moisture ( $r = 0.82$ ,  $p < 0.001$ ). Soil moisture derived from Sentinel-1 ranged from 8–24% volumetric water content, with critical stress during the pre-monsoon period (April–June). Land surface temperature increased by 0.6°C per decade in severely degraded zones. Wind erosion was the dominant degradation process, affecting nearly 156,000 ha through sand dune movement and vegetation loss. Areas within the Thal Canal irrigation command showed improved vegetation (NDVI increase 0.12–0.18) and better soil moisture retention. Change detection revealed that 12,400 ha shifted from moderately to severely degraded conditions between 2001 and 2023 due to groundwater extraction, overgrazing, and deforestation, while afforestation in Khushab improved 8,600 ha. The Random Forest model achieved 88% classification accuracy, providing a basis for targeted soil conservation and sustainable land management in desert ecosystems.

## Synthesis of Fe Doped GO-ZnO Nanoparticles for The Photocatalytic Degradation of Pharmaceutical Drugs

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Environmental degradation has intensified due to the expanding pharmaceutical industry and the excessive release of harmful chemicals and pharmaceutical waste. The present study proposes a remediation approach based on a green, time-saving, simple, and single-step technique for synthesizing graphene oxide (GO) from agricultural waste (sugarcane bagasse). This method utilizes non-graphitic sources, avoids the use of hazardous chemicals, and is both energy-efficient and cost-effective. A novel photocatalyst based on Fe-embedded graphene oxide–zinc oxide (GO–ZnO) nanocomposites was synthesized using a hydrothermal technique and applied for the photocatalytic degradation of pharmaceutical compounds (ibuprofen and acetaminophen). Various characterization techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), UV–Vis spectroscopy, photoluminescence (PL), scanning electron microscopy (SEM), and energy-dispersive X-ray (EDX) analysis, were used to evaluate the synthesized nanocomposites. Morphological analysis confirmed the well-organized sheet-like structure of GO with ZnO and Fe inclusions. PL analysis revealed a significant reduction in electron–hole recombination after Fe doping. XRD results confirmed high crystallinity, with characteristic peaks at 29.42°, 38.37°, 44.57°, 64.86°, and 78.05°, corresponding to the (100), (101), (103), (200), and (202) planes of the hexagonal wurtzite structure of ZnO. The Fe-doped GO–ZnO nanocomposite demonstrated excellent photocatalytic performance, achieving removal efficiencies of 98% for ibuprofen and 91% for acetaminophen within 70 minutes of irradiation. The degradation followed pseudo-first-order kinetics and the Langmuir–Hinshelwood model. Thermodynamic analysis, indicated by negative  $\Delta G^\circ$  and positive  $\Delta H^\circ$ , confirmed that the

process is spontaneous and endothermic. The study concludes that the synthesized nanocomposites are effective and environmentally friendly photocatalysts for the degradation of pharmaceutical pollutants.

## Waste-Derived TiO<sub>2</sub>–ZNF/CP Bioaerogel for Photo-Electrocatalytic Treatment of Polyethylene Contaminated Effluents

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The growing concern over polyethylene (PE) pollution has highlighted the need for eco-friendly treatment methods for plastic-contaminated wastewater. Polyethylene is the most widely produced and used plastic, accounting for approximately 27% of global plastic production, which is projected to reach 121.4 million tons by 2026. Due to its durability and low cost, PE is extensively used across various industries, leading to significant environmental challenges. It is commonly discharged into water bodies from industries such as cosmetics, packaging, plastics, and paints, posing serious risks to both the environment and human health. This study aims to investigate the potential application of a TiO<sub>2</sub>-ZNF/CP bioaerogel as a catalyst for the degradation of polyethylene in industrial wastewater. The photo-electrocatalytic degradation of PE was evaluated under different operational parameters, including pH, catalyst dosage, and initial pollutant concentration. Treatment efficiency was assessed using the chemical oxygen demand (COD) method to quantify degradation within a controlled reaction time. The study further evaluates the feasibility of bio-based aerogels as sustainable materials for polyethylene degradation and examines the influence of operational conditions on process efficiency. The findings highlight the effectiveness of photo-electrocatalysis as a promising and environmentally friendly approach for the accelerated degradation of polyethylene in wastewater treatment systems, with potential applications in energy-efficient and sustainable pollution control.

## The Effect of Different Organic Amendments on Availability and Absorption of Active Pharmaceutical Ingredients by Plants

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Pharmaceutical residues in agricultural soils pose serious risks to crop health and food safety. This study evaluated the effects of azithromycin, metformin hydrochloride, and diclofenac sodium on physiological responses, yield, pharmaceutical uptake, and bioaccumulation factor (BAF) in spinach (*Spinacia oleracea*) and radish (*Raphanus sativus*). Results showed that pharmaceutical contamination reduced radish yield, with azithromycin and metformin causing the greatest decline, reaching a minimum yield of 270 g per pot in unamended soil. However, the application of pressmud and biochar

significantly ( $P < 0.05$ ) improved radish yield, increasing it to 500 g per pot. Pharmaceutical exposure also increased electrolyte leakage (up to 42%) and enhanced antioxidant enzyme activities, including superoxide dismutase (SOD; 95 U g<sup>-1</sup> FW), peroxidase (POD; 112 U g<sup>-1</sup> FW), and catalase (CAT; 105 μmol H<sub>2</sub>O<sub>2</sub> decomposed min<sup>-1</sup> g<sup>-1</sup> FW), indicating oxidative stress. Among the tested compounds, metformin resulted in the highest pharmaceutical accumulation in radish (20 μg g<sup>-1</sup>) and spinach (21 μg g<sup>-1</sup>), with BAF values exceeding 2.5. In contrast, diclofenac exhibited the lowest uptake (4 μg g<sup>-1</sup>) and BAF values below 1.0. Salicylic acid effectively mitigated diclofenac-induced stress, particularly in spinach. Principal component analysis revealed clear separation between amended and unamended treatments, indicating distinct physiological and biochemical responses. Overall, these findings demonstrate that targeted soil amendments such as pressmud, biochar, and salicylic acid can enhance crop resilience and reduce pharmaceutical accumulation in edible plant tissues, thereby improving food safety in contaminated agroecosystems.

## Assessment of Effect of Raw City Effluents on Concentration of Potentially Toxic Heavy Metals and Soil Enzymes in Peri Urban Areas

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Heavy metals are important environmental pollutants that pose serious risks to soil, plants, and water resources. The application of raw municipal effluent to agricultural land is widely practiced by farmers and local administrators for various economic and agronomic reasons. The enrichment of untreated city effluent with organic matter and plant nutrients makes it an attractive irrigation source for the farming community. However, it also contains heavy metals and other contaminants that degrade soil and water quality and may negatively impact human health. This study assessed heavy metal pollution in peri-urban areas of Faisalabad (Uchkera, Chak 279 R.B, Chak 235 R.B, and Chak 236 R.B) irrigated with raw municipal effluent. Atomic Absorption Spectrophotometry was used to determine metal concentrations. Soil quality index (SQI), soil enzyme activities, and water physicochemical parameters were also evaluated. Results showed that the maximum concentrations of Fe, Zn, Cu, Pb, and Cd in plant samples were 1.39, 0.37, 2.57, 0.14, and 0.007 mg kg<sup>-1</sup>, respectively, while Ni was not detected in any samples. In soil samples, the maximum concentrations were 7.06 mg kg<sup>-1</sup> for Fe, 0.187 mg kg<sup>-1</sup> for Zn, 3.85 mg kg<sup>-1</sup> for Cu, 0.076 mg kg<sup>-1</sup> for Pb, and 0.006 mg kg<sup>-1</sup> for Cd. The concentrations of Fe and Cu in both soil and plant samples exceeded WHO and FAO permissible limits, whereas Pb exceeded permissible thresholds in some locations. In contrast, Zn and Cd levels remained within recommended limits. Across all physicochemical parameters (EC, pH, TSS, DO, SAR, RSC, and P), significant spatial variations were observed between sites irrigated with treated and untreated wastewater. Although heavy metal accumulation in some samples exceeded WHO guidelines, the health risk index (HRI) for adults remained below 1, indicating minimal immediate health risk from consumption. Soil pollution indices revealed varying degrees of contamination across sites, highlighting the environmental and agricultural implications of wastewater irrigation in peri-urban regions of Faisalabad, Pakistan.

## Vermicompost Application: A Promising Approach to Boost Spinach Growth in Soil Affected by Chromium Contamination

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Chromium (Cr) is a polyvalent element that exists in multiple oxidation states, with trivalent Cr(III) and hexavalent Cr(VI) being the most common in the natural environment. Elevated Cr levels in cultivated soils adversely affect crops by inhibiting growth and inducing oxidative stress in plants such as spinach. Vermicompost, as an organic amendment, improves soil fertility by enhancing aeration, porosity, bulk density, water-holding capacity, pH, electrical conductivity, and nutrient availability, including nitrogen, phosphorus, and potassium. A pot experiment was conducted at the Department of Soil and Environmental Sciences, Ghazi University, Dera Ghazi Khan, to evaluate the effects of vermicompost on spinach (*Spinacia oleracea* L.) grown in Cr-contaminated soil. The study assessed plant growth, Cr bioavailability, root-to-shoot transfer, and biochemical responses under eight treatments arranged in triplicate. Chromium contamination significantly influenced plant growth, composition, and various soil and crop parameters. However, the application of vermicompost at different levels (8%, 16%, and 24%) mitigated Cr toxicity and significantly improved plant growth. Maximum root length was observed in the treatment with 24% vermicompost (T3), while severe Cr toxicity (T4) reduced root length to 7.6 cm. Increasing vermicompost levels also reduced Cr bioavailability (e.g., 0.24 mg kg<sup>-1</sup> in T3 and T7). These results demonstrate that vermicompost is an effective and environmentally friendly amendment for mitigating chromium toxicity, enhancing spinach growth, and supporting sustainable agriculture in contaminated soils.

## Quantitative Morphological Analysis and Genotypes Evaluation of Groundnut (*Arachis hypogaea* L.) for Enhanced Yield under Calcareous Soil

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Groundnut (*Arachis hypogaea* L.) is an important leguminous oilseed crop valued for its high nutritional content, including protein, lipids, and essential dietary nutrients. Agronomic performance plays a key role in determining yield potential in groundnut and other crops. This study was conducted

at the National Agricultural Research Centre (NARC), Islamabad, under calcareous soil conditions to evaluate the agronomic performance of ten groundnut genotypes. The crop was sown in April 2024 and harvested in September 2024 using a Randomized Complete Block Design (RCBD) with three replications. Analysis of variance (ANOVA) revealed significant ( $P \leq 0.05$ ) genotypic differences for all measured traits. Genotype GP36 showed superior performance in key yield-related traits, recording the highest leaf length (5.83 cm), leaf width (3.26 cm), and pod yield (4,103.3 kg ha<sup>-1</sup>). In contrast, the tallest plants were observed in GP42 (41.53 cm), the widest canopy in GP39 (48.73 cm), and the thickest stems in GP38 (6.30 mm). Based on its high pod yield, genotype GP36 is recommended for cultivation by local farmers to enhance productivity. Furthermore, it represents a valuable genetic resource for future breeding programs aimed at improving groundnut crops.

## Improving Composting Efficiency of Municipal and Kitchen Wastes Using Bioinoculants and Labile Organic Amendments

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Rapid composting of organic municipal solid waste (MSW) and kitchen waste (KW) using microbial inoculants significantly shortens degradation time and improves compost quality. Rapid population growth and urbanization have intensified the global challenge of disposing municipal solid waste (MSW) and kitchen waste (KW), often dumped in landfills despite composting's potential to convert organic matter into valuable fertilizer for soil conditioning and plant growth. This study synthesizes findings from two experiments examining microbial inoculation—phosphate-solubilizing bacteria (PSB) and cellulose-degrading bacteria (CDB), used singly or in consortia—with bulking agents like poultry manure or garden waste (GW) to accelerate composting and enhance quality parameters. Lab-scale setups used 500g batches of MSW or KW in plastic containers, inoculated with isolated strains (1.25ml microbial solutions) and amendments (e.g., 25g GW), monitored over 35 days across heating, cooling, and maturation phases. Key parameters assessed included pH, electrical conductivity (EC), moisture content (MC), total organic carbon (TOC), total nitrogen (TN), total/available phosphorus (P), available potassium (K<sup>+</sup>), NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, humic substances, temperature, and seed germination index (SGI) as maturity indicators; one-way ANOVA analyzed differences. 16S rRNA sequencing identified strains: PSB as *Acinetobacter pittii* (99.83% similarity), *Serratia marcescens*, and CDB as *Bacillus cereus* (90% similarity), *Klebsiella pneumoniae*. Microbial consortia (PSB+CDB) achieved the highest feedstock degradation in the shortest time, outperforming single inoculants, with bulking agents enhancing aeration and process efficiency. Final compost met maturity standards (e.g., stable C/N ratio, high SGI), confirming microbial inoculation as an effective strategy for producing nutrient-rich, pathogen-free bio-amendments.

## Biosorption of Trace Metals from Freshwater Using Cultured Periphyton Biofilms

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Contamination of freshwater systems with trace metals (TMs) has emerged as a significant environmental concern, posing serious risks to aquatic ecosystems and human populations dependent on these water resources. Industrial effluents, agricultural runoff, and urban wastewater discharges are major contributors to the accumulation of toxic metals such as arsenic (As) in rivers and lakes. Owing to their chemical stability, non-biodegradable nature, and potential for bioaccumulation and biomagnification, trace metals persist in aquatic environments and can enter the food chain. Their effective removal is therefore essential for safeguarding ecological integrity and public health. The present study investigates the biosorption capacity of three distinct periphyton biofilm communities (PPBFs), namely epiphyton, epilithon, and metaphyton, for the removal of trace metals from simulated river water under controlled laboratory conditions. Periphyton consists of complex microbial assemblages, including algae, bacteria, and fungi, embedded within an extracellular polymeric substance (EPS) matrix and naturally attached to submerged surfaces. These biofilms are increasingly recognized for their capacity to immobilize contaminants through physicochemical interactions. Periphyton samples were isolated from freshwater environments and cultured using a Bio-carrier of Organic Natural Aquatic Mate (BONAM) to promote biomass growth and structural stability. Scanning Electron Microscopy (SEM) analysis revealed a porous and filamentous morphology characterized by interconnected microcavities, discrete microbial cells, and a dense extracellular matrix. This structural configuration enhances surface area and provides numerous reactive sites for metal binding. Functional group analysis indicated the abundance of surface-active moieties, particularly carboxylic groups, which facilitate metal sequestration via ion exchange, electrostatic attraction, and surface complexation mechanisms. Among the three biofilm types, epiphyton demonstrated the highest removal efficiency. At an initial trace metal concentration of 20 mg L<sup>-1</sup>, epiphyton achieved 79.50% arsenic removal within 144 hours. However, removal efficiency declined to 57.40% and 51.60% at concentrations of 40 mg L<sup>-1</sup> and 60 mg L<sup>-1</sup>, respectively, suggesting saturation of available adsorption sites at higher contaminant levels. Temperature significantly influenced biosorption performance. Maximum removal (75.05%) was observed at 15 °C, decreasing to 69.50% at 25 °C and 61.00% at 35 °C, indicating that lower temperatures may favor adsorption stability. Kinetic modeling showed that the process followed pseudo-first-order kinetics, implying that surface adsorption dominated the removal mechanism. Under optimized conditions (90 hours, neutral pH, 25 °C, 1.0 g L<sup>-1</sup> biomass, 20 mg L<sup>-1</sup> TMs), epiphyton achieved approximately 92% total trace metal removal. These findings highlight the potential of epiphytic periphyton biofilms as sustainable and cost-effective biomaterials for freshwater remediation.

## Legacy Effect of Long-Term Urban Wastewater Irrigation Contrived Topsoil Multifunctionality via Microplastic Littering Pathway

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Using wastewater to irrigate urban soil increases the number of environmental stressors, such as microplastics (MP), yet their relationships with soil multifunctionality remain largely unknown. Globally, topsoil in most ecosystems is increasingly eroded by intensive land use practices. Therefore, restoring topsoil is particularly important to optimize soil multifunctionality for future land use decisions. To address this, we conducted a standardized survey of topsoil (0–20 cm) from an urban agricultural corridor in Faisalabad across three distinct irrigation regimes: canal water (CIW), municipal wastewater (MW), and mixed wastewater (MXW), and two textural classes: sandy clay loam and sandy loam. The selected sites have a 20-year history of distinct land use and irrigation practices. Topsoil multifunctionality was calculated from 16 surrogate soil ecosystem functions. Regardless of irrigation regime, a significant increase in total, large, and small MP stocks was recorded in sandy loam soil compared to sandy clay loam soil. On average, large MP stocks exceeded those of small MP across soil types and irrigation regimes. Similarly, significantly greater deterioration in topsoil multifunctionality (-0.68) was found in sandy loam soil irrigated with MXW. Most importantly, our regression analysis found a significant negative association between all MP and soil multifunctionality under wastewater irrigation. Overall, we found that irrigation regime was the strongest predictor of variation in soil ecosystem functions. Our results highlight that repeated use of wastewater in urban soils should be reconsidered in the context of future urban land use planning, as it is a key factor in MP pollutant loading and reduced soil multifunctionality.

## Interactive Controls of Climatic Conditions, Soils' Physicochemical Properties, and Quality of Residue Inputs on Priming Effect of Soil Organic Matter

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Soil organic carbon (SOC) dynamics are critical for understanding soil fertility, health, and carbon sequestration. This work studies the response (in terms of SOC dynamics) of soils originating from different agro-climatic zones of Pakistan towards addition of litter of different complexity. We marked three sampling sites from diverse agricultural systems in different koppen climate zones of Pakistan. Soils showed vast variations in climate conditions and physiochemical properties involved in carbon sequestration such as texture, and basic cations specially  $\text{Ca}^{+2}$ , (TRB), native carbon content nutrient availability. Leaf, stem and root litters of maize were added to discern the role of chemical complexity of fresh organic carbon in native SOC decomposition (priming effect). Our results indicate that soil MAP is a significant positive control over soil priming effect while effect of temperature was insignificant. Physiochemical properties specially TRB and texture were basic and significant controls of priming effect. For instance, clayey soil exhibited a lower priming effect on litter addition as compared to sandy soil, where microbes tend to decompose added litter instead of native soil organic matter that resulted in very low priming effect. Additionally, The effectiveness of soil carbon sequestration capacity in controlling priming effect is significantly moderated by nutrients ( $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , Mineral-N) availability. Adequate nutrients supply was found to synergistically improve SOC levels and reduce priming effect. Our findings reveal that chemically complexed litter significantly enhances the priming effect, stimulating microbial activity and leading to increased decomposition of native SOC for nutrient mining.

## Engineering Metal–Organic Frameworks (MOFs) Catalysts for Sustainable Environmental Remediation

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Rapid industrial development and urban expansion have increased environmental pollution, creating a vital requirement for sustainable and efficient remediation technologies. In recent years, metal–organic frameworks (MOFs) have gained significant attention as advanced functional materials for environmental applications due to their tunable porosity, exceptionally high surface area and versatile chemical structures. These unique properties make MOFs highly favorable for the transformation and removal of a wide range of environmental pollutants, including organic contaminants, heavy metals, and emerging pollutants. Presently, various remediation technologies are being considered to mitigate environmental pollution, such as membrane filtration, adsorption, electrocatalysis and photocatalysis. In this context, MOF have emerged as favorable materials because they can act as catalysts, adsorbents, or precursors for the development of advanced hybrid materials with high performance. Recent research trends highlight the engineering of MOF structures, composite formation, and MOF-derived nanomaterials to improve catalytic activity, stability, and environmental applicability. Overall, the growing interest of scientist in MOF-based materials reflects their significant potential to lead next-generation strategies for environmental remediation, offering tunable, efficient, and sustainable solutions for pollution reduction.

## Selenium in Soil: Fractionation at Different Depth of Three Parent Materials (Loess, Shale & Sandstone)

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Soil selenium forms differed with the sources of soil parent material and genesis affected distribution of selenium forms and bioavailability. Selenium bioavailability depends on its forms than total concentration. The objectives were to assess the relationship of soil selenium fractions at different depth and developing stage of three parent materials. Samples of three replicated soils were selected at three different level of development in each of loess, shale and sandstone residuum were taken. Samples were analyzed for pH, texture, total organic carbon, selenium fractions and total selenium. The variance in basic parameters, selenium fractions at horizon level was analyzed by multivariate

analysis of variance (MANOVA). Soil selenium was fractionated into carbonate bound, manganese-iron bound, organic matter bound, humic compounds bound, sulfide bound and residual selenium. The shale derived soils had the highest total selenium ranged from 374 to 670  $\mu\text{g kg}^{-1}$ , which had strong positive relation with sulfides bound ( $r^2$  0.91), recalcitrant selenium ( $r^2$  0.88) and humic selenium ( $r^2$  0.83) indicating their contribution in total selenium. The maximum content of selenium fractions bound to carbonates, humic compounds and sulfide were in shale soil profile while content of Mn-Fe oxide bound, organic matter bound selenium fractions were more in loess soils. Sandstone soils were rich in residual selenium. This study will help the understanding about the selenium status in soils to control the diseases caused by selenium deficiency in animals and humans.

## Microemulsion Assisted Biodiesel Production from De-Oiled Olive Waste Using Oleaginous Bacteria

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The escalating global demand for sustainable energy necessitates innovative strategies that couple renewable fuel production with effective waste management. Biodiesel represents a promising alternative to fossil-derived diesel owing to its biodegradability, lower emissions, and engine compatibility. However, large-scale production is still hindered by the high cost and scarcity of feedstocks. Utilizing agro-industrial residues for microbial lipid synthesis offers a circular and sustainable approach to biofuel generation. Among these residues, de-oiled olive waste is an abundant and underutilized biomass ideal for conversion within an integrated biorefinery framework. This study investigates a microemulsion-assisted strategy to enhance biodiesel production from microbial lipids generated by the oleaginous bacterium *Serratia surfactantfaciens*, isolated from olive mill wastewater. The strain was evaluated for its capacity to accumulate lipids and degrade organic waste when cultivated on de-oiled olive residues. Lipids extracted from the bacterial biomass were converted to fatty acid methyl esters (FAMES) via acid-catalyzed methanolysis and subsequently analyzed for composition and fuel quality. Under baseline culture conditions, *S. surfactantfaciens* accumulated lipids equivalent to 33% of its dry biomass while achieving reductions of 41.03% in organic matter and 29.1% in chemical oxygen demand within 120 hours. Process optimization involving pH, temperature, agitation, and nutrient supplementation resulted in an increased lipid yield of 39% at pH 5, 30 °C, and 200 rpm, using ammonium chloride and sucrose as nitrogen and carbon supplements, respectively. Gas chromatography–mass spectrometry revealed a predominance of even-chain saturated fatty acids, with oleic ( $\approx$  67%) and palmitic acids as principal components. The absence of polyunsaturated species and the strong presence of monounsaturated and saturated fractions suggest enhanced oxidative stability and favorable combustion characteristics comparable to vegetable oil-derived biodiesel. Incorporating a microemulsion phase during transesterification significantly improved mass transfer efficiency, shortened reaction time, and increased biodiesel yield. Overall, this work demonstrates that combining microemulsion-assisted conversion with microbial valorization of olive-processing residues provides an efficient, cost-effective, and environmentally sustainable route for biodiesel production. The proposed approach contributes to circular bioeconomy initiatives by transforming industrial waste into high-value renewable energy.

# Geospatial Analysis of Land Use Change and Its Impact on Soil Quality in the rapidly Urbanizing region of Pakistan

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Rapid unplanned urbanization in developing countries poses a significant threat to soil quality degradation and food security. The study presents an integrated geospatial approach by assessing the land use land cover change and soil degradation in twin cities of Rawalpindi and Islamabad from 2010-2025. Landsat imagery was used to perform Land use landcover change analysis whereas, spatial distribution of heavy metal contamination was mapped using interpolation technique, Inverse Distance weighting in ArcGIS. Results indicate the substantial increase in buildup area by 45% until 2025 along with the reduction in water bodies. Elevated concentrations of cadmium were reported in soils along Soan River, exceeding permissible limits and posing serious ecological and health risks. Increased concentrations of lead, nickel and chromium were also observed across multiple sites in study area indicating deterioration of soil quality. Bioaccumulation of these heavy metals in food chain compromise the food safety. The study highlights the urgent need for sustainable land use planning and improved soil quality in rapidly urbanizing landscapes.

## POSTERS

### Evaluating The Effect of Neem Oil Coated N and P Fertilizers on Maize (*Zea mays* L.) Growth under Water Stress

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Water scarcity and irregular rain patterns are leading to drought stress in Pakistan under the current scenario of climate change. Coated fertilizers are developed to fulfill crop nutrient demand under water stress conditions. Nitrogen (N) and phosphorus (P) play a vital role in plant growth and development. Approximately 50% of nitrogen is lost due to volatilization, runoff, denitrification, and leaching, causing low use efficiency and environmental deterioration, while a significant portion of phosphorus becomes fixed with calcium. The objective of the study was to evaluate the effect of neem oil-coated (0.25% and 0.5%) urea and diammonium phosphate (DAP) fertilizers to improve the availability of major nutrients. A pot experiment with seven treatments was conducted under a completely randomized design at ISES, UAF. Maize (*Zea mays* L.) was grown as a test crop for 45 days. Physiological parameters were recorded at the full growth stage, and after harvesting agronomic parameters and plant chemical parameters (N, P, K, and NO<sub>3</sub><sup>-</sup>) were assessed. Pre- and post-soil chemical analyses were also conducted. Data were analyzed statistically using Statistix 8.1. The results showed that maximum shoot length (105 cm), fresh biomass (84 g), N (3.4%), P (0.36%), and K (2.78%) uptake were recorded in T4 (0.5% neem oil coating on both urea and DAP) at field capacity. T4 also showed maximum shoot length (88 cm), fresh biomass (64 g), N (3.01%), P (0.34%), and K (2.13%) uptake under 50% water-stressed conditions. Postharvest soil analysis also showed maximum nutrient availability in T4 at field capacity (N: 0.059%, P: 6.8 mg kg<sup>-1</sup>, K: 210 mg kg<sup>-1</sup>, NO<sub>3</sub><sup>-</sup>: 18.3 mg kg<sup>-1</sup>, and NH<sub>4</sub><sup>+</sup>: 13.01 mg kg<sup>-1</sup>) and under 50% drought conditions (N: 0.04%, P: 5.6 mg kg<sup>-1</sup>, K: 184 mg kg<sup>-1</sup>, NO<sub>3</sub><sup>-</sup>: 17.6 mg kg<sup>-1</sup>, and NH<sub>4</sub><sup>+</sup>: 11.7 mg kg<sup>-1</sup>). These findings demonstrate that neem oil-coated fertilizers can reduce nutrient losses and improve maize productivity under drought conditions, supporting sustainable fertilizer use in climate-vulnerable areas.

### Silicon Nutrition Optimization for Mitigating the Deleterious Effects of Saline Water on Growth, Yield and Physiological Characteristics of Wheat in Hydroponics

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Water scarcity can be mitigated either by increasing water use efficiency or by utilizing non-conventional water sources for irrigation. Saline water is a potential option; however, its salt ions can deteriorate soil properties and reduce plant growth if not properly managed. Silicon (Si) nutrition may enhance wheat productivity under saline irrigation. A hydroponic study was conducted to optimize Si levels for wheat cultivar Dilkash-2019 under saline water (EC 8 dS m<sup>-1</sup>). Treatments included tap water (control) and saline water with five Si levels (30, 60, 90, 120, and 150 ppm). Saline water increased Na<sup>+</sup> and decreased K<sup>+</sup> concentrations in plant tissues, reducing physiological and yield traits. Silicon at all levels significantly reduced Na<sup>+</sup> accumulation and improved wheat productivity, with the highest improvement at 60 ppm. Specifically, 60 ppm Si reduced shoot Na<sup>+</sup>: K<sup>+</sup> ratio by 74.37%, transpiration by 26.05%, stomatal conductance by 35.71%, H<sub>2</sub>O<sub>2</sub> by 55.12%, and malondialdehyde by 50.84%, while enhancing chlorophyll content by 33.56%, photosynthesis by 49.93%, and grain yield by 72.94% compared to saline water without Si. Silicon at 60 ppm is recommended to improve wheat productivity under saline water irrigation.

## Environmental Risk Profiling and Spatiotemporal Characterization of Heavy Metal Pollutants in Relation to Heterogeneous Land Utilization Patterns within Nowshera District

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Soil heavy metal contamination is persistent and toxic, posing ecological and public health risks. This study assessed the spatial distribution and ecological risks of heavy metals under different land-use types in Nowshera District, Pakistan. Seventy-six surface soil samples were collected from industrial, urban, rural, and agricultural regions and analyzed for 14 heavy metals. GIS-based mapping revealed contamination hotspots primarily in industrial and urban areas, with rural and agricultural regions showing lower contamination. Industrial activities contributed Pb, Zn, and Cu, whereas urban sources enriched soils with asbestos, Cr, and Pb. Risk assessment indices identified industrial zones as high-risk areas, with Cd and Pb being primary contributors to ecological toxicity. Multivariate analysis indicated sources as industrial, lithogenic, and agrochemical. The study underscores the need for

regulated industrial emissions, urban waste management, and sustainable agrochemical practices, with geospatial tools aiding targeted policy interventions.

## Physiological and Yield-Based Evaluation of Cotton Genotypes under Different Irrigation Regimes

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The revival of the cotton crop requires concerted and strategic efforts. Among various approaches, the development and adoption of drought-tolerant varieties have become imperative to sustain and enhance cotton productivity, particularly under prevailing irrigation water shortages driven by climate change. In this context, the present study was conducted at the experimental field of the Central Cotton Research Institute (CCRI), Sakrand, to evaluate the drought tolerance of newly developed cotton strains. Two sets of genotypes were assessed: Set A, comprising non-Bt cotton genotypes, and Set B, consisting of Bt cotton genotypes. These genotypes were evaluated under three irrigation regimes representing different levels of water stress: severe stress (21-day irrigation interval, approximately four irrigations), moderate stress (14-day interval, approximately six irrigations), and no stress (7-day interval, approximately eight irrigations). The experiment was laid out in a split-plot design with three replications. The non-Bt genotypes included CRIS-694, CRIS-797, and CRIS-698, with CRIS-613 as the standard, while the Bt genotypes comprised Bt.CRIS-714, Bt.CRIS-716, and Bt.CRIS-723, with Bt.CRIS-508 as the standard variety. Statistical analysis revealed significant ( $p < 0.05$ ) differences among irrigation treatments, genotypes, and their interactions. Among non-Bt genotypes, CRIS-694 exhibited superior performance across varying levels of water stress, followed by CRIS-698, outperforming the standard variety CRIS-613. Similarly, within the Bt varieties, Bt.CRIS-723 recorded the highest yield under drought conditions, followed by Bt.CRIS-714 and Bt.CRIS-716, compared to Bt.CRIS-508. Water stress significantly affected shedding per plant across all genotypes, with shedding percentage increasing by 10% progressively under higher drought stress, indicating the adverse impact of limited water on cotton reproductive development.

## Plant Species Diversity, Sustainability Constraints, and Adaptive Strategies in Nursery Sector in Bahawalnagar District: Evidence from Ethnobotanical Data

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Nursery enterprises play a pivotal role in supporting biodiversity conservation, household economies, and the regional horticulture sector in Pakistan. In southern Punjab, particularly Bahawalnagar District, nursery growers operate under challenges posed by climatic variability, market fluctuations, and limited resources. Despite their importance, limited empirical evidence exists on plant species diversity, sustainability constraints faced by nursery operators, and the adaptive strategies employed. This study contributes to filling this gap through an ethnobotanical assessment. The objectives were to document plant species diversity maintained by nursery growers, identify economic, social, and environmental sustainability constraints, and examine adaptive strategies. A mixed-methods design was employed, involving structured questionnaires, semi-structured interviews, and expert consultations across ten nurseries and 100 stakeholders in five tehsils of Bahawalnagar (Bahawalnagar, Chistian, Haroonabad, Fort Abbas, and Minchinabad). Plant species identification was performed using AI-assisted tools (Google Lens, PictureThis) and validated by taxonomic experts. Relative Frequency of Citation (RFC) was used to assess species prominence, while thematic analysis guided interpretation of sustainability challenges and coping strategies. Surveyed nurseries exhibited substantial species diversity, including medicinal, ornamental, fruit, and vegetable plants. Dominant species belonged to Asphodelaceae, Lamiaceae, Rutaceae, Crassulaceae, Rosaceae, Myrtaceae, and Meliaceae families. *Aloe barbadensis* Miller (aloe vera) and *Mentha arvensis*/M. *piperita* (mint) displayed the highest prominence (RFC = 0.20), reflecting strong consumer demand. Key constraints included limited financial capital, labour shortages, low-quality planting materials, pest and disease pressures, climate-related stresses, and market competition, mapped onto economic, social, and environmental pillars of sustainability. Adaptive strategies included budgeting, organic pest management, recycling of resources, and informal cooperation networks. These findings highlight both the ecological richness and structural vulnerabilities of the nursery sector. While growers demonstrate adaptive capacity, sustainability remains constrained without institutional, financial, and technical support. Targeted interventions in capacity building, climate-resilient nursery practices, and supply-chain strengthening are essential to enhance long-term viability.

## Ecological Assessment of Plant Communities and Soil Properties of Botanic Garden in Bahawalnagar Campus of The Islamia University, Bahawalpur, Pakistan

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Botanic gardens play a crucial role in plant species conservation, education, and research, while contributing to local economies through tourism and educational programs. The Islamia University Bahawalpur (IUB) Bahawalnagar Campus features a botanical garden, yet limited information exists

on its plant community composition and soil characteristics. This study identified plant species and families present in the campus botanic garden and assessed soil properties. Ten soil samples (0–10 cm depth) were collected across two plots. Visual soil evaluation and destructive analyses were employed to characterize the soils. Dominant plant community types were identified using Google Lens and validated through expert consultation. Results revealed light brown, sandy loam soils with uniform texture and weakly to moderately pedaled structure throughout the sampled depth. Plant communities included species from Myrtaceae (6), Moraceae (5), Fabaceae (1), Apocynaceae (3), Rosaceae (24), Cupressaceae (8), Combretaceae (1), Euphorbiaceae (3), Rubiaceae (1), Asparagaceae (1), and Rutaceae (1). Most species had medicinal uses. Recommendations include cultivating more ornamental plants, expanding the garden area, developing standardized assessment manuals, and providing students training in visual and research-based plant community evaluation to enhance engagement with local industry.

## Sustainable Upcycling of Marine Plastic Waste for the Development of A Value-Added Product for Electric Vehicles

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Global plastic production has reached alarming levels, exceeding 300 million tonnes annually. Microplastics accumulate in soil, impair soil properties, microbiota, and plant growth, and pose risks to human health. The dual challenge of marine plastic pollution and sustainable transport requires innovative, circular economy solutions. This study developed a sustainable composite material from upcycled marine plastic waste for non-structural electric vehicle components. Bio-based reinforcements and compatibilizers enhanced mechanical strength, durability, and environmental sustainability. The resulting material is lightweight, strong, and suitable for EV parts, while reducing ocean plastic pollution and fossil resource dependency. The study provides a foundation for converting a pervasive pollutant into a valuable resource, advancing sustainable manufacturing in electric mobility.

## Human Hair-Derived Liquid Nitrogen Fertilizer for Improved Crop Nutrition

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Sustainable nitrogen management is a critical agricultural challenge due to soil nitrogen deficiency, rising fertilizer costs, and environmental impacts of synthetic N inputs. Human hair, rich in keratin and containing up to 17% nitrogen, represents an underutilized bio-waste. This study developed a human hair-derived liquid nitrogen fertilizer via alkaline hydrolysis and optimized extraction using

temperature, reaction time, and alkali concentration. Soil fertility and maize growth were assessed under a completely randomized pot experiment with control, urea, and three fertilizer rates. Hair-derived fertilizer significantly improved soil nitrate availability, cation exchange capacity, and maize growth, achieving 5–10% higher growth and biomass than conventional urea. This demonstrates a circular, low-input, and climate-resilient alternative to synthetic nitrogen fertilizers.

## Comparative Effects of Soil and Foliar Applied ZnO and FeO Nanoparticles on Yield and Nutrients Acquisition in Wheat

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Zinc (Zn) and iron (Fe) deficiencies in human diets are major contributors to malnutrition, particularly in developing countries. Wheat is a staple crop providing more than 50% of daily caloric intake in many regions; therefore, enhancing micronutrient concentrations in wheat grains is essential to combat hidden hunger. Agronomic biofortification is an effective strategy to increase Zn and Fe levels in edible plant parts. Recently, nano-fertilizers have emerged as a promising innovation due to their enhanced nutrient use efficiency, reduced application rates, minimized environmental impact, and sustained crop productivity. In this study, ZnO and FeO nanoparticles were synthesized using the co-precipitation method. The synthesized nanoparticles were calcined and characterized using UV–Vis spectroscopy and dynamic light scattering (DLS). A field experiment was conducted at the experimental farm of the Nuclear Institute of Agriculture (NIA), Tandojam, to evaluate the effects of soil and foliar application of ZnO and FeO nanoparticles on wheat growth and nutrient enrichment. The experiment was arranged in a randomized complete block design with three replications and six treatments: T1 = control; T2 = NPK (150–90–60 kg ha<sup>-1</sup>); T3 = NPK + foliar spray (150 ppm Zn + 50 ppm Fe); T4 = NPK + soil-applied Zn (3 kg ha<sup>-1</sup>) + Fe (1.5 kg ha<sup>-1</sup>); T5 = half recommended soil dose + half foliar dose of Zn and Fe; and T6 = NPK + ZnSO<sub>4</sub> (7.5 kg ha<sup>-1</sup>) + FeSO<sub>4</sub> (3 kg ha<sup>-1</sup>). Results indicated that the balanced application of ZnO and FeO nanoparticles through soil and foliar methods significantly improved wheat growth, yield, and micronutrient concentrations in grains. Treatment T5 produced the highest number of spikelets (21), tillers (212 m<sup>-2</sup>), 1000-grain weight (53 g), grain yield (6211 kg ha<sup>-1</sup>), and Zn and Fe concentrations in grain and straw. In contrast, the control treatment recorded the lowest values. Characterization results showed characteristic surface plasmon resonance peaks at 372 nm for ZnO and 190 nm for FeO nanoparticles. Particle size analysis using DLS indicated particle sizes ranging from 30 to 62 nm. The findings demonstrate that nano-enabled fertilization can significantly enhance wheat productivity and grain micronutrient density, offering a promising approach for sustainable biofortification.

## Optimizing Rice Straw Incorporation with Decomposers to Enhance Soil C/N Balance and Wheat Growth: A Growth Room Study

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Rice straw management after harvest has become a major challenge for farmers. To evaluate the effects of rice straw incorporation with microbial decomposers on wheat growth, a growth room experiment was conducted at the Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad. The study investigated different ratios of rice straw combined with microbial decomposers to determine their influence on straw decomposition, soil physicochemical properties, nutrient release, and wheat growth. The results indicated that the application of decomposers significantly accelerated the decomposition process by reducing the carbon-to-nitrogen (C/N) ratio compared to the control treatment. Enhanced decomposition improved nutrient mineralization in soil, which subsequently promoted wheat growth and development. The findings suggest that the incorporation of microbial decomposers with rice straw is an effective strategy for improving straw decomposition, enhancing soil fertility, and increasing wheat productivity.

## Water-Saving Agriculture: Hydrogel-Driven Moisture Conservation Strategy for Resilient Millet Yield

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Water scarcity is a major constraint to crop production in rainfed agriculture, particularly in sandy-dominated soils of the Pothwar region. Hydrogels are water-absorbing polymers capable of retaining large quantities of water, thereby reducing deep percolation losses and improving soil moisture availability. A three-year field study (2020–2022) was conducted at a farmer’s field in Sohawa, Jhelum, to evaluate the effects of hydrogel application on soil moisture conservation and pearl millet productivity. The experiment was arranged in a randomized complete block design with different hydrogel application rates. The soil was classified as sandy loam with pH 7.9, EC 0.82 dS m<sup>-1</sup>, organic matter 0.81%, available phosphorus 6.05 mg kg<sup>-1</sup>, and available potassium 106 mg kg<sup>-1</sup>. Seasonal rainfall during the study period was 604 mm (2020), 527 mm (2021), and 632 mm (2022). Hydrogel application significantly increased soil moisture content compared to the control. The highest moisture levels were recorded with 10 kg ha<sup>-1</sup> hydrogel (11.2%, 11.4%, and 11.8% during 2020, 2021, and 2022, respectively), whereas the control plots recorded moisture levels of 7.5%, 7.9%, and 7.7%. Grain yield and biological yield were significantly improved by hydrogel application. The highest grain yield (1167 kg ha<sup>-1</sup>) and biological yield (5.63 t ha<sup>-1</sup>) were obtained with 10 kg ha<sup>-1</sup> hydrogel in 2020. Similar trends were observed in 2021 and 2022, although slightly lower yields were recorded due to

rainfall variability. Notably, hydrogel applied at 7.5 kg ha<sup>-1</sup> produced yields statistically comparable to the highest rate, indicating high efficiency at a reduced application level. The results suggest that hydrogel application at 7.5 kg ha<sup>-1</sup> represents a cost-effective and climate-resilient strategy for improving millet productivity under rainfed conditions.

## Graphene Oxide-Mediated Enhancement of Compost Efficacy in Promoting Maize (*Zea mays* L.) Growth and Biomass Yield

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Graphene oxide (GO), a derivative of graphene, has recently gained attention for its potential applications in agriculture. Although both compost and graphene oxide have individually demonstrated positive effects on plant growth, their combined impact on crop productivity remains largely unexplored. This study evaluated the synergistic effects of compost and graphene oxide on the growth and biomass yield of maize (*Zea mays* L.). Treatments included compost applied at three levels (0, 0.5%, and 1.0%) combined with GO concentrations of 0, 10, and 50 mg L<sup>-1</sup>. The experiment consisted of nine treatments, including individual and combined applications of compost and GO. Results showed that both compost and GO independently improved plant growth parameters. Compost application increased root length from 22 to 26 cm, root fresh weight from 0.19 to 0.27 g, and leaf number from 3.6 to 4.3. Graphene oxide applied individually further enhanced root elongation (29–32 cm), biomass accumulation (0.23–0.26 g), and leaf production (4.6–4.7). The greatest improvements were observed with the combined treatment of 0.5% compost and 10 mg L<sup>-1</sup> GO, which produced the highest root length (46 cm), root fresh weight (0.66 g), and leaf number (6.0). These results indicate a strong synergistic interaction between compost and graphene oxide in promoting maize growth. The study demonstrates that integrating organic amendments with nanomaterials can significantly enhance crop productivity and represents a promising strategy for sustainable agricultural development.

## Zinc Nutrition Optimization for Improving Growth Yield, and Grain Quality Wheat (*Triticum aestivum* L.)

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Wheat (*Triticum aestivum* L.) a member of Poaceae family a major source of nutrients and energy. It occupies a prominent position in the staple foods. It can provide 70% of daily calories and 20% of global protein consumption for each person. Zinc is needed for the synthesis of DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), as well as for the stabilization of cell membranes and ribosomes and defense against free radicals. 50% of the soil used to grow wheat yields harvests with low levels of

bioavailable zinc or crops lacking zinc. According to reports, the fifth most common cause of sickness and mortality in underdeveloped nations is zinc deficiency in humans. To achieve this goal a comprehensive study is designed to optimize the different levels of Zn application for improving growth, yield and grain quality characteristics of wheat on alkaline calcareous soil. Experimental plan will be comprised seven treatments including control (no Zn application), 20, 40, 60, 80, 100 and 120 mg Zn kg<sup>-1</sup> soil. Each treatment will be replicated for five times. Zinc will be applied in the form of zinc sulfate (ZnSO<sub>4</sub>·7H<sub>2</sub>O). Experiment will be conducted according to “Randomized completely blocked design” (RBCD). Plant growth, physiological and yield contributing characteristics will be recorded. Plant samples will be analyzed for Zn concentration. After harvesting, wheat grains will also be analyzed for different quality parameters such as Zn concentration. Pre-sowing and post-harvest soil analysis will be done for Zn concentration and other physico-chemical characteristics.

## Spatial Distribution and Multi-Matrix Assessment of Heavy Metal Deposition Around Brick Kilns in Kallar Syedan, Rawalpindi District, Pakistan

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Brick kiln operations represent a significant source of atmospheric pollution in many developing countries. These activities release potentially toxic heavy metals into the atmosphere, which subsequently deposit into surrounding environmental compartments. In Pakistan, the rapid expansion of brick kilns in peri-urban areas such as Kallar Syedan in Rawalpindi District has intensified environmental concerns. However, existing research has largely focused on single environmental matrices or limited sampling sites, resulting in an incomplete understanding of spatial contamination patterns and multi-pathway heavy metal dispersion. This study aims to assess the spatial distribution and accumulation of selected potentially toxic heavy metals around brick kilns in Kallar Syedan using a multi-matrix environmental approach. The research will evaluate heavy metal concentrations in soil, vegetation, and deposited dust samples collected along defined distance gradients from kiln sources to identify contamination gradients and potential pollution hotspots. Systematic field sampling will be conducted, followed by laboratory analysis using standard analytical techniques. Spatial analysis tools will be applied to map deposition patterns and evaluate the influence of kiln proximity on surrounding environmental compartments. The study is expected to generate baseline spatial contamination data and provide an integrated assessment framework to support environmental monitoring, regulatory decision-making, and pollution mitigation strategies in brick kiln-affected regions of Pakistan.

## Photocatalytic Degradation of brilliant Blue Dye from Textile Wastewater using Zinc Oxide

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The textile industry generates large volumes of wastewater containing toxic and non-biodegradable synthetic organic dyes, posing serious environmental challenges. The discharge of untreated dye-containing effluents into water bodies has detrimental effects on aquatic ecosystems and can pose carcinogenic risks to human health. Reactive dyes, particularly azo dyes, account for nearly 50% of global dye production and represent a significant environmental hazard due to their persistence and toxicity. During textile manufacturing, approximately 11–15% of dyes are discharged into wastewater, leading to elevated chemical oxygen demand (COD) and biological oxygen demand (BOD) levels, which contribute to eutrophication in aquatic environments. Conventional treatment methods for dye removal, including incineration, biological treatment, and physical processes, often suffer from limitations such as high operational costs, long treatment times, and the generation of secondary pollutants, including volatile organic compounds. Therefore, advanced treatment technologies are required to effectively degrade persistent dye pollutants. Advanced Oxidation Processes (AOPs) have emerged as highly efficient techniques for the degradation of recalcitrant organic compounds in wastewater. Among these methods, photocatalysis has gained considerable attention due to its ability to degrade soluble dyes that cannot be removed by traditional treatment methods. Photocatalytic processes utilize a light source and semiconductor catalysts to accelerate the degradation of organic contaminants. In this study, zinc oxide (ZnO) was employed as a photocatalyst for the degradation of Brilliant Blue dye from wastewater. ZnO nanoparticles were synthesized using the sol–gel method and activated under sunlight to enhance photocatalytic activity. The proposed method is expected to achieve approximately 70–80% degradation of Brilliant Blue dye, demonstrating the potential of ZnO-based photocatalysis as an effective and environmentally sustainable approach for textile wastewater treatment.

## Development and Utilization of Urea Doped Paper Mulberry (*Broussonetia Papyrifera*) Bioadsorbent for Heavy Metal Removal from Waste Water

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Heavy metal contamination of water resources represents a significant environmental and public health challenge, particularly in developing countries such as Pakistan. Rapid industrialization, urban expansion, and agricultural runoff have contributed to elevated concentrations of toxic metals such as lead (Pb), cadmium (Cd), and chromium (Cr) in surface and groundwater systems. Although conventional treatment technologies are capable of removing heavy metals, they are often expensive and generate secondary waste, highlighting the need for sustainable and low-cost alternatives. This study investigates the development of a novel nitrogen-enriched bioadsorbent derived from Paper Mulberry (*Broussonetia papyrifera*) leaves for the removal of heavy metals from wastewater. Fresh leaves were collected, washed, dried, and ground into uniform particles. The biomass was subsequently impregnated with urea and chemically activated using sodium hydroxide to enhance nitrogen content and surface functional groups. Batch adsorption experiments were conducted to optimize key operational parameters, including pH, contact time, adsorbent dosage, and temperature.

The prepared bioadsorbent was characterized using ultraviolet–visible spectroscopy, scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR) to examine surface morphology and functional groups responsible for metal binding. Heavy metal removal efficiency was quantified using inductively coupled plasma optical emission spectroscopy (ICP-OES). Adsorption kinetics were evaluated using pseudo-second-order models to determine the adsorption mechanism. The reusability and stability of the bioadsorbent were assessed through multiple adsorption–desorption cycles using hydrochloric acid or EDTA as regeneration agents. The results are expected to demonstrate that the nitrogen-enriched Paper Mulberry bioadsorbent is a cost-effective, environmentally friendly, and efficient material for heavy metal removal from wastewater. This research provides a foundation for large-scale applications of forest biomass-based bioadsorbents as sustainable technologies for industrial wastewater treatment and environmental remediation.

## Climate-Driven Changes in Leaf Traits and Phenology of *Acacia Nilotica* in Pakistan: Evidence from Herbarium Specimens

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Climate-driven shifts in plant phenology and functional traits are widely documented; however, empirical evidence from arid and semi-arid regions of South Asia remains limited, particularly for long-lived woody species. In Pakistan, most phenological studies rely on short-term field observations, restricting the ability to detect long-term ecological trends associated with climate change. This study proposes a herbarium-based approach to investigate historical changes in leaf functional traits and phenology of *Acacia nilotica*, an ecologically and economically important native tree species widely distributed across Pakistan. Digitized and physical herbarium specimens preserved at the Pakistan Museum of Natural History and affiliated collections will be analyzed to quantify temporal changes in leaf morphological traits, including leaf size, shape, and proxies for specific leaf area, as well as leaf margin characteristics. Phenological information such as flowering time and leaf-out timing will also be extracted from specimen labels and images. These traits and phenological data will be integrated with historical climate records, including temperature and precipitation data, to evaluate climate–trait and climate–phenology relationships over multiple decades. Statistical analyses will be conducted using regression and mixed-effects modeling frameworks to account for temporal autocorrelation, spatial clustering, and uneven sampling intensity. Established bias-correction techniques will be applied to minimize potential limitations associated with herbarium data, including collection bias and incomplete metadata. By integrating trait-based and phenological responses within a single species framework, this study addresses a key gap in regional climate–plant ecology by examining the linkage between structural leaf traits and seasonal phenological shifts under long-term climate variability. The findings are expected to provide valuable historical baselines for trait-based ecological research in Pakistan and improve understanding of woody plant responses to climate change in understudied dryland ecosystems.

# Microbial Degaradtion of Microplastics in Surface Water of Rawalpindi

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Plastics are vital to nearly every economic sector worldwide due to their widespread use in consumer goods, construction, agriculture, and healthcare. However, their excessive use poses a serious threat to the ecosystem and human health. This study reviews the relationship between microorganisms and plastic polymers, focusing on biodegradation mechanisms. It covers types of plastics based on thermal and biodegradable properties, degradation and biodegradation processes, types of degradable plastics, characterization of biodegradation, and factors influencing these processes. The accumulation of plastics on land and in marine environments has increased interest in biodegradation strategies. Many microorganisms have developed survival mechanisms that enable them to utilize and degrade plastic polymers. The efficiency of biodegradation depends on polymer type, environmental conditions, and microbial activity. Microorganisms possess significant potential for the biodegradation and bioremediation of plastic waste. Understanding microbe–polymer interactions can support the development of sustainable and environmentally friendly approaches for managing plastic pollution.

# Effect of Seed Priming Techniques on Growth and Yield of Wheat under Rainfed Conditions of Pothohar

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Seed priming is a simple, low-cost, and effective technique for improving crop establishment, early growth, and overall productivity, particularly under rainfed conditions where moisture stress and erratic rainfall limit crop performance. A comprehensive field experiment was conducted at the Soil and Water Conservation Research Institute (SAWCRI), Chakwal, during 2020–2024 to evaluate the effects of different seed priming agents on the productivity of spring wheat (*Triticum aestivum* L.). The experiment included six treatments: T1 (control, unprimed seed), T2 (water soaking), T3 (zinc soaking), T4 (phosphorus soaking), T5 (urea soaking), and T6 (ascorbic acid soaking), arranged in a randomized complete block design (RCBD) with three replications. Data were recorded for plant height, number of tillers per plant, spike length, number of spikelets per spike, 1000-grain weight, and grain yield. Seed priming significantly improved growth and yield compared with the control. Ascorbic acid priming produced the highest number of tillers (179 plant<sup>-1</sup>), maximum spikelets per spike (20), and highest grain yield (3341 kg ha<sup>-1</sup>). Urea priming resulted in the maximum 1000-grain weight (41.1 g), while phosphorus priming improved plant height and spike development. The control treatment recorded the lowest performance, with a grain yield of 2964 kg ha<sup>-1</sup>. Seed priming, particularly with ascorbic acid, urea, and phosphorus, is an effective and practical strategy for enhancing wheat

productivity under rainfed conditions. Its adoption can improve crop establishment, increase yield stability, and support sustainable agriculture in semi-arid regions.

## Green Manuring for Sustainable Wheat Production under Semi-Arid Rainfed Conditions of Pothwar Region, Pakistan

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Green manuring is a sustainable soil fertility management practice that improves soil health, nutrient availability, and crop productivity in rainfed agricultural systems. In semi-arid regions such as Chakwal and Talagang districts of Pakistan, wheat production is constrained by low soil organic matter, nutrient depletion, and erratic rainfall. To demonstrate the effectiveness of green manuring under varying rainfall regimes, a field experiment was conducted under the Fertilizer Right Pakistan Project during 2024–2025 in rainfed areas of the Pothwar region. The experiment was established at four sites, including two low-rainfall sites in Talagang District and two medium-rainfall sites in Chakwal District. Cowpea (*Vigna unguiculata* L.) was used as the green manure crop in the low-rainfall zone, while guar (*Cyamopsis tetragonoloba* L.) was used in the medium-rainfall zone. Four treatments were evaluated at each site: T1, fallow–wheat under farmer practice (F–FP); T2, fallow–wheat with recommended fertilizer dose (F–RF); T3, green manure–wheat under farmer practice (GM–FP); and T4, green manure–wheat with recommended fertilizer dose (GM–RF). The recommended fertilizer (N:P:K) dose was: 32:23:12 kg acre<sup>-1</sup> for the low-rainfall zone and 40:28:12 kg acre<sup>-1</sup> for the medium-rainfall zone. Green manure crops were incorporated into the soil at the flowering stage prior to wheat sowing. The results clearly demonstrated the advantages of green manuring over conventional fallow-based systems. The lowest wheat grain yield (1366 kg ha<sup>-1</sup>) was recorded in T1 (F–FP), while the application of recommended fertilizer in fallow–wheat (T2: F–RF) increased yield to 1516 kg ha<sup>-1</sup>. Significant yield improvements were observed under green manuring treatments. Wheat yield under GM–FP (T3) reached 1936 kg ha<sup>-1</sup>, representing a 42% increase over fallow–wheat under farmer practice. The highest wheat grain yield (2244 kg ha<sup>-1</sup>) was obtained in GM–RF (T4), which was 64% higher than T1 and 48.0% higher than T2. The superior performance of green manure-based treatments was attributed to improved soil organic matter, enhanced biological nitrogen fixation, improved soil structure, and increased soil moisture retention. The demonstration-led and farmer-participatory approach adopted under the Fertilizer Right Pakistan Project enhanced farmer awareness and adoption of green manuring as a practical alternative to prolonged fallow periods. The study concludes that integrating green manuring with site-specific fertilizer management is a cost-effective, climate-resilient, and sustainable strategy for improving wheat productivity and yield stability in rainfed agroecosystems of the Pothwar region under changing climatic conditions.

## Screening for Resilience: Hydroponic Selection of Waterlogging-Tolerant Cotton

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Cotton is a major contributor to Pakistan's economy; however, its productivity is increasingly threatened by waterlogging-induced root hypoxia, which disrupts plant growth, gas exchange, ion homeostasis, and redox balance. This study aimed to evaluate eleven indigenous cotton cultivars for waterlogging tolerance using morphological, physiological, and biochemical traits under a controlled hydroponic system. The experiment was conducted in a lathhouse using three aeration treatments: 24 h day<sup>-1</sup> (T1, control), 12 h day<sup>-1</sup> (T2, moderate stress), and 6 h day<sup>-1</sup> (T3, high stress). After 50 days of growth, data on shoot and root biomass, leaf chlorophyll, stomatal conductance, net photosynthetic rate, transpiration rate, root porosity, root anatomy, ion accumulation, and antioxidant status were collected. The data were statistically analyzed, and cultivars were classified using cluster analysis. Significant variation was observed in morphological traits, while aeration duration primarily affected root development and biomass. The variety CYTO-124 maintained the highest shoot length across treatments, whereas Desi Cotton exhibited the greatest root length (up to 64.5 cm) under moderate stress, while CIM-707 consistently showed poor growth. Significant variation in leaf chlorophyll was observed among cultivars, indicating a genotype × treatment interaction. Stomatal conductance, transpiration, and root porosity were mainly influenced by treatment, with reduced conductance under hypoxia; however, CIM-554 maintained net photosynthetic rate under low oxygen conditions. Waterlogging induced the formation of cortical air spaces (aerenchyma), which was identified as a key tolerance mechanism in CYTO-124, Desi Cotton, and CIM-707. Aeration treatments significantly affected Na<sup>+</sup>, SOD, POD, and MDA concentrations. Tolerant responses were associated with better K<sup>+</sup> retention, lower Na<sup>+</sup> accumulation, and stronger antioxidant activity in FH Tri-Star, FH-142, MNH-886, and FH-333, whereas elevated MDA levels under hypoxia caused oxidative damage in CIM-707, FH Tri-Star, and Desi Cotton. Cluster analysis grouped Desi Cotton, FH-142, and CIM-707 as tolerant cultivars, indicating that tolerance ranking depends on the traits considered. Overall, increased root porosity and maintenance of K<sup>+</sup>/Na<sup>+</sup> balance emerged as key indicators for screening waterlogging tolerance and provide targets for breeding resilient cotton genotypes.

## Escalating Climate Extremes and Their Impacts on Agriculture in Pakistan: Lessons from Heat Waves, Droughts, Floods, and Pathways to Climate-Resilient Farming

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Pakistan is among the most climate-vulnerable countries globally and is experiencing a rapid increase in the frequency, intensity, and spatial extent of extreme climate events. A severe heatwave began early in March and persisted through June, with maximum temperatures reaching 49.5 °C in Nawabshah. This event coincided with intense meteorological and agricultural drought, with pre-monsoon rainfall reduced to 25–35% of long-term averages across Sindh, Balochistan, southern Punjab, and arid regions of Khyber Pakhtunkhwa. The resulting soil moisture depletion and evapotranspiration stress led to widespread crop failure in wheat, vegetables, and fodder crops, while acute water scarcity in the Cholistan Desert triggered livestock mortality and pastoral migration. These conditions were followed by catastrophic flooding in 2022, driven by accelerated glacier melt in the Hindu Kush–Karakoram–Himalayan region and unusually intense monsoon rainfall, which submerged nearly one-third of the country. Sindh experienced record rainfall, with Padidan receiving 1,764 mm during July–August 2022, leading to crop losses of nearly 50% and affecting approximately 33 million people. Climate extremes intensified again in 2025, with short-duration extreme rainfall events, including a 423 mm cloudburst in Chakwal within 24 hours and Punjab’s highest recorded rainfall (557 mm in Gujrat on 3 September 2025). These events caused flash floods, landslides, and infrastructure damage, resulting in 111 fatalities, including 53 children. Agricultural losses were severe, with over 2.2 million hectares of cropland damaged and economic losses exceeding US\$1.23 billion. Punjab alone lost approximately 60% of rice, 35% of cotton, and 30% of sugarcane production, while livestock losses exceeded 22,800 animals. Flood-induced soil erosion, sedimentation, nutrient leaching, and secondary salinization further degraded soil health. Future climate projections indicate increased warming, more frequent heat extremes, and greater variability in monsoon rainfall, posing serious threats to Pakistan’s agriculture-based economy. Addressing these risks requires a transition toward climate-resilient agriculture supported by science-based policies. Key strategies include adopting drought- and heat-tolerant crop varieties, diversifying cropping systems, adjusting sowing calendars, and improving water management through efficient irrigation systems, rainwater harvesting, and soil conservation practices. Integrating these approaches offers a pathway to enhance resilience, safeguard food security, and protect rural livelihoods under a changing climate.

## Hydrogels as an Innovative Moisture Conservation Technology for Sustainable Rainfed Agriculture in The Potohar Plateau of Pakistan

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Climate change poses a major threat to agricultural sustainability, particularly in semi-arid and rainfed regions such as the Potohar Plateau of Pakistan, where drought, erratic rainfall, high evapotranspiration, and poor soil structure limit productivity. Hydrogels, or superabsorbent polymers (SAPs), have emerged as a promising solution for improving soil moisture retention and enhancing crop resilience. This review examines the role of hydrogels in sustainable agriculture, focusing on their application under rainfed conditions. It discusses hydrogel synthesis methods, classification, and

agricultural applications, including soil amendment, seed coating, and root-zone placement. Reported application rates typically range from 0.1–5% (w/w) in soil or 2.5–5.0 kg ha<sup>-1</sup>, depending on crop type, soil texture, and climatic conditions. Evidence from field studies conducted in arid and semi-arid regions indicates that hydrogel application can enhance soil water holding capacity by 20–50%, reduce irrigation frequency and improve nutrient-use efficiency. Yield improvements of 20–30% have been reported in major crops such as wheat, maize, lentils, and vegetables, particularly under water-limited conditions. In addition to yield enhancement, hydrogels contribute to improved root development, reduced soil compaction, and greater tolerance to drought stress. Despite these benefits, challenges associated with hydrogel adoption include high initial costs, limited farmer awareness, and environmental concerns related to the persistence of synthetic polymers in soil. Recent advancements in biodegradable hydrogels derived from natural polymers such as starch, cellulose, and chitosan offer environmentally safer alternatives with comparable water-retention performance. The integration of hydrogels with complementary practices such as mulching, conservation tillage, and targeted subsidy programs is recommended to maximize their effectiveness and adoption in the Potohar region. In conclusion, hydrogels offer a viable and innovative solution for moisture conservation in rainfed agriculture. Their judicious use can significantly reduce irrigation requirements, stabilize crop yields, and enhance the economic sustainability of farming systems in the Potohar Plateau. Future research should focus on long-term field evaluations, cost–benefit analyses, and the development of locally produced biodegradable hydrogels tailored to regional soil and climatic conditions.

## Sustainable Bio-Composite Panels for Green Buildings

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The development of sustainable construction material is critical because it help to reduce the environmental footprint of the building sector while promoting the utilization of renewable and cost-effective resources. This study focuses on the development of bio-composite panels using agriculture residue, such as legumes and cereal hulls, as an eco-friendly alternative to traditional construction material. These agriculture residues are abundantly present and often underutilized which make them best raw material for sustainable green building applications. The work emphasizes on the early-stage processing and treatment of raw material to enhance their properties for composite formulation. The collected residues are initially cleaned, mechanically processed and crushed to achieve uniformity. The fibers are then subjected to alkaline chemical treatment using 0.4 % sodium hydroxide to modify the fibers surface. This treatment removes non-cellulosic components and surface impurities and increases the roughness and potential for fiber-binder interaction. Fibers are then thoroughly washed with distilled water and neutralized using 0.5% acetic acid to restore the neutral pH level and prevents further chemical degradation. After neutralization, fibers are dried in oven at 60 °C to remove the excess moisture content for composite formulation. For developing panels, a total batch mass of 1kg (1000g) is selected and divided into raw materials, binders and additives according to the selected formulation design. At the current stage of research, raw material processing, chemical treatment, neutralization and drying have been successfully completed. The next phase involves composite formulation and fabrication of bio-composite panels using treated fibers, binders and additives. After that the panels will be conditioned, optimized and evaluated for mechanical and physical properties to assess their suitability for building applications. The optimized results will be presented in poster

form. This study demonstrates the feasibility of using legumes and cereal hulls as sustainable and eco-friendly raw materials for bio-composite panel development.

## From Stress to Stability: Integrating Soil Health Restoration and Resource Conservation for Climate-Resilient Crop Production in Semi-Arid Regions of Pakistan

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Climate change–induced stresses, including rising temperatures, erratic rainfall, droughts, floods, and progressive soil degradation, pose a serious threat to sustainable crop production in semi-arid regions such as Pakistan. These stresses rarely operate independently; rather, their impacts are strongly mediated by soil health. Degraded soils with poor structure, low organic matter, and reduced water-holding capacity act as a “stress multiplier,” intensifying crop vulnerability and accelerating yield instability under rainfed farming systems. This study highlights the importance of integrating soil health restoration with resource conservation practices to build resilient agroecosystems capable of withstanding climatic variability. The work draws on field-based research and farmer-led demonstrations conducted by the Soil and Water Conservation Research Institute (SAWCRI), Chakwal, in the Pothwar region—an area characterized by highly variable rainfall, soil erosion, and moisture stress. A range of soil and water conservation interventions were evaluated, including in-situ moisture conservation techniques, erosion control structures, rainwater harvesting systems, green manuring, gypsum application for saline and sodic soil reclamation, and on-farm composting using livestock waste. These practices were implemented under real farm conditions to assess their impact on soil properties, moisture availability, and crop productivity. Results demonstrated that integrated soil health and resource conservation strategies significantly improved soil moisture retention, nutrient availability, and overall soil physical condition. Gypsum application effectively reduced the adverse effects of saline irrigation water, while composting enhanced soil organic matter and nutrient recycling. In-situ moisture conservation and erosion control measures minimized runoff losses and improved rainfall-use efficiency. Collectively, these interventions resulted in yield improvements of up to 20% under rainfed conditions compared to conventional farmer practices during seasons of moisture stress and rainfall irregularity. The local farmers were actively engaged in the implementation and evaluation of conservation measures, ensuring local relevance, practicality, and long-term sustainability. The study concludes that soil health restoration, when combined with effective water and resource conservation strategies, is essential for transforming agriculture from stress to stability in climate-vulnerable regions. The findings provide practical, low-cost, and climate-smart solutions for sustainable agricultural development under changing climatic conditions.

## Corruption Destroys Soil and Agriculture

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Corruption in Pakistan has severely affected the agricultural sector, undermining efforts to improve soil health, water management, and fertilizer use efficiency. Numerous projects aimed at agricultural development have been implemented; however, many have failed to deliver tangible benefits to farmers due to mismanagement and misuse of resources. While these projects often show success in reports and documentation, their practical impact on farming communities has been limited, leading to economic losses and reduced farmer confidence. The misallocation of research funds and lack of transparency have further weakened agricultural progress. As a result, farmers continue to struggle with declining soil fertility, low productivity, and limited access to effective technologies. Addressing corruption and ensuring accountability in agricultural programs is essential for achieving sustainable soil management, improving crop productivity, and enhancing food security. Strengthening governance and promoting transparency can help restore trust and support the development of a more resilient agricultural system in Pakistan.

## Enhancement of Anaerobic Digestion of Poultry Slaughtering Waste Through Metal- Modified Activated Carbon

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Poultry production generates a large amount of organic waste including blood, feathers, intestines, and other parts, which contain high amounts of lipids, proteins, moisture, and other biodegradable organic substances. The disposal and management of such materials require proper attention because these materials give off a bad smell, allow harmful bacteria to grow, and cause serious risks to public health and the ecosystem. Anaerobic digestion is considered as one of the best approaches towards sustainable waste management and renewable energy generation. However, its effectiveness can be reduced by some harmful compounds such as ammonia, volatile fatty acids, and hydrogen sulfide, which are produced during the hydrolysis of proteins, contribute to the reduction of methane yield, inhibit microbial growth, and affect overall process stability. Activated carbon derived from renewable sources like plant leaves, bark, and twigs can increase the anaerobic digestion process effectively by adsorbing inhibitory substances that are produced during the hydrolysis of proteins and providing attachment surfaces for bacteria. The metal-modified activated carbon provides a vast surface area for microbial colonies and helps in the generation of biofilms, which contribute to direct interspecies electron transfer and enhance the syntrophic relationship between methanogens and other bacteria. In this research, biogas was generated from the poultry slaughtering waste, which includes offal, feathers, and blood. To enhance process stability and digestion rate biomass based activated carbon

was used, which was synthesized from the biomass of paper mulberry (*Broussonetia papyrifera*) and thereafter it was modified by two metals, molybdenum and iron to enhance its adsorbent capacity and to improve its physical characteristics such as, porosity and surface area to make it effective for the adsorption of inhibitors produced during the aerobic digestion. The unmodified and modified activated carbon were added to different treatments at various dosages along with a control treatment in order to observe their effect on waste degradation and biogas production. During the experiments, it was observed that among all experimental conditions, the treatment containing metal-modified activated carbon of 3g/L produced higher biogas yield and methane as compared to control and treatments with unmodified activated carbon. Use of metal-modified activated carbon is a promising technique for anaerobic digestion and production of high-quality methane.

## Eco-friendly Rhamnolipids Biosurfactant Production from Potato Peels

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Biosurfactants, especially rhamnolipids, have gained attention as eco-friendly alternatives to synthetic surfactants due to their biodegradability and low toxicity. However, their industrial application is limited due to high production costs. In the present study, potato peel waste was explored as a renewable and low-cost carbon source for the production of rhamnolipids by native bacterial isolates. Fresh potato peels were collected from kitchen waste and potato frying outlets, oven-dried at 60 °C, and ground into powder for use as substrate. Soil samples were collected from oil-contaminated sites in the vicinity of Attock Oil Refinery, Rawalpindi, for bacterial isolation. A total of 30–50 morphologically distinct bacterial colonies were isolated and screened for biosurfactant production using the emulsification index test. Among these, three efficient isolates were selected for further fermentation studies. Rhamnolipid production was carried out in 100 mL Mineral salt medium supplemented with 20 g/L potato peel hydrolysate in 250 mL Erlenmeyer flasks. Fermentation was conducted at 37 °C for up to 120 h using a 4% inoculum. Biosurfactants were recovered through acid precipitation followed by solvent extraction. Surface activity, emulsification index, and critical micelle concentration (CMC) were determined to characterize rhamnolipid production. In addition, stability of the produced rhamnolipids was evaluated under varying pH, salinity, and temperature conditions. The results obtained from this study, including rhamnolipid yield, surface activity, and stability characteristics demonstrates the potential of potato peel waste as an economical substrate for rhamnolipid production and highlights the role of indigenous bacteria in developing cost-effective and environmentally friendly biosurfactants.

## Bioremediation of Buprofezin in Potato Vegetated Soil by Augmentation of Bacterial Inocula

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Buprofezin is a thiadiazinone-based insect growth regulator widely used to control sucking insect pests in agriculture. Despite its effectiveness in integrated pest control, the ecological (by disrupting the soil structure) and toxicological (persistence and bioaccumulation in crops) issues are the rising concern. Buprofezin resistant consortium was developed through enrichment studies, comprising of *Chelatococcus caeni*, *Rhodococcus rhodochrous*, *Pseudomonas indologydans*, and *Acinetobacter junii*. Initial pot scale studies were performed in 5 kg soil pots, with vegetation of *Solanum tuberosum*, spiked with 2mg kg<sup>-1</sup> of buprofezin. The process of biodegradation was augmented by adding consortium. Further, the consortium was immobilized on biochar to evaluate the effect of carrier materials on the process of biodegradation, effect of molasses as nutrient and compost as biofertilizer was also determined. Quantification of buprofezin was done by High-Performance Liquid Chromatography. The Results revealed that treatment containing combination of biochar (as carrier for consortium), molasses and compost, showed up to 90% degradation of buprofezin as compared to other treatments and control. While enhanced plant growth was observed in pots augmented with consortium either alone or immobilized on biochar. It is concluded that biochar provided a stable surface for microbial colonization to speed up the process of biodegradation, while molasses and compost acted as organic nutrient sources, stimulating bacterial growth and metabolic processes. Kinetic parameters revealed that buprofezin immobilization is highly proficient as indicated by significant increase in the rate of biodegradation and decrease in half-life of buprofezin.

## Indigenous Bacterial Cultures for Glyphosate Remediation and Sustainable Crop Production

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This study evaluated three indigenous bacterial cultures (BCs), isolated from glyphosate-contaminated soils of Punjab, Pakistan, for their ability to degrade glyphosate and improve mungbean growth under herbicide stress (600 and 700 mg kg<sup>-1</sup> soil). Severe glyphosate contamination caused substantial reductions in mungbean performance, with declines of up to 93.1% in growth, 84.2% in physiological attributes, 91.5% in nutrient uptake, and marked decreases in soil microbial biomass carbon (62.5%) and nitrogen (64.3%) compared with the uncontaminated control. Inoculation with all three bacterial cultures significantly mitigated glyphosate toxicity, enhanced plant growth, and promoted herbicide degradation, with the most pronounced effects observed at 600 mg kg<sup>-1</sup> glyphosate. Overall performance followed the order BC3 > BC1 > BC2. Among them, bacterial culture 3 consistently showed superior efficacy, improving mungbean growth by up to 80.7% and physiological performance by 66.7%, while reducing stress-related enzymatic activity by up to 36.4% relative to uninoculated contaminated controls. Notably, bacterial culture 3 achieved up to 78.6% glyphosate removal from soil and substantially limited its transfer into the food chain by reducing glyphosate accumulation in roots (68.4%), shoots (75.2%), and grains (76.7%). These findings demonstrate that the developed indigenous bacterial cultures, particularly BC3, represent promising microbial bioresources for sustainable crop production and effective glyphosate bioremediation, contributing directly to United

Nations Sustainable Development Goals related to zero hunger (SDG 2) and good health and well-being (SDG 3).

## Impact of Compost and Biochar on Maize (*Zea mays* L.) Crop under Saline Soil

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Soil salinity is one of the most significant factors that affect the production of maize (*Zea mays* L.) adversely, especially in those zones where excessive salinity levels lower the seed germination, plant growth, absorption of nutrients, and ultimate production. It is thus critical to develop sustainable management of soils to reduce salinity stress to enable maize to be produced sustainably. The experiment was done to determine the effectiveness of compost and biochar in reducing salinity stress in the salt-affected soil. The experiment had following six treatments: control (no amendment), compost (5%), biochar (5%), compost + biochar (1:1), compost + biochar (2:1), and compost + biochar (1:2). Maize performance was evaluated based on the level of germination rate, plant height, biomass output, and yield. The findings revealed that the amendment treatments enhanced the growth and yield of maize in comparison to the control. Compost-biochar mixture application revealed the better outcome compared to their individual applications, and the ratio of 1:1 compost- biochar produced the highest growth parameter and yield. Biochar and compost had a positive impact on plant performance in saline conditions through improvement of soil pH buffering and nutrient availability, soil structure and moisture retention, respectively. To sum up, the application of compost and biochar in combination displays the synergetic effect in alleviating the adverse effects of soil salinity on maize.

## Upcycling Sugarcane Filter Cake into Phosphorus-Enriched Liquid Fulvic Acid for Sustainable Phosphorus Management in Calcareous Soils

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Phosphorus (P) availability in calcareous soils is intrinsically low and is expected to decline further under changing climatic conditions due to enhanced P fixation and reduced nutrient-use efficiency. This study investigated the potential of fulvic acid extracted from pressmud (sugarcane filter cake), a sugar industry byproduct rich in organic carbon and organic acids, to enhance P availability in calcareous soils. Extracted fulvic acid (EFA) was chemically characterized and subsequently converted

to phosphorus-enriched liquid fulvic acid (PELFA) using rock phosphate (RP) and single super phosphate (SSP) as P sources. Phosphorus release dynamics were evaluated at 1%, 2%, and 4% PELFA concentrations during a two-month incubation study in calcareous soils collected from three agro-ecological locations of Sindh, Pakistan (Khairpur, Sakrand, and Badin). Pressmud had a pH of 7.25, EC of 1.11 dS m<sup>-1</sup>, and organic carbon content of 36%. The EFA contained 49.6% C, 4.75% H, and 2.45% N, with distinct functional groups confirming its chemically active organic nature. Application of PELFA significantly enhanced P release from both RP and SSP. Rock phosphate showed greater P release at later incubation stages, whereas SSP exhibited rapid initial P release, reflecting contrasting pH-mediated solubilization mechanisms. Increasing PELFA concentrations significantly increased AB-DTPA extractable P across all soil types, demonstrating a clear dose-dependent response. Overall, the results indicate that PELFA derived from sugarcane filter cake is an eco-friendly, climate-resilient, and sustainable approach for improving phosphorus availability in calcareous soils, contributing to enhanced soil resilience and sustainable agricultural production under changing climate scenarios.

## Evaluating the Effect of Vermicompost on Growth and Yield of Maize under Saline Conditions

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Salinity is a major environmental stress that limits agricultural productivity, particularly in arid and semi-arid regions. Poor irrigation practices, excessive use of agrochemicals, and climate change have exacerbated soil salinization worldwide. Maize, an important staple crop, is moderately sensitive to salinity stress. Vermicompost is widely used as an organic amendment for soil reclamation and fertility improvement. It enhances soil structure, increases nutrient availability, and improves crop productivity, while reducing dependence on synthetic fertilizers. This study investigated the effect of vermicompost combined with recommended fertilizer doses on the growth and yield of maize under saline conditions. A field experiment was conducted using a randomized complete block design (RCBD) with six treatments: T<sub>1</sub> (control), T<sub>2</sub> (100% recommended fertilizer dose, RDF), T<sub>3</sub> (vermicompost @ 2.5 t ha<sup>-1</sup>), T<sub>4</sub> (vermicompost @ 2 t ha<sup>-1</sup> + 25% RDF), T<sub>5</sub> (vermicompost @ 1.5 t ha<sup>-1</sup> + 50% RDF), and T<sub>6</sub> (vermicompost @ 1 t ha<sup>-1</sup> + 75% RDF), each with three replications. Results indicated that T<sub>6</sub> significantly improved plant growth and yield under saline conditions. Improvements were observed in plant height, leaf number, stem diameter, cob length, grains per cob, 1000-grain weight, and potassium (K<sup>+</sup>) concentration, while sodium (Na<sup>+</sup>) concentration in leaf tissues was reduced compared to the control. The study concludes that integrating vermicompost with inorganic fertilizers is an effective and sustainable approach for improving maize productivity under saline conditions.

## Evaluating the Potential of Various Potassium Fertilizers for Wheat (*Triticum aestivum* L.) Grown on Haplocambid Soil

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Potassium (K) is an essential macronutrient that plays a vital role in photosynthesis, water and nutrient transport, and plant tolerance to abiotic stresses. A field experiment was conducted on Typic sodic Haplocambid/Haplic Yermosols during the Rabi season of 2023–2024 to evaluate the comparative effects of POLY4, sulphate of potash (SOP), muriate of potash (MOP), and their blends on wheat (*Triticum aestivum* L.) production. A randomized complete block design (RCBD) was employed with three replications per treatment. Treatments included individual sources applied at 100% and combinations of two sources applied at 50% each (SOP, MOP, and POLY4). Results showed that POLY4, either alone or in combination with SOP or MOP, significantly improved growth parameters such as plant height, number of tillers, chlorophyll content, and leaf area index, as well as yield attributes including 100-grain weight, grain protein content (%), and nutrient uptake. The 100% POLY4 treatment produced the highest grain yield and K uptake efficiency, while the combined application of SOP + POLY4 demonstrated synergistic effects. Additionally, POLY4 improved K recovery efficiency and grain quality, with a cost–benefit ratio comparable to conventional practices. These findings suggest that POLY4, due to its multi-nutrient composition and slow-release characteristics, can serve as an effective alternative or supplement to traditional potassium fertilizers in sustainable wheat production systems. Overall, the application of POLY4, either alone or in combination with SOP, significantly improved plant growth and wheat grain yield on a sustainable basis.

## Mitigation of Lead Uptake in *Zea mays* L. through Soil Amendemnts with Elemental Sulfur and Bagasse-Derived Biochar

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Soils contaminated by discharges from lead-acid battery dismantling and recycling facilities may contain elevated levels of plant-available lead (Pb). Reducing the phytoavailability of Pb in such soils can help limit its uptake by food crops, thereby decreasing risks to human health and the environment. This pot experiment aimed to reduce plant-available Pb in contaminated soil using *Zea mays* (maize). The soil was amended with elemental sulfur (ES), bagasse biochar (BSBC), and their combination. The study examined how these treatments influenced Pb availability in soil and its uptake by maize. Results indicated that the combined BSBC + ES treatment was the most effective. Compared with the control, it reduced DTPA-extractable Pb and decreased Pb uptake in shoots, roots, and grains by up to 47%. Additionally, the treatment improved plant growth parameters such as height, leaf area, and pigment contents (chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids). Acidified biochar proved

effective in immobilizing Pb in soil. Therefore, the combined application of BSBC (2.5%) + ES (2.5%) is considered a reliable, cost-effective, and efficient method for stabilizing Pb in contaminated soils.

## Effects of Bentonite Application on Soil Moisture Conservation and Wheat Yield in Rainfed Sandy Loam Soils of Pothwar, Pakistan

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Feeding a growing global population amid escalating climate variability represents one of humanity's most pressing challenges, particularly in rainfed agricultural systems that constitute the majority of the world's croplands yet remain highly vulnerable to water scarcity. In South Asia's key food production regions, including Pakistan's Pothwar Plateau, climate change is manifested through increasingly erratic rainfall patterns and extended droughts punctuated by intense monsoon events, which severely test the limited water-holding capacity of the sandy loam soils that dominate these landscapes. These rainfed soils, characterized by rapid drainage, poor moisture retention, and critically low organic matter content, impose fundamental constraints on achieving both food security and climate resilience. Enhancing soil moisture retention in water-limited rainfed systems is therefore critical for climate-resilient food production. This three-year study (2022–2025), conducted in the sandy loam soils of Pothwar, Pakistan, evaluated the use of bentonite clay as a soil amendment to improve wheat productivity under rainfed conditions. Treatments consisted of bentonite applied at 0, 1.25, 1.875, and 2.5 t ha<sup>-1</sup>. Our findings show that bentonite application significantly alters soil–water relationships in sandy loam systems by creating micro-scale water reservoirs that capture rainfall during surplus periods and gradually release moisture during dry spells. Soil moisture content increased significantly with bentonite application, showing a 25% improvement at 2.5 t ha<sup>-1</sup> (4.31% compared with 3.45% in the control). This improved water retention translated directly into higher grain yields, with the highest application rate increasing yield by 12.7% (3962 vs. 3517 kg ha<sup>-1</sup>). These benefits were consistent across contrasting rainfall years—wet (720 mm), dry (540 mm), and normal (558 mm)—demonstrating strong climate resilience. Rainfall use efficiency improved by 12.1%, while economic analysis confirmed strong viability, with benefit–cost ratios ranging from 2.3:1 to 3.2:1. The 1.875 t ha<sup>-1</sup> rate provided an optimal balance, capturing approximately 70% of the yield benefit with lower input cost. Overall, these findings demonstrate that bentonite is a practical and scalable soil amendment that enhances moisture retention, stabilizes yields, and supports sustainable intensification in rainfed agroecosystems.

## Geospatial Analysis of Soil Characteristics and Nutrients Shows The Need for Site-Specific Soil Management Practices

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Soil surveys and spatial analysis are crucial for developing site-specific nutrient management plans aimed at improving crop productivity and soil health. This study was conducted to evaluate and compare the spatial distribution patterns of soil pH, electrical conductivity (EC), organic matter, total nitrogen (N), Olsen phosphorus (P), extractable potassium (K), and micronutrients (B, Cu, Fe, Zn, and Mn) in cultivated soils of Sahiwal and Faisalabad districts, Punjab, Pakistan. A total of 2,209 soil samples were collected from two depths (0–15 cm and 15–30 cm) and analyzed using geospatial and statistical techniques. Results indicated that the overall nutrient status of Sahiwal District was better than that of Faisalabad District. In general, soils were alkaline with low EC and organic matter content (approximately  $\leq 1\%$ ). Total nitrogen and Olsen phosphorus were slightly lower in areas with higher potassium levels in the surface soil layer. Among micronutrients, B, Cu, Fe, and Zn concentrations were higher in Sahiwal District, whereas Mn was relatively higher in Faisalabad District. Spatial distribution maps further confirmed that Sahiwal District exhibited comparatively better soil fertility status than Faisalabad District. Given that soil properties can gradually vary across adjacent agroecological zones, differences may be attributed to variations in agricultural practices, environmental conditions, and anthropogenic activities. These factors warrant further investigation to better explain the observed spatial variability and to support targeted recommendations. It is therefore suggested that farmers adopt site-specific fertilizer management, integrate improved agronomic practices, and use high-quality irrigation water to enhance and sustain soil fertility.

## Assesment of Pollution Load on Marine Sediments of Karachi Coast

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Marine sediments are important sinks for trace element pollution and play a major role in determining the fate and impacts of a wide range of contaminants. The Karachi Harbour area is considered one of the most heavily polluted marine sites in Pakistan. It includes the semi-enclosed Manora Channel and the Keamari Fish Harbour. This study will investigate pollution levels using marine sediment and seawater samples by establishing baseline inventories of stable isotopes, chemical parameters, and coliform bacteria in coastal marine waters. Seawater and sediment samples will be collected along the Karachi coast to assess the pollution load resulting from anthropogenic activities. Concentrations of

Fe, Mn, Cr, Cd, Ni, Pb, Se, Sr, Zn, and Cu will be determined to evaluate the extent of metal contamination. Stable carbon isotope analysis ( $\delta^{13}\text{C}$ ) will be conducted to identify potential sources of pollution in selected sediments. In addition, total coliform, fecal coliform, and total bacterial counts will be determined using the membrane filtration technique to assess microbial contamination.

## Effect of EC Variations on Hydroponic Lettuce Grown in Cocopeat Using Rainwater

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The global population is steadily increasing, leading to a rising demand for freshwater and intensifying water scarcity. At the same time, the reduction of cultivable land and limited water resources necessitate the development of sustainable and resource-efficient food production systems. These challenges highlight the need for alternative agricultural practices that ensure food security while minimizing water consumption and environmental impacts. Hydroponic farming has emerged as a promising approach due to its high water-use efficiency and suitability for controlled environments. In parallel, rainwater harvesting offers an environmentally friendly and sustainable water source; however, rainwater lacks essential nutrients required for optimal plant growth and must therefore be supplemented before use. This study evaluated the potential of nutrient-enriched rainwater for lettuce (*Lactuca sativa* L.) cultivation in a hydroponic system using cocopeat as a growing medium. Rainwater was collected and used to prepare nutrient solutions at different electrical conductivity (EC) levels through controlled nutrient supplementation. Cocopeat was selected due to its favorable physical properties, including high water-holding capacity and good aeration. Lettuce seedlings were grown in pots throughout their growth cycle to assess the effects of different EC treatments. Plant growth responses were evaluated by measuring key morphological and physiological parameters, including plant height, number of leaves, leaf length and width, leaf area, fresh weight, and total biomass accumulation. Plant performance was monitored at different growth stages under each EC level. The results showed that EC significantly influenced lettuce growth and yield. Optimal EC levels enhanced nutrient uptake, resulting in improved vegetative growth and higher biomass production. In contrast, low EC levels caused nutrient deficiencies, while excessively high EC levels induced osmotic stress and nutrient imbalance, leading to reduced growth. Overall, the findings demonstrate that precise nutrient management is essential for effective use of rainwater in hydroponic systems. Maintaining appropriate EC ranges is critical for maximizing lettuce productivity. The integration of rainwater harvesting with hydroponic cultivation offers a cost-effective, water-efficient, and environmentally sustainable strategy for vegetable production, particularly in urban and resource-limited settings. This approach contributes to addressing future food and water security challenges through sustainable agricultural innovation.

# Augmentation of Aquifer Recharge Techniques Coupled with Overland and Rooftop Rainwater Harvesting

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Rapid population growth has intensified pressure on natural resources, while freshwater scarcity continues to increase, creating urgent demand for alternative water supply strategies. Rainwater harvesting and storage have therefore gained significant attention as sustainable options to partially meet urban, rural, and agricultural water requirements. This study presents the conceptual design and physical implementation of a safe aquifer recharge system integrating both domestic (rooftop) and agricultural (field-based) rainwater harvesting techniques. It also provides recommendations for suitable rainwater harvesting and artificial aquifer recharge systems for Pakistan, particularly the Pothwar region of Punjab. The proposed system comprises six core components: a collection surface (roof or contamination-free field), conveyance network, cistern or storage tank, stilling basin, filtration unit, and recharge well (sink). A pilot-scale demonstration was conducted at the Soil and Water Conservation Research Institute, Chakwal, using a 1,000 m<sup>2</sup> rooftop and a 2,500 m<sup>2</sup> adjacent orchard. Rainwater from rooftops was collected in 500-gallon storage tanks and passed through a filtration unit composed of sand (10%), fine gravel (70%), and coarse gravel (20%) before recharge through a nano-tube irrigation and infiltration system. Field runoff from the orchard was directed into a 100 m<sup>2</sup> vegetated grass area and then into an 8 m<sup>3</sup> stilling basin, followed by sequential horizontal and vertical filtration layers of sand and graded gravel before aquifer recharge. Results indicated that a 10 mm rainfall event generated approximately 9 m<sup>3</sup> of recharge water from rooftop harvesting and about 20 m<sup>3</sup> from field runoff. Water quality analysis showed minimal sediment load (≈1 ppm) in field-collected water, while rooftop harvested water was clear with electrical conductivity below 200 μS/cm. Groundwater quality beneath the recharge site improved from 800 to 750 μS/cm within one week after rainfall events. Cost–benefit analysis revealed that the initial investment (PKR 0.5 million) could be recovered within two to three years through irrigation savings, particularly for high-value crops such as chili and garlic cultivated on small plots. Overall, the study demonstrates that integrated rainwater harvesting and aquifer recharge systems offer a cost-effective, scalable, and environmentally sustainable solution for water-scarce regions.

## Environmental and Morphological Analysis of Pollen from Selected Ayubia National Park Plants Using Scanning Electron Microscopy

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Pollen morphology is widely recognized as a reliable tool in plant taxonomy, systematics, and environmental assessment due to the stability, diversity, and species-specific nature of pollen

characters. This study focuses on the morphological and environmental analysis of pollen from selected plant species of Ayubia National Park, Pakistan, using scanning electron microscopy (SEM) to generate high-resolution micromorphological data. Ayubia National Park, located in the moist temperate Himalayan region, is an ecologically significant and biodiversity-rich area characterized by diverse vegetation, altitudinal variation, and distinct climatic conditions, making it an ideal site for palynological investigation. Pollen samples were collected from selected angiosperm taxa representing multiple families. Both qualitative and quantitative pollen traits were examined to assess morphological variation and its taxonomic and ecological significance. Standard palynological techniques, including acetolysis and sputter coating, were applied prior to SEM analysis. Key parameters measured included pollen size, shape, symmetry, polar and equatorial diameters, P/E ratio, aperture type, colpi dimensions, exine thickness, and surface ornamentation. The results revealed substantial pollen diversity among the studied taxa. Pollen grains exhibited a range of shapes, including oblate, prolate, peroblate, spheroidal, and sub-prolate forms, with sizes varying from small to large. Most species showed tricolporate pollen, a common angiosperm feature. SEM imaging enabled detailed visualization of apertures and fine surface structures that are often not clearly resolved under light microscopy. Exine ornamentation was identified as a key diagnostic feature, with patterns such as reticulate, psilate, echinate, perforate, and granulate structures effectively distinguishing closely related taxa. Variation in exine thickness and sculpturing not only supported taxonomic differentiation but also suggested potential adaptive responses to environmental factors such as temperature fluctuations, humidity, and other biotic and abiotic stresses in mountainous ecosystems. From an environmental perspective, pollen morphology provides insights into plant–environment interactions, where robust exine structures may enhance pollen survival and dispersal under changing climatic conditions. Overall, this study demonstrates that SEM-based pollen analysis is a powerful approach for accurate species identification, biodiversity documentation, and ecological interpretation, contributing valuable baseline data for conservation, aeropalynology, and climate change-related research in sensitive mountain ecosystems.

## Humic and Fulvic Acids and Their Mixtures: Effects on Soil Properties and Phosphorus Availability in Calcareous Soils

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Calcareous soils have high calcium carbonate ( $\text{CaCO}_3$ ) content and alkaline pH, which severely restrict phosphorus (P) availability. A 60-day soil column experiment was conducted to evaluate the effects of humic acid (HA), fulvic acid (FA), and their mixture (HFA) on soil properties and P availability. Six amendment treatments (HA 2%, FA 2%, HA 4%, FA 4%, HFA 2%, and HFA 4%) were applied with five P levels (0%, 25%, 50%, 75%, and 100% of the recommended dose of P). The combined application of HFA 4% significantly reduced soil pH (8.34 to 8.08), enhanced  $\text{CaCO}_3$  dissolution (8.7%), increased cation exchange capacity (49.77 meq 100 g<sup>-1</sup>), improved organic matter content (1.5%), and increased

labile and non-labile carbon pools (0.17% and 0.69%). Alkaline phosphatase activity and microbial biomass carbon were also substantially enhanced. The P availability increased markedly under HFA mixture 4%, reaching 30.0 and 29.4 mg kg<sup>-1</sup> at P100% and P75%, respectively, after 15 days, before declining to 23.6 and 22.9 mg kg<sup>-1</sup> by day 60. Leachate P losses under HFA mixture 4% ranged from 0.26–0.53 mg L<sup>-1</sup> at day 15 and declined to 0.19–0.42 mg L<sup>-1</sup> by day 60. Importantly, HFA 4% reduced fixed P (apatite-P) from 94% to 46% of applied P while increasing labile P from 4.51% to 27%. Overall, application of HFA mixture at 4% combined with 75–100% recommended P fertilizer significantly improved soil biogeochemical properties, enhanced P availability, and reduced P fixation in calcareous soils.

## Valorization of Agricultural Waste–Derived Biochar for the Sustainable Removal of Heavy Metals from Contaminated Water

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Rapid industrialization and agricultural activities have led to the severe contamination of water resources with heavy metals, posing significant risks to ecosystems and human health. Conventional treatment methods for heavy metal removal are often costly, energy-intensive, and generate secondary pollutants. In recent years, the use of agricultural waste-derived biochar has emerged as an environmentally friendly and sustainable alternative for water remediation. This study investigates the potential of biochar produced from agricultural residues as a low-cost adsorbent for the removal of selected heavy metals from aqueous solutions. Biochar was synthesized through controlled pyrolysis and characterized using physicochemical techniques to evaluate its surface properties and functional groups. Batch adsorption experiments were conducted to assess the effects of pH, contact time, initial metal concentration, and biochar dosage on removal efficiency. The adsorption behavior was analyzed using kinetic and isotherm models to elucidate the underlying mechanisms. Results demonstrated that the biochar exhibited high adsorption capacity and strong affinity toward heavy metal ions, primarily through surface complexation and ion exchange processes. The findings highlight the dual environmental benefits of agricultural waste valorization and effective water treatment, suggesting that biochar-based adsorption systems can serve as a sustainable solution for mitigating heavy metal pollution in water resources.

## Investigation of Metal–Organic Frameworks as Efficient Adsorbents for Environmentally Relevant Methane Capture and Carbon Dioxide Adsorption

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The rapid rise in atmospheric greenhouse gases, particularly methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), has become a major environmental concern due to their strong contributions to global warming and climate change. Methane has a global warming potential more than 25 times higher than CO<sub>2</sub> over a 100-year period, while CO<sub>2</sub> is a primary byproduct of fossil fuel combustion, highlighting the need for effective capture and mitigation strategies. Metal-Organic Frameworks (MOFs), a class of crystalline porous materials formed by metal ions coordinated with organic ligands, have emerged as promising adsorbents because of their high surface areas, tunable pore structures, chemical stability, and selective adsorption properties. This study systematically evaluates the adsorption performance of selected MOFs for methane and carbon dioxide capture. The synthesized MOFs were characterized using X-ray diffraction (XRD), Brunauer-Emmett-Teller (BET) surface area analysis, scanning electron microscopy (SEM), and thermogravimetric analysis (TGA) to establish structure–performance relationships. Adsorption experiments were conducted under controlled temperature and pressure conditions to determine gas uptake capacities, adsorption kinetics, and selectivity. The results show that certain MOFs exhibit significantly higher CO<sub>2</sub> adsorption capacity with strong selectivity over CH<sub>4</sub>, indicating their suitability for selective gas separation and environmental applications. The effects of key operational parameters, including temperature, pressure, and gas composition, were further examined to optimize adsorption performance. Isotherm and kinetic analyses using Langmuir, Freundlich, and pseudo-second-order models provided insight into adsorption mechanisms and enabled prediction of behavior under practical conditions. In addition, cyclic adsorption–desorption tests were carried out to assess the stability and reusability of the MOFs, which are essential for continuous gas capture systems. Overall, the findings highlight the strong potential of MOFs for greenhouse gas mitigation, offering high adsorption capacity, selectivity, and recyclability. This work supports the development of efficient and sustainable adsorbent materials for methane capture and carbon dioxide sequestration, with promising implications for large-scale industrial applications and climate change mitigation efforts.

## Boosting Chilli Growth and Yield with Indigenous Root-Colonizing Bacteria

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Chilli is a high-value cash crop in Pakistan, placing the country among the world's leading producers. In Sindh province, its cultivation plays a key role in enhancing farmer income due to strong domestic demand and export potential. This study investigated indigenous root-associated bacterial communities of chilli collected from major cultivation sites in Mirpur Khas, Sindh. Among thirteen locations, the highest bacterial population density (8.77 log cfu g<sup>-1</sup> soil) was recorded in soils from Matli Road, Digri, whereas the highest populations of phosphate-solubilizing and nitrogen-fixing bacteria were observed at Naukot Road Jhuddo (7.85 log cfu g<sup>-1</sup>) and Malkani Road Jhuddo (7.71 log cfu g<sup>-1</sup>), respectively. Ten morphologically distinct bacterial isolates were selected and evaluated for plant growth-promoting traits. These isolates produced Indole-3-Acetic Acid (6.29–10.11 mg L<sup>-1</sup>), solubilized inorganic phosphate (27.08–56%), and demonstrated nitrogen fixation and biofilm formation capabilities. Application of a consortium of three selected isolates in combination with 75%

of the recommended mineral fertilizer significantly improved chilli growth and yield parameters under net-house conditions, including plant height (56.5 cm), number of branches (47.83), flowers (16 plant<sup>-1</sup>), fruits (12 plant<sup>-1</sup>), fresh fruit weight (97 g plant<sup>-1</sup>), fruit length (4.30 cm), and fruit girth (7.80 mm). Molecular identification based on 16S rRNA gene sequencing classified the isolates as *Stenotrophomonas* sp. (NIA-C18), *Brevundimonas* sp. (NIA-C26), and *Alcaligenes* sp. (NIA-C30). These results demonstrate the potential of these indigenous bacteria as bioinoculants for sustainable chilli production in Sindh with reduced reliance on chemical fertilizers.

## Contamination in Drinking Water under Different Sectors of Islamabad: Monte Carlo Simulation-Based Quantitative Microbial Risk Assessment and Sensitivity Analysis

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Access to clean drinking water is a fundamental human right and a key determinant of public health; however, cities in Islamabad continue to face persistent water quality challenges. This study presents a comprehensive evaluation of drinking water contamination across different sectors of Islamabad using an advanced probabilistic health risk model integrated with physical, chemical, and microbiological analyses. The study addresses a critical knowledge gap by comparing water quality across sectors, particularly between newly developing areas and older, established ones. The investigation involves the systematic collection and analysis of 105 water samples from selected residential areas and a primary source at Khanpur Dam. Samples will be evaluated for key physicochemical parameters, including pH, turbidity, total dissolved solids (TDS), nitrates, and residual chlorine, along with microbiological contamination using *Escherichia coli* as an indicator of fecal pollution. A central innovation of this study is the application of a Quantitative Microbial Risk Assessment (QMRA) framework enhanced through Monte Carlo simulation. This approach translates measured *E. coli* concentrations into quantifiable health risks for three population groups: children, adults, and the elderly. The model estimates daily exposure doses, annual infection probabilities, and the associated burden of disease expressed as Disability-Adjusted Life Years (DALYs). Monte Carlo simulation, with 10,000 iterations, generates robust probability distributions of risk outcomes while accounting for variability and uncertainty in parameters such as ingestion rates and pathogen concentrations. Sensitivity analysis further identifies the most influential factors contributing to health risks, enabling targeted intervention strategies. The study is expected to produce a high-resolution spatial profile of water quality across Islamabad, highlighting contamination hotspots and sector-specific vulnerabilities. QMRA outputs will provide scientifically grounded estimates of public health risks, aligned with guidelines from the World Health Organization and the United States Environmental Protection Agency. Ultimately, the findings aim to support evidence-based decision-making by policymakers and water management authorities, guiding infrastructure development, monitoring frameworks, and public health interventions to mitigate waterborne diseases and advance progress toward Sustainable Development Goal 6.

## Iron Bio-Fortification through Integrated Agronomic Approaches for Improving Growth, Yield and Iron Content of Cereal Crop

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Biofortification of crops is a sustainable strategy to combat global malnutrition. Iron (Fe) is a critical micronutrient essential for plant growth, yield, and grain quality. Although abundant in soil, its bioavailability to plants is often limited. To enhance wheat grain biofortification and crop productivity, eight treatments were evaluated: NPK (recommended dose, RD); NPK + 10 kg ha<sup>-1</sup> soil-applied Fe (SA-Fe); NPK + 20 kg ha<sup>-1</sup> SA-Fe; NPK + 0.2% foliar-applied Fe (FA-Fe); NPK + seed inoculation (SI); NPK + 10 kg ha<sup>-1</sup> SA-Fe + SI; NPK + 20 kg ha<sup>-1</sup> SA-Fe + SI; and NPK + 0.2% FA-Fe + SI. The experiment was conducted in a completely randomized block design (RCBD) with three replicates at the Soil Chemistry Section, Ayub Agricultural Research Institute, Faisalabad. Results showed that NPK + 20 kg ha<sup>-1</sup> SA-Fe + SI significantly increased wheat grain yield to 5.26 t ha<sup>-1</sup>. This treatment also improved grain phosphorus (13% increase) and potassium (5.7% increase) content compared to non-inoculated controls. Additionally, NPK + 0.2% FA-Fe + SI enhanced Fe concentration in wheat grains to 45.7 µg g<sup>-1</sup>. These findings indicate that combining chemical fertilizers with siderophore-producing bacterial inoculation is an effective approach to enhance wheat growth, yield, and grain quality.

## Field-Scale Hydrological and Agronomic Assessment of Climate-Resilient Irrigation Innovations: A Multi Year Comparative Performance Analysis in Rainfed Pothowar, Punjab

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Water scarcity poses a significant challenge to rainfed citrus production on Pakistan's Pothowar Plateau. To address this, field experiments were conducted at the Soil and Water Conservation Research Institute, Punjab, to compare the performance of smart irrigation systems with conventional irrigation methods under rainfed conditions. Conventional methods, including flood, border, basin, and furrow irrigation, are low-cost, require minimal maintenance, and do not rely on power. However, these methods suffer from low water-use efficiency. In contrast, several smart irrigation systems were adapted to local soil, climate, and management conditions, including bubbler, buried stone pocket,

spiral pipe, drip, micro-tube, and responsive drip irrigation (RDI). Conventional irrigation applied 6.56–9.72 m<sup>3</sup> of water per 9–10 plants, yielding 8,316–10,584 kg ha<sup>-1</sup> with low water productivity (2.05–3.54 kg m<sup>-3</sup>). Smart systems, however, used only 2.02–4.14 m<sup>3</sup> of water while achieving higher yields of 10,258–12,632 kg ha<sup>-1</sup> and markedly improved water productivity (5.93–11.31 kg m<sup>-3</sup>), representing 65–80% water savings. Among smart methods, the buried stone pocket achieved the highest water productivity (11.31 kg m<sup>-3</sup>), followed by RDI (8.66 kg m<sup>-3</sup>) and bubbler irrigation (7.91 kg m<sup>-3</sup>). Smart irrigation also enhanced key agronomic traits, including fruits per plant (97–121 vs. 88–101), plant height (2.1–2.6 m), and canopy area (5.1–6.6 m<sup>2</sup>). The improved performance of these systems is attributed to precise root-zone water application, reduced evaporation and runoff losses, and adaptability to local conditions. Notably, RDI, which operates on low-pressure and root-zone moisture responsiveness, shows potential for integration with rooftop rainwater harvesting to ensure a continuous water supply. Overall, smart irrigation systems offer a sustainable and water-efficient strategy for enhancing citrus production in semi-arid rainfed regions.

## Improving Maize Productivity and Nutrient Use Efficiency by Boron Fortified DAP

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Di-ammonium phosphate (DAP) is the most commonly used mineral phosphate fertilizer applied to soils to meet crop phosphorus (P) requirements and reduce yield losses. However, only 5–25% of the applied P is taken up by plants during the growing season. This low efficiency is due to several factors, including the solubility rate of DAP. The solubilized phosphate anions can precipitate or adsorb onto soil constituents, making them unavailable to plants. Phosphorus adsorption and precipitation in soil are primarily influenced by soil pH and calcium carbonate content. One strategy to improve fertilizer use efficiency is blending DAP with organic and inorganic stabilizing agents (e.g., vegetable oil, biopolymers, compost, sulfur, copper, boron), which slow its dissolution and function as a controlled-release fertilizer to better match crop demand. In this context, the Soil Chemistry section at AARI, Faisalabad, developed a boron-enriched DAP formulation. This modified, controlled-release fertilizer releases P in accordance with plant demand, enhancing fertilizer use efficiency, increasing crop yield by 8–10%, improving quality parameters by 5–8%, and reducing the environmental risks associated with excessive fertilizer use.

## Optimizing Graphene Oxide and Vermicompost Rates for Biomass Production of Maize (*Zea mays* L.)

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Graphene oxide (GO) has gained considerable attention due to its unique structural and functional properties. However, region-specific studies examining the combined effects of GO and vermicompost (VC) under Pakistani soil conditions are limited. This study therefore evaluated the integrated impact of GO and VC on maize growth and biomass yield. The experiment included five treatments: (1) control, (2) 0+1.0 (0 mg L<sup>-1</sup> GO + 1.0% VC), (3) 25+1.0 (25 mg L<sup>-1</sup> GO + 1.0% VC), (4) 50+1.0 (50 mg L<sup>-1</sup> GO + 1.0% VC), and (5) 75+1.0 (75 mg L<sup>-1</sup> GO + 1.0% VC), each replicated three times under controlled pot conditions using 0.5 kg of soil per pot. Results showed that both GO and VC individually enhanced maize growth compared to the control. Notably, their combined application produced a more pronounced improvement across all measured growth parameters. Treatments with moderate GO levels (25–50 mg L<sup>-1</sup>) combined with 1.0% VC achieved the greatest increases in plant height, leaf number, and biomass accumulation, suggesting a synergistic interaction between GO and VC. Overall, the findings indicate that integrating graphene oxide with vermicompost is more effective at promoting maize growth than applying either amendment alone. This study highlights the potential of combining nanomaterials with organic amendments as a sustainable strategy to enhance soil health, improve nutrient availability, and boost crop productivity while reducing dependence on chemical fertilizers.

## Wastewater Irrigation Impact on Heavy Metal Contamination of Vegetables. A Potential Threat to Food Security

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Heavy metal contamination arising from vegetable production using wastewater irrigation in metropolitan cities of Punjab (Pakistan) poses a serious threat to human health. The long-term use of industrial and municipal wastewater for irrigation can lead to the accumulation of heavy metals in agricultural soils and crops. Therefore, a two-year study was conducted in urban and peri-urban areas of Faisalabad to assess the extent of heavy metal contamination associated with wastewater irrigation. Edible portions of vegetable samples were collected from various sites where wastewater was used as an irrigation source, along with corresponding soil and wastewater samples. These samples were analyzed for lead (Pb), cadmium (Cd), nickel (Ni), and chromium (Cr). Geographic coordinates of sampling sites were recorded using a global positioning system (GPS), and spatial mapping was performed using ArcGIS. The results revealed significant concentrations of heavy metals in soil, wastewater, and vegetable samples. In vegetables, Cr ranged from 0.61 to 38.36 mg/kg, Pb from 0.48 to 23.74 mg/kg, Cd from 0.03 to 9.11 mg/kg, and Ni from 0.13 to 12.47 mg/kg. Among the samples, 98% were contaminated with Cr, 55% with Pb, 52% with Cd, and 4% with Ni. Chromium levels were notably higher than those of the other metals. These findings highlight the serious risks associated with wastewater irrigation. It is therefore strongly recommended that the use of untreated wastewater for irrigation be discontinued and that strict monitoring protocols be implemented.

## Effect of Different Levels and Methods of Application of ZnSO<sub>4</sub> on Yield and Yields Components of Maize

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Maize is an important cereal crop in Pakistan, ranking after wheat and rice, and zinc (Zn) is a vital micronutrient that enhances crop growth, grain quality, and yield. To evaluate the effect of ZnSO<sub>4</sub> on maize, a field experiment was conducted during summer 2024 at the Agriculture Research Station Harichand, Charsadda. The experiment included four ZnSO<sub>4</sub> levels (0, 2, 4, and 6 kg ha<sup>-1</sup>) applied via two methods (soil and foliar) in a Randomized Complete Block Design (RCBD) with three replications. Results showed that all measured parameters increased compared to the control (water only). The highest plant height (216.57 cm) and grain yield (4365.0 g) were recorded with foliar application of ZnSO<sub>4</sub> at 6 kg ha<sup>-1</sup>, whereas the lowest plant height (201.23 cm) and grain yield (3517.7 g) occurred with soil application at the same rate. Optimal biological yield (11,661 g) was achieved with 2 kg ha<sup>-1</sup> ZnSO<sub>4</sub>, while the lowest (9,308 g) occurred in soil-applied treatments. The maximum 1000-grain weight (322.47 g) was observed with foliar spray at 2 kg ha<sup>-1</sup>, and the minimum (314.63 g) in the control. Phenological traits were also influenced by Zn application: days to silking (67.33) and tasseling (60.00) were highest with foliar spray at 4 kg ha<sup>-1</sup>, while the lowest silking (57.33) and tasseling (53.66) were observed with soil application at 6 kg ha<sup>-1</sup>. Leaf area was highest (43.99 cm<sup>2</sup>) with foliar spray at 4 kg ha<sup>-1</sup> and lowest (39.29 cm<sup>2</sup>) with soil application. The highest number of plants at harvest (64.83 ha<sup>-1</sup>) and harvest maturity (98.0) were recorded with foliar application at 6 kg ha<sup>-1</sup> and 2 kg ha<sup>-1</sup>, respectively, whereas the lowest values occurred with soil-applied ZnSO<sub>4</sub>. These results indicate that maize positively responded to ZnSO<sub>4</sub> application, and foliar application at 6 kg ha<sup>-1</sup> is more effective than soil application in improving growth, yield, and related agronomic traits.

## Characterization and BTEX-Degrading Capacity of Indigenous Soil Bacterial Consortia from Petrol Stations and Workshops in Rawalpindi

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Rawalpindi is home to a large population and a dense transport network, with all types of vehicles traversing its roads. Consequently, soils surrounding petrol stations and mechanical workshops are frequently contaminated with volatile organic compounds commonly found in petroleum products. These compounds may include, but not limited to, benzene, toluene, ethylbenzene and xylene (BTEX). These pollutants are known contributors to a range of health problems, including cancer, genetic mutations, leukemia, and immunotoxicity. While various physical and chemical remediation methods have been developed, they are often expensive and produce toxic by-products. In the face of financial constraints and the growing threats of climate change, there is an urgent need for sustainable and

cost-effective alternatives. Scientific evidence supporting microbial remediation remains limited, highlighting the need for localized solutions. This study aims to address this gap by exploring strategies for restoring contaminated soils and reducing the disease burden associated with environmental pollution.

## Mineralization Potential and Nitrogen Losses From Humic Acid Coated Urea

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An incubation experiment was conducted to assess the nitrogen mineralization capacity and nitrogen loss reduction efficiency of humic acid-coated urea (HACU) under the semi-arid agro-climatic conditions of Peshawar, Khyber Pakhtunkhwa, Pakistan. The study evaluated the effects of three nitrogen sources [normal urea, HACU, and urea + humic acid (urea + HA)] applied at three nitrogen levels (270, 360, and 450 mg N kg<sup>-1</sup> soil) on nitrogen dynamics, microbial activity, and soil health. Results showed that HACU and urea + HA significantly improved nitrogen retention, mineralization, and microbial activity compared to regular urea. HACU at 450 mg N kg<sup>-1</sup> exhibited the highest mineral nitrogen concentration (398 mg kg<sup>-1</sup> on day 2 and 220 mg kg<sup>-1</sup> on day 16), while urea + HA at 360 mg N kg<sup>-1</sup> showed the maximum microbial respiration (271 µg g<sup>-1</sup> soil d<sup>-1</sup>) and cumulative CO<sub>2</sub> evolution (2,650 µg g<sup>-1</sup> soil). The highest urease activity was observed with HACU (51 µg NH<sub>4</sub><sup>+</sup>-N g<sup>-1</sup> h<sup>-1</sup>), indicating more efficient nitrogen transformation. Ammonia volatilization was significantly lower with HACU (110.9 mg kg<sup>-1</sup> week<sup>-1</sup>) than with urea (131.0 mg kg<sup>-1</sup> week<sup>-1</sup>), and HACU at 450 mg kg<sup>-1</sup> exhibited the lowest nitrogen loss percentage (29.2%). Additionally, urea + HA produced the highest soil pH (7.88), whereas HACU resulted in the highest electrical conductivity (0.75 dS m<sup>-1</sup>), soil organic carbon (0.62%), and total nitrogen (0.07%) at 450 mg kg<sup>-1</sup>. Overall, the study demonstrates that humic acid-based nitrogen fertilizers, particularly HACU, are highly effective in enhancing nitrogen use efficiency, improving soil biochemical properties, and reducing environmental nitrogen losses. These findings support the use of humic-enhanced formulations as a sustainable and agronomically efficient alternative to regular urea in semi-arid agricultural environments.

## Enhancing Climate-Resilient Crop Production through Organic Matter Types and Optimized Fertilizer Rates: Effects on Soil Microbial Populations and Yield

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Wheat is Pakistan's main cereal crop and a staple food crucial for national food security. However, its productivity is often limited by low availability of essential nutrients. A field experiment was conducted to assess the combined effects of organic amendments and chemical fertilizers on soil microbial activity, plant growth, and wheat yield in low-fertility clay loam soil. The experimental soil had very low fertility, with organic matter (0.75%), organic carbon (0.435%), nitrogen (0.020%), and phosphorus (2.15 mg kg<sup>-1</sup>). Two organic sources were tested: OM-1 (19% organic matter, 1.14% N) and nutrient-rich OM-2 (30% organic matter, 1.80% N, 2.0% P<sub>2</sub>O<sub>5</sub>, 0.65% K<sub>2</sub>O). Application of OM-2 combined with 75% of the recommended fertilizer (RF) resulted in the highest plant height (29–133 cm from 30 to 120 DAS) and maximum tiller number (3.68–11.40 plant<sup>-1</sup>). This treatment also enhanced soil bacterial populations (8.8 log CFU g<sup>-1</sup> at 30 DAS) and chlorophyll content. The highest grain yield (5.29 t ha<sup>-1</sup>), straw yield (10.47 t ha<sup>-1</sup>), and harvest index (0.53) were recorded under OM-2 + 75% RF. Post-harvest soil fertility improved, with OM-2 + 75% RF increasing organic matter to 1.42% and organic carbon to 0.82%. The highest soil N, P, and K, as well as plant N (0.69%), grain N (1.94%), and protein content (4.31%), were observed under OM-2 + 100% RF. Overall, integrating nutrient-rich organic matter, especially OM-2, with 75% of the recommended fertilizer significantly enhanced soil fertility, microbial activity, and wheat yield. These results highlight the effectiveness of integrated nutrient management in improving soil health and crop productivity in nutrient-deficient soils, offering a practical strategy for sustainable and climate-resilient wheat production.

## Isolation of Rhizobia Capable of Producing Biosurfactants to Improve Growth of Lentil in Water Stressed Condition

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Climate change induced stresses is a major limiting factor for lentil (*Lens Culinaris Medik*) production in rain-fed area of Pakistan (Potohar Region). These abiotic stresses adversely affect plant growth, nodulation and biological nitrogen fixation ultimately reducing yield and threatening food security. Through symbiosis, rhizobia play a critical role in the production of lentil crop. However studies shows that the effectiveness of rhizobia is negatively effected by higher temperature and less moisture. Recent studies revealed that the biosurfactants can retain soil moisture and act as a agent for plant microbe positive interaction and also help in nutrient uptake. Present study aims to isolate native rhizobia strain from the lentil nodule of the Potohar region and evaluate their potential for biosurfactant production and tolerance to heat and drought stress. Root nodules will be collected from the healthy plant, and rhizobia will be isolated using standard microbiological techniques. The isolate will be characterized on the basis of, physiological, biochemicals and morphological properties. Screening for biosurfactant production will be carried out using qualitative and quantitative assays. Heat and drought tolerance will be assessed under controlled laboratory conditions using elevated temperature and osmotic stress treatments. Rhizobial strain will be further assesd for inoculation experiment under normal and stress conditions. The aim of this study to isolate rhizobial strain with different properties like stress tolerant, biosurfactant producing and that will be capable of enhancing lentil growth by fixing nitrogen under heat and drought stress. These findings will contribute to the

development of climate bio-inoculants suitable for sustainable lentil production in the Potohar region under changing climatic conditions.

## Effect of Sawdust on Different Doses of Nitrogen Rate in Wheat Crop under Drought Stress and Irrigated Condition

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Water scarcity and declining soil organic matter threaten sustainable wheat production under semi-arid conditions. A field experiment was conducted during Rabi 2024–25 at the Research Farm of DSPN, ARI Tarnab, Peshawar, to evaluate the effect of sawdust mulch on nitrogen efficiency and wheat performance under drought stress and normal irrigation. The study was arranged in a three-factor factorial RCBD with 24 treatments and three replications. Treatments consisted of two irrigation regimes (drought stress and normal irrigation), four nitrogen levels (0, 50, 75 and 100% of recommended dose), and three sawdust levels (0, 3 and 6 t ha<sup>-1</sup>). Wheat variety ‘Gulzar-2019’ was used, while phosphorus and potassium were applied at recommended rates. Results revealed that irrigation and nitrogen significantly improved most growth and yield parameters, whereas sawdust effects were more pronounced through interactions. The highest plant height (100.67 cm), spike length, grains spike<sup>-1</sup> (56), 1000-grain weight (47.70 g), biological yield (11,667 kg ha<sup>-1</sup>), and grain yield (4,236 kg ha<sup>-1</sup>) were recorded under irrigated conditions with 100% nitrogen combined with 6 t ha<sup>-1</sup> sawdust. Nitrogen application markedly increased grain yield (from 2,974 to 3,868 kg ha<sup>-1</sup> across N levels). Sawdust significantly enhanced grain yield (up to 3,561 kg ha<sup>-1</sup>) compared to control (3,281 kg ha<sup>-1</sup>), particularly when combined with nitrogen. Importantly, 75% nitrogen with sawdust produced yields statistically comparable to 100% nitrogen without sawdust under both irrigation regimes, indicating improved nitrogen-use efficiency. Under drought stress, sawdust partially mitigated yield losses by improving moisture conservation and nutrient utilization. The study concludes that integrating sawdust mulch (3–6 t ha<sup>-1</sup>) with optimized nitrogen (75% of recommended dose) can sustain wheat productivity while reducing fertilizer requirements, especially under limited irrigation. This integrated approach offers a practical strategy for enhancing resource-use efficiency and climate resilience in wheat-based systems of semi-arid regions.

## Risk Evaluation of Microplastics Pollution in Agricultural Soils Irrigated with Wastewater

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Microplastics have emerged as a pervasive and persistent pollutant in terrestrial ecosystems, particularly in agricultural soils receiving wastewater for irrigation (En-Nejmy et al., 2024). Increasing

water scarcity in urban and peri-urban regions of Pakistan has resulted in the widespread use of untreated or partially treated wastewater for crop production (Punjab Environmental Protection Department, 2025). While wastewater irrigation provides nutrients and supports agricultural productivity, it simultaneously introduces a complex mixture of contaminants into soils, including microplastics and associated chemical pollutants (Aydin et al., 2025). Microplastics, defined as plastic particles smaller than 5 mm, are resistant to degradation and can persist in soils for long periods, interacting with soil physical, chemical, and biological processes (Kang, 2025). This study aims to investigate the occurrence, distribution, and characteristics of microplastics in agricultural soils irrigated with wastewater in the Rawalpindi region and to evaluate their potential environmental and human health risks. Soil samples from wastewater-irrigated fields and freshwater-irrigated control fields will be analyzed to determine microplastic abundance, size distribution, morphology, and polymer composition. In addition, selected soil physicochemical properties and heavy metal concentrations will be assessed to examine possible interactions between microplastics and co-contaminants (Rubab et al., 2025). Potential human exposure pathways, including food consumption and occupational contact, will also be evaluated through a preliminary health risk assessment framework. The findings of this research will provide baseline data on microplastic contamination in agricultural soils of Rawalpindi and contribute to a better understanding of the implications of wastewater irrigation on soil quality and food safety (Mushtaq et al., 2010). The study will support evidence-based recommendations for sustainable wastewater reuse and environmental protection policies in Pakistan.

## Effect of Humic Acid-Enhanced Phosphate Fertilizers on Phosphorus Diffusion and Availability

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In low fertility tropical acid soils with higher amounts of iron and aluminum oxides, most of the applied phosphorus is adsorbed to soil colloids, resulting in low phosphorus mobility and availability. Humic acid treated phosphate fertilizers were hypothesized to increase phosphorus diffusion and availability from applied fertilizer. A sixty (60) days incubation experiment was conducted under controlled environment to study the effect of humic acid treated phosphate fertilizers on phosphorus diffusion and availability at various incubation intervals. The treatments included commercial SSP and Acidulated Rock Phosphate (ARP at 50% and 100% acidulation level) as base fertilizers. The ARPs were prepared from Bayovar rock phosphate. Humic acids from two sources (lignitic coal and farmyard manure compost) were coated on commercial SSP while complexed with ARP. The overall results highlighted that humic acid improved phosphorus diffusion and availability in treated fertilizers as compared to the untreated fertilizers. Humic acid complexed-ARP fertilizer also resulted in higher total and available P as compared to other fertilizers. Humic acid from lignitic coal resulted in higher total and available P concentrations as compared to compost derived humic acid.

## Mitigating Runoff-Induced Nutrient Losses through Integrated Organic Amendments to Improve Soil Health and Enhance Wheat Yield under Mountainous Conditions

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Sustainable nutrient management is essential for improving soil health and crop productivity, particularly in erosion-prone mountainous regions. Excessive reliance on chemical fertilizers has contributed to soil degradation, necessitating the integration of organic and inorganic nutrient sources. The present study evaluated the impact of organic amendments combined with inorganic fertilizers on soil erosion, nutrient losses, soil properties, and wheat yield under varying slope conditions at two sites of the University of Poonch, Rawalakot, Azad Kashmir. The experiment was conducted using a factorial randomized complete block design with three replications. Four nutrient treatments were tested across two sites using wheat variety 'Borlaug'. Post-harvest soil samples (0–15 cm) were analyzed to assess physico-chemical properties and nutrient status. Results demonstrated that integrated treatments, particularly wheat husk plus NPK (WH + NPK) and poultry manure plus NPK (PN + NPK), significantly enhanced growth and yield parameters. Maximum grain yield (2755.6 and 2500.0 kg ha<sup>-1</sup>) and biological yield (3433.3 and 3207.4 kg ha<sup>-1</sup>) were recorded under WH + NPK and PN + NPK, respectively. These treatments also reduced runoff losses, sediment concentration, and nutrient losses (N, P, K, and organic matter). Improved soil properties were observed, including reduced bulk density (1.11 g cm<sup>-3</sup>), increased organic matter (3.0%), and enhanced nutrient concentrations. The findings indicate that integrated nutrient management significantly improves soil structure, reduces erosion and nutrient losses, and enhances wheat productivity in degraded mountainous soils. The study highlights the potential of organic amendments combined with inorganic fertilizers as a sustainable strategy for soil conservation and crop production in fragile agro-ecosystems.

## Bio-Solubilization of Phosphorus from Rock Phosphate and Other P Fertilizers in Calcareous Silt Loam Soil Using Phosphate-Solubilizing Bacteria and Poultry Manure

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This study evaluated the role of phosphate-solubilizing bacteria (PSBs) in enhancing phosphorus (P) availability from different P sources and improving maize (*Zea mays* L.) growth and P-use efficiency in

calcareous soil. Soil incubation (100 days) and greenhouse experiments were conducted using rock phosphate (RP), single superphosphate (SSP), poultry manure (PM), and RP+PM, applied with and without three indigenous and one exotic PSB. Results showed that PSB inoculation significantly increased P solubilization from all sources, particularly RP and RP+PM, and reduced P losses from SSP. Soil P recovery increased from 4–25% without PSBs to 14–30% with PSBs, while maize biomass increased by 12–30% and P-use efficiency by 20–73% in PSB-treated soils. Organic acid production (gluconic and oxalic acids) by PSBs was identified as a key mechanism for enhanced P solubilization. Overall, the combined use of indigenous PSBs and organic amendments improved soil P availability, reduced P losses, and enhanced P uptake by maize, highlighting their potential for sustainable P management.

## Reimagining Wastewater: Treated Greywater for Urban Forestry in Gwadar, Pakistan

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Sewage Treatment Plants (STPs) play a vital role in urban wastewater management and sustainable water reuse, particularly in water-scarce coastal regions such as Gwadar. This study evaluated the treatment efficiency of two operational STPs by analyzing influent and effluent samples, with a focus on assessing the suitability of treated greywater for urban afforestation initiatives under the Gwadar Development Authority (GDA). Physicochemical parameters including pH, chemical oxygen demand (COD), biological oxygen demand (BOD<sub>5</sub>), total suspended solids (TSS), total dissolved solids (TDS), and selected heavy metals were examined. Effluent pH ranged from 7.6 to 8.3, remaining within the National Environmental Quality Standards (NEQS) limits (6–9). COD decreased from 210–176 ppm at the inlet to 138–112 ppm at the outlet, indicating a treatment efficiency of 35–45%. BOD<sub>5</sub> was reduced from 135–96 ppm to 73–62 ppm, with an efficiency of 46–55%. TSS declined from 240–190 ppm to 160–106 ppm, reflecting a removal efficiency of 40–55%. TDS decreased from 4,670–1,925 ppm to 3,320–2,380 ppm, with final values remaining below the NEQS limit of 3,500 ppm. Trace metals including lead (0.042–0.107 ppm), chromium (0.6–1.15 ppm), and nickel (0.11–0.8 ppm) were all within permissible limits, while cadmium, mercury, and oil & grease were not detected. Overall, the findings indicate that the Gwadar STPs achieve moderate reductions in organic load and produce effluent of acceptable quality for non-potable reuse. The treated greywater, enriched with residual nutrients, shows strong potential for irrigation and soil improvement within GDA’s urban greening and afforestation programs, aligned with the Gwadar Smart Port City Master Plan (2019–2025). To ensure safe and sustainable reuse, regular monitoring, process optimization, and the integration of nutrient-recovery practices are recommended, supporting climate-resilient and environmentally responsible urban development.

# Assessing Long-Term Yield and Soil Fertility under Organic Farming Systems

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The intensive and non-judicious use of synthetic fertilizers in conventional wheat-based farming systems has raised serious concerns regarding soil degradation, environmental pollution, escalating input costs and long-term sustainability in Pakistan. Being staple wheat is crucial for national food security, therefore, it is of urgent need to evaluate a sustainable alternative not only to maintain productivity but also to improve soil health. A long-term agronomic trial was conducted to assess the impacts of converting conventional cropping systems to organic farming under local agro-ecological conditions of Peshawar, Pakistan. A long-term field experiment was established to compare conventional and organic farming systems during the rabi-season of 2019-2020 that continued through 2024-2025. Conventional plots received recommended doses of chemical fertilizers, while organic plots were managed using farmyard manure, compost and Sesbania incorporation as green manure. Results from the yearly averages depicted wheat grain yield, water use efficiency, protein content and nutrient uptake were statistically comparable between the two systems. Despite modest yield differences, organic farming significantly improved soil organic matter, organic carbon and nitrogen, phosphorus and potassium contents. This long-term monitoring demonstrates that organic farming can enhance soil fertility and system sustainability with minimal compromise in crop productivity. These findings support organic farming as a viable and sustainable alternative for wheat-based cropping systems.

## Phenotypic and Functional Screening of Microbial Isolates for Biofertilizer Potential

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A research trial was conducted to isolate and characterize rhizobacterial and rhizobial strains from chickpea, berseem, compost tea, wheat, maize and potato to evaluate their plant growth-enhancing traits. Isolates were evaluated for optical density (OD), colony-forming units (CFU), Auxins [indole-3-acetic acid (IAA)] production, Gram reaction, acid production and phosphorus solubilization. Significant differences were observed among the strains. The highest OD (2.55) was recorded in berseem, followed by compost tea (2.16) and chickpea (2.09), whereas maize (1.77) and potato (1.90) showed the lowest OD. Compost tea isolate exhibited the highest IAA production (5.56 mg L<sup>-1</sup>), while chickpea (4.66 mg L<sup>-1</sup>) and berseem (3.98 mg L<sup>-1</sup>) also showed notable levels. The lowest IAA was recorded in potato (1.92 mg L<sup>-1</sup>). Berseem isolate showed the highest viable count (2.56 × 10<sup>7</sup> CFU mL<sup>-1</sup>), followed by compost tea (2.03 × 10<sup>7</sup>) and wheat (1.70 × 10<sup>7</sup>), whereas potato had the lowest count (2.71 × 10<sup>6</sup> CFU mL<sup>-1</sup>). Gram staining revealed four Gram-negative isolates (chickpea, berseem,

compost tea, maize) and two Gram-positive isolates (wheat, potato). All strains produced acid, but none showed phosphorus solubilization on Pikovskaya's agar. These findings suggest that chickpea and compost tea isolates are promising candidates for biofertilizer development due to high IAA production and moderate to high CFU counts, while berseem isolates excel in biomass and viability. Although phosphorus solubilization was absent, acid production indicates potential for indirect nutrient mobilization, underscoring the importance of screening strains for multiple beneficial traits.

## Nano Silicon–Coated Urea: An Innovative Strategy to Mitigate Nitrogen Losses and Enhance Nitrogen Use Efficiency

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Nitrogen (N) losses are frequently associated with the application of conventional urea, primarily due to its rapid hydrolysis rate in soil. This accelerated transformation increases the susceptibility of urea-derived nitrogen to loss availability, particularly ammonia ( $\text{NH}_3$ ) volatilization. The problem is especially severe in alkaline soils with high pH, where volatilization represents a major route of nitrogen loss. In warm and alkaline agro-ecological conditions, such as those prevalent in the Indus Basin, substantial nitrogen losses through  $\text{NH}_3$  volatilization significantly reduce nitrogen use efficiency (NUE). These losses not only compromise crop productivity but also contribute to environmental concerns, including atmospheric pollution and ecosystem imbalance. Therefore, this study was conducted to investigate an innovative and eco-friendly solution through the development of nano-silicon–coated urea synthesized from rice husk, an abundant agricultural byproduct. Nano-silicon was produced via hydrochloric acid (HCl) pre-treatment followed by thermal incineration at 700 °C, and its functional groups were characterized using Fourier Transform Infrared Spectroscopy (FTIR). To evaluate the effectiveness of nano-Si–coated urea in reducing  $\text{NH}_3$  volatilization losses, a two-week laboratory experiment was conducted at the Sindh Agriculture University, Department of Soil Science. The experiment comprised two treatments ( $T_1$  = conventional urea;  $T_2$  = nano-Si–coated urea) applied at a uniform rate of 160 kg N ha<sup>-1</sup>, with three replications arranged in a Completely Randomized Design (CRD). The forced-draft technique was employed to capture nitrogen losses. Results indicated that nano-silicon–coated urea reduced nitrogen losses by 30–45% compared to conventional urea. The nano-Si formulation significantly reduced cumulative ammonia volatilization, thereby enhancing Nitrogen Use Efficiency (NUE) by 15–20%. This study demonstrates the potential of utilization of agricultural waste into high-value nano-inhibitors, offering a suitable and climate-smart strategy for nutrient management in nitrogen-sensitive ecosystems.

## From Hormone to Harvest: Unlocking Auxin for Improved Sesame Yield and Mineral Nutrition under Limited Nutrient Supply

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Continuous nutrient mining and declining soil fertility reduce crop productivity and food security. Further, ever-increasing prices of fertilizer are compelling farmers to curtail fertilizer inputs. In this context, exogenous application of auxin (indole 3-acetic acid) under low fertilizer input is compensating approach to minimize crop losses and improve nutrient use efficiency. Auxin is a crucial class of plant hormones (primarily Indole-3-acetic acid or IAA) that regulate growth, development, and environmental responses by stimulating cell elongation, division, and differentiation. A field experiment was executed at farm area of Soil Chemistry Section, Ayub Agricultural Research Institute, Faisalabad with different treatments including recommended and reduced rate of fertilizer with and without IAA application on sesame. Three level of Indole 3- Acetic Acid as foliar spray (0, 25 and 50  $\mu\text{M}$ ) and four levels of fertilizers (70,80, 90 and 100% of recommended rate of NPK) were applied using split plot design with three replications. Results showed that application of IAA @ 25  $\mu\text{M}$  along with 100% RD of NPK improved the sesame yield up to 6% as compared to the sole application of 100% RD of NPK. This increase was more profound (13%) with 25  $\mu\text{M}$  IAA under reduced supply of fertilizer (70% RD of NPK) in comparison to the 70% RD of NPK. These findings demonstrated that application of IAA @ 25  $\mu\text{M}$  effectively mitigate the stress condition as well as low fertilizer application, improve sesame yield and enhancing crop yield under limited nutrient levels.

## Genotypic Variation in Indigenous Cotton Cultivars for Phosphorus Acquisition and Utilization in Calcareous Soil

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Low phosphorus availability in calcareous-alkaline soils has been a concern for agriculture due to its fixation by calcium. However, a considerable genetic variation for phosphorus uptake and utilization has been reported among cotton varieties. This study aimed to exploit genotypic variation in phosphorus acquisition and utilisation efficiency among indigenous cotton cultivars to select phosphorus-efficient cotton varieties and reduce high fertilizer input costs. Fifteen cotton cultivars were evaluated in a pot culture experiment under variable phosphorus levels in a greenhouse under a completely randomised design. There were two treatments ( Low P: 5 mg kg<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and adequate P: 20 mg kg<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>) and four replications in this study. The plants were harvested at the vegetative stage, and data about plant height, shoot fresh weight, shoot dry weight, number of leaves per plant, leaf chlorophyll, root fresh weight, root dry weight, and root length were recorded. Tissue phosphorus was determined using standard analytical procedures. The available data were used to compute total phosphorus uptake, phosphorus acquisition efficiency, phosphorus use efficiency, and phosphorus stress factor for the cotton varieties. The cotton varieties were classified into low-uptake and efficient-

uptake groups using cluster analysis. The results revealed significant varietal variation ( $p \leq 0.01$ ) among cotton varieties for the studied traits. Under low phosphorus treatment, the cotton varieties, CKC-3 and FH-SuperCotton, maintained higher P uptake ( $18.7 \pm 1.2$  and  $17.9 \pm 0.9$  mg pot<sup>-1</sup>), greater root dry weight ( $4.8$ – $5.1$  g pot<sup>-1</sup>), longer roots, higher leaf SPAD values (42–45), and a reduction of 12–15% in shoot dry weight. We have found that varieties CIM-482 and FH-444 were more P-efficient, as indicated by higher PUE ( $> 52$  g shoot DW per mg P uptake) and a 20–25% reduction in biomass under low P treatment compared to the control (adequate P). The poor P-efficient varieties include VH-305, MNH-1035, and FH-114, which showed more than 55% reduction in shoot dry weight, root dry weight below  $2.1$  g pot<sup>-1</sup>, and phosphorus stress factor (PSF) exceeding 60%, confirming their high sensitivity to phosphorus deficiency. The P uptake and PUE have shown a strong correlation with shoot and root dry weights ( $r = 0.87$ ,  $p < 0.001$ ). Based on cluster analysis, the cotton varieties were classified into three groups: the high P-efficiency group included CKC-3 and FH-SuperCotton; the moderate P-efficiency group comprised CIM-602, FH-900, CIM-663, SLH-77, IR-13, and FH-663; and the low P-efficiency group included VH-305, MNH-1035, FH-114, Cyto-124, and CIM-448. These results demonstrate that substantial diversity exists among our cotton varieties in P acquisition and utilisation, which can be exploited to develop highly efficient P cultivars. The cultivation of promising cotton varieties will reduce the cost of phosphatic fertilisers and lower production costs for the farmers. The varieties with higher P uptake and utilization efficiency can also be used as donors to improve existing cotton varieties through hybridization in breeding programs.

## Inoculation Effect of Phosphorus Solubilizing Bacteria with Organic and Inorganic Fertilizers on Soil Phosphorus Concentrations and Crop Yield

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A two-year field study (2022-24) at the University of Agriculture, Peshawar, Pakistan, investigated an integrated nutrient management approach using phosphate-solubilizing bacteria (PSB) combined with organic and inorganic phosphorus (P) sources to enhance phosphorus availability in alkaline-calcareous soils. The study included an incubation phase over 60 days and field experiments in a randomized complete block design with seven P source treatments (rock phosphate, single superphosphate, compost, and sugarcane bagasse ash) and two levels of PSB inoculation (*Pseudomonas striata*). The results showed that in the incubation study, resin-extractable P peaked at  $7.00$  mg g<sup>-1</sup> under SSP + bagasse ash + PSB at 10 days, while Olsen P reached  $8.04$  mg g<sup>-1</sup> under SSP + compost + PSB, whereas the water-soluble P was highest at  $3.49$  mg L<sup>-1</sup> under SSP + compost + PSB at 10 days. In the maize field experiment, PSB-inoculated plants showed greater height ( $195.8$  cm), cob length ( $18.5$  cm), grain yield ( $3796$  kg ha<sup>-1</sup>), and biological yield ( $11563$  kg ha<sup>-1</sup>) compared to non-inoculated plots. The treatment combining PSB with compost and SSP (T5) yielded  $3796$  kg ha<sup>-1</sup> and biological yield of  $11563$  kg ha<sup>-1</sup> with the highest P uptake ( $23.3$  kg ha<sup>-1</sup>) and phosphorus use efficiency (23.6%). For wheat, inoculated plants achieved a maximum height of  $108.0$  cm and grain yield of  $10584$  kg ha<sup>-1</sup>, with T5 again showing the best results having higher grain yield with higher P uptake of  $26.8$  kg ha<sup>-1</sup> and phosphorus use efficiency of 20.06% among the treatments combinations. Post-harvest soil analysis indicated significant increases in soil P fractions including AB-DTPA ( $4.63$  mg kg<sup>-1</sup>), Olsen

(5.34 mg kg<sup>-1</sup>), and resin-extractable P (4.83 mg kg<sup>-1</sup>), with the highest levels in the PSB-compost-SSP combination. The study concluded that integrating PSB with compost and SSP enhances phosphorus solubilization, improved plant uptake efficiency, and significantly boosted crop productivity and soil fertility, making it a sustainable phosphorus management strategy for maize and wheat cultivation.

## Earthworms with Low Dose N-MoS<sub>2</sub> Improve Soybean Yield and Quality by Reconfiguring Rhizosphere Chemistry and Strengthening Nitrogen Fixation

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Nano-enabled fertilizers can enhance biological nitrogen fixation (BNF) and increase yield in legumes; however, their interactions with earthworms remain poorly understood. We performed a 120-day greenhouse experiment applying low-dose n-MoS<sub>2</sub> at 10 mg kg<sup>-1</sup> with earthworms to evaluate interactive effects on soybean yield and underlying mechanisms. Earthworms combined with n-MoS<sub>2</sub> treatment promoted Mo release and transport, with translocation and bioaccumulation increased 44 and 26% respectively. Furthermore, the rhizosphere soil shifted towards NO<sub>3</sub> dominance while pH remained stable and consistent with sustained nitrification. Belowground, root system architecture expanded by 33-82% and nodulation upregulated by 51-61% relative to control. Similarly, leaf performance was maximized under the n-MoS<sub>2</sub> with earthworm treatment as photosynthetic capacity and gas exchange efficiency by 23-32%, and 23-27%, respectively. Additionally, NR, NiR, GS, GOGAT and urease increased 30-46% in shoots and 23-43% in roots. Moreover, shoot and root N contents increased by 56-68%, while nitrogenase activity and BNF increased by 51-40%, respectively. Consequently, pods, seeds, and grain yield per plant increased by 90, 64 and 41% respectively. Accordingly, seed protein and soluble sugars improved by 44 and 98% respectively. Collectively, our findings shows that earthworm amplify the efficacy of n-MoS<sub>2</sub>, mobilizing Mo and strengthening BNF to deliver higher soybean yield and improved seed quality, supporting a practical, low-input strategy for sustainable production.

## Nanotechnology for Climate Resilient Agriculture: Key Challenges to Field Based Adoption

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Climate change is affecting the agriculture by intensifying climate-induced stressors and threatening global food security. Despite rapid growth in nano-enabled agricultural solutions, field evidence remains limited and heterogeneous. The current review evaluates 59 field-based studies encompassing 161 nanomaterial-crop-stress combinations, involving 34 distinct nanomaterials (NMs) and 19 crop species. Across these studies, nano-enabled interventions improved crop yields by 18-67%, enhanced stress resilience by 20-48%, and reduced disease severity by 35-62% in reported studies, typically linked to improved nutrient-use efficiency and antioxidant defenses. However, many field trials lacked comparisons with conventional inputs, multi-season or dose-response validation, limiting impact and translatability of the findings. Drawing on scientific and economic insights, we propose a roadmap for upscaling of nanotechnology in agriculture, emphasizing long-term trials, farmer engagement, and harmonized global risk governance as key factors for upscaling nano-enabled agriculture. With strategic investment and collaborative research, nano-enabled agriculture could strengthen resilient, sustainable food systems under climate change.

## Evaluate the Impact of Legume (*Chick pea*) to Improve Soil Diversity and Health under Changing Climate: A Solution for the Nutrient Restoration

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Legumes are important crops mainly grown as a source of energy and protein, essential amino acids, dietary fiber, minerals and vitamins and play significant role in addressing global nutritional security. Pulses are usually grown under rainfed, highly unstable and complex environment with substantial variability in soil and environmental factors high year-to-year and variation in soil moisture. Pulses are vital component of agricultural biological diversity in term of land degradation and nutrient restoration, essential for tackling climate change, can mitigate climate change by reducing the dependence on synthetic fertilizers that artificially introduce nitrogen (N) in the soil. Therefore study was conducted to address the climate change option for the sustainable agriculture. The study was conducted at the experimental site of Soil and Environment Research Institute, Agriculture Research Sindh Tandojam. Study was conducted in the RCBD (Randomized Completely Block Design) with five

treatments of nitrogen and phosphorus fertilizer as T1 (Control), T2=50% (Rec.doz) T3= 75%, T4=50% and T5= 25% was applied with four repeats. Soil was analyzed before and after the field trial for the physicochemical properties including texture, EC, pH, O.M, N, P and K. Where the key parameters of chickpea crop itself prove to produce more plant height (cm) biological yield (Kg/ha), number of branches per plant, number of pods per plant and grain yield @50% recommended dose of nitrogen and remaining credits with the help of nitrogen fixing ability of legume. The study will enhance the understanding of productivity improvement in the system-based approach. Furthermore, the research outcomes highlighted significant results to provide roadmap for the researchers, academia, policy makers, national and international non-governmental organizations to connect farmers and growers to promote them for soil health and can reduce the cost of chemical fertilizers to make nutrient (mainly nitrogen) restoration.

## Sustainable Soil Fertility Management Through Application of Recycled Fruit and Vegetable Based Biochar

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Agricultural waste management and soil degradation are major challenges in sustainable agriculture. This study evaluated the potential of biochar produced from fruit and vegetable waste as a soil amendment to improve soil health and maize (*Zea mays* L.) yield. The field experiment was conducted at the farm area of Soil Chemistry Section, Ayub Agricultural Research Institute (AARI). Biochar was prepared through pyrolysis of fruit and vegetable waste under controlled conditions where biochar was applied through integrated approach at three rates: 0 t ha<sup>-1</sup> (control), 1 t ha<sup>-1</sup>, and 2 t ha<sup>-1</sup> using randomized complete block design with three replications. All the chemical fertilizers were used as recommended dose. Soil samples were analyzed for pH, electrical conductivity (EC), organic matter, available nitrogen, phosphorus and potassium. The results showed that biochar application significantly improved soil organic matter, nutrient availability while soil pH was decreased toward neutrality. A reduction in soil EC was also observed, indicating improved soil health. Results also showed that biochar application significantly improved plant growth and yield components of maize compared to the control. The maximum improvement in plant height, biomass accumulation, and grain yield was recorded where biochar applied 2 t ha<sup>-1</sup>, followed by 1 t ha<sup>-1</sup>. Overall, fruit and vegetable waste-derived biochar proved to be an effective, low-cost, and environmentally friendly soil amendment, contributing for enhancing maize productivity and supporting sustainable agricultural practices.

## Whole Genome Sequence Analysis of A Rhizobacterium Rz-7 Provides Novel Mechanistic Insights Depicting Stress Tolerance and Yield Improvement in Bread Wheat (*Triticum aestivum* L.)

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Global agriculture is increasingly affected by various abiotic stresses due to climate change. Among these, drought is considered as a major limiting factor for food productivity. To mitigate these impacts on agriculture, plant-beneficial bacteria offer climate-smart and sustainable solution. Present study reports in silico, in vitro and in vivo analysis of a desert-native bacterial strain RZ-7 for its plant-growth-promoting and stress tolerance potential. Whole genome sequence analysis revealed 23 contigs and a genome size of 4.1 Mb. Functional annotation indicated genes related to indole-3-acetic acid (IAA) production, nitrogen metabolism, phosphate solubilization, exopolysaccharides, and siderophore biosynthesis. The genome also encoded heavy metal resistance, antibiotic biosynthesis and degradation pathways, and genes involved in osmolyte production, GABA biosynthesis, glutathione metabolism, and ROS detoxification. Taxonomic analysis revealed RZ-7 as Cronobacter muytjinesii. Pangenome analysis showed that the species is open for diversity, with conserved genes linked to growth-promotion and stress response. In vitro assays confirmed IAA production, phosphate and zinc solubilization, and siderophore production. In vivo drought-stress experiments revealed a 33.6% increase in root area, 71.4% increase in root fresh weight, and 15.4% increase in leaf area at 60 DPI in RZ-7-inoculated plants compared to uninoculated controls. At maturity, grain weight increased by 69.5%, yield improved by 38.6%, and the number of grains increased by 24% under half-water conditions. These findings demonstrate the growth-promoting and drought-alleviating potential of RZ-7. Large-scale field trials may further validate its efficacy as a biofertilizer for Climate-Smart Agriculture.

## Development of Eco-Friendly Bioformulation Using PGPRs and Neem Leaf Extract for Enhancing Soil Health and Sustainable Crop Productivity

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In Pakistan, trivial progress in biopesticides and excessive reliance on chemical pesticides are adversely impacting the market value of various crops including cotton. The use of chemical pesticides also has some drawbacks like contamination of soil and water bodies, can kill beneficial insects and a major cause of resistance in insect pests. Among various other factors, cotton is strongly affected by pest attacks like chewing insects prompting widespread use of chemical pesticides. This study was conducted to explore the potential of Neem leaf extract (NLE), PGPRs (plant growth promoting rhizobacteria) by encapsulating them in alginate beads and storax against *Spodoptera frugiperda* (Fall armyworm: FAW) and *Helicoverpa armigera* (Pink bollworm). The alginate beads were prepared from sodium alginate and  $\text{CaCl}_2$ . An ethanol-based Neem leaf extract (powder form) was prepared and then freeze dried. NLE was used separately and in combination with PGPRs against the target pests. Insect bioassays were conducted using PGPRs based alginate and storax formulations against FAW. The results of the bioassays revealed statistically significant reduction in insect population (number) when NLE and PGPRs were used separately. However, the combination of PGPRs encapsulated in alginate beads, storax and NLE at a precise ratio effectively reduced the insect incidence on cotton plants under controlled laboratory and glasshouse conditions. The use of this approach has improved the PGPR activity in soil resulting in improved nutrient solubilization that ultimately enhanced the plant health and crop productivity. In a nutshell, this research will help to develop a bioformulation having insecticidal activity against chewing as well as sucking insect pests and it will also be an environment friendly approach towards a sustainable agriculture in terms of enhancing soil health and crop productivity.

## Mitigation of Multiple Abiotic Stresses in Spring and Autumn Maize Using Silicon-Modified Biochar

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Co-occurrence of cadmium (Cd) and drought stress coupled with salinity disrupts plant metabolism and physiological processes, posing a major constraint to sustainable maize production in arid and semi-arid regions. Integrating organic amendments with beneficial nutrients has shown significant potential for enhancing plant resilience against multiple abiotic stresses. In this context, silicon-enriched biochar (Si-BC) has emerged as a promising strategy for improving soil conditions and crop stress tolerance. This study evaluated the effectiveness of Si-doped BC as a mitigation strategy against combined effects of salinity ( $\text{EC}_e=6.2 \text{ dS m}^{-1}$ ), drought (imposed at the V4-V5 growth stage) and Cd contamination ( $20 \text{ mg kg}^{-1}$ ) in maize. During the spring season, a pot experiment was conducted with thirteen treatments, including two controls, individual applications of silicic acid and sodium silicate (@  $150 \text{ kg ha}^{-1}$ ), three types of BC derived from rice husk, cotton sticks and maize stalks (@  $0.5\% \text{ w/w}$ ), and their combined applications as Si-BC (@  $75 \text{ kg Si ha}^{-1}$  and  $0.25\% \text{ BC}$ ). The residual effects of these treatments were evaluated in the subsequent autumn maize crop. The results revealed that silicic acid-doped rice husk biochar (SA-RBC) outperformed all other individual and Si-doped BC treatments across both growing seasons. In spring maize, SA-RBC significantly increased the plant height, root fresh weight, shoot fresh weight, root dry weight, shoot dry weight and root length by 31.68%, 74.69%, 41.92%, 71.73%, 105.39% and 76.58%, respectively, compared with stressed control. Furthermore, SA-RBC produced 12.0% and 13.03% greater shoot biomass and 47.88%, 35.0% higher

root biomass compared to its respective individual SA and RBC counterparts, respectively. In addition, pronounced residual effects of SA-RBC were observed in autumn maize crop, where plant height, shoot and root fresh biomass, and root length increased by 38.15%, 41.36%, 88.23% and 77.20%, respectively, compared with untreated stressed control. Overall, Si-doped RBC demonstrated strong mitigation potential against combined salinity, drought and Cd stress, while also imparting significant residual benefits to subsequent maize crops, highlighting its promise as a climate-resilient soil amendment.

## Hydrogels A Way Farward For Food Security in Rainfed Areas

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Food security and soil sustainability is major problem in rainfed areas of pothwar plateau. Farming in these areas fully dependent on rainwater. The need of the day is to explore the role of hydrogels to retain rainfall water. To address this issue and ruling the role of hydrogels and to fulfill the increasing need of energy of the population of rainfed areas a field study was conducted at Village Pindsultani area, District Attock, Pakistan with sandy loam soil texture. The sandy soils with course texture are low in available water and nutrients and drain out quickly resulting in less yield. The present study was conducted on wheat crop for four consecutive years from 2021 to 2024. The treatment plan was control (no hydrogel), hydrogel @ 05 kg ha<sup>-1</sup>, 7.5 kg ha<sup>-1</sup> and 10 kg ha<sup>-1</sup> with three replications under Randomizes Complete Block Design. Results showed that a significant increase of water contents (30 to 36%), grain yield (32 to 35%) and nutrient uptake (3.57 to 5.4 mg/kg of P<sub>2</sub>O<sub>5</sub> and 65 to 90 kg/mg of K<sub>2</sub>O) was quantified in 7.5 kg ha<sup>-1</sup> and 10 kg ha<sup>-1</sup> respectively as compared with control. This study suggested for inclusion of hydrogels to store and retain water in rainfed areas which ultimately resulted in increase of yield and nutrients availability.

## Effect of Rhizobacteria on the Wheat Productivity under Climate Induced Heat Stress

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The seasonal variation is considered an important indicator of climate change that is posing a threat to crop production. Temperature variation during the growing season causes heat stress, which has a detrimental impact on the grain filling period of wheat and generally reduces the crop yield. The colonization of the plant rhizosphere by plant growth-promoting rhizobacteria (PGPR) contributes to nutrient cycling and stress management. The objective of the research was to evaluate the influence of PGPR on wheat yield parameters and soil health to mitigate seasonal variation by adjusting sowing

dates. Two different sowing dates (15-11-2022 and 15-12-2022) were selected for the experiment. The treatments were the application of seed coating with PGPR, including Azospirillum, Azotobacter, Pseudomonas, Bacillus, consortium, and one control for both early and late sowing wheat. Therefore, a field experiment was conducted with inoculated and non-inoculated seeds in the field area of the Ayub Agriculture Research Institute, Faisalabad. The results showed that a significant high wheat yield was observed with the application of Consortium ( $5.4 \pm 0.4$  tons ha<sup>-1</sup>) under early sowing. Compared to late sowing, the application of Azospirillum and Azotobacter significantly increased soil microbial biomass carbon under early sowing. Whereas, consortium and Bacillus increased the  $\beta$ -glucosidase and chitinase activity under late sowing, while Bacillus, Pseudomonas and Azotobacter improved the acid phosphatase and leucine aminopeptidase activity under late sowing. The applications of consortium ( $0.801 \pm 0.01$  %) and Bacillus ( $0.803 \pm 0.02$  %) showed the highest soil organic carbon in early sowing than late sowing. Furthermore, consortium significantly increased shoot nitrogen under early sowing and grain N under late sowing. Whereas Azotobacter increased the shoot phosphorus under early sowing and grain P under late sowing. The potassium shoot content was significantly high under early sowing with the application of Azospirillum while Pseudomonas increased the K content under late sowing. The soil N content was significantly highest with the application of Bacillus ( $0.42 \pm 0.02$  mg N kg<sup>-1</sup> soil) and consortium ( $0.41 \pm 0.01$  mg N kg<sup>-1</sup> soil) under late sowing. The significantly highest soil extractable P content was observed in consortium ( $47 \pm 2.2$  mg P kg<sup>-1</sup> soil) under early sowing, while under late sowing, the highest soil extractable P content was observed with the application of Azospirillum ( $47 \pm 2.6$  mg P kg<sup>-1</sup> soil). The soil extractable K content was significantly highest with the application of Azospirillum ( $126 \pm 4.1$  mg K kg<sup>-1</sup> soil) in early sowing. It was concluded that the application of PGPRs could be an efficient strategy to increase wheat productivity under heat stress.

## Impact of Different Irrigation Methods on Yield and Yield Attributes of Citrus in The Pothowar Region

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Water is one of the most important factors for the optimal growth and production of agricultural crops, including fruit plants such as citrus. In semi-arid regions where rainfall is limited and irregular, efficient irrigation management becomes essential for sustaining crop productivity. The Pothowar region of Pakistan experiences water scarcity and uneven rainfall distribution; therefore, the adoption of suitable irrigation techniques is crucial for improving citrus yield and ensuring efficient water utilization. There are different irrigation techniques in usage for field crops as well as orchards. A study was conducted in soil and water conservation research station, Fateh Jang, Pothowar, Pakistan to evaluate various irrigation techniques for economic utilization of water in citrus orchard. The irrigation techniques studied were: 1) Basin irrigation (control), 2) Surface Drip Irrigation 3) Bottle irrigation ,4) Pitcher Irrigation and 5) Perforated Plastic Sleeves Irrigation applied to citrus plants for four years. The experimental results revealed that the surface drip irrigation produced the highest plant height (188 cm), number of branches (9.25), plant periphery (343 cm), fruits per plant (353) and fruit weight (170

g) compared with other irrigation techniques. The maximum increase in citrus yield was 51% with basin irrigation. Moreover, the maximum increment in water productivity was 83% in surface drip irrigation as compared to other irrigation techniques. Another important outcome of the study was the improvement in water productivity. Surface drip irrigation demonstrated the highest water use efficiency among all the irrigation systems tested. This indicates that drip irrigation not only improves plant growth and yield but also conserves water by delivering it directly to the root zone of the plants, thereby minimizing evaporation and runoff losses. In conclusion, the findings of this study clearly demonstrate that surface drip irrigation is a highly efficient irrigation method for citrus cultivation in the Pothowar region of Pakistan. It significantly improves plant growth, fruit yield, and water use efficiency compared with traditional irrigation techniques. Therefore, the adoption of surface drip irrigation can play an important role in enhancing citrus production while conserving limited water resources in semi-arid regions like Pothowar.

## Impact of N Sources and Tillage Depths on N Use Efficiency in Wheat Crop

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Nitrogen (N) management is crucial in agricultural crop production due to the low use efficiency of nitrogenous fertilizers and significant losses. Tillage practices influence agricultural sustainability by impacting soil properties, soil processes, nutrient efficiency, and crop production. The objective of this 2-year field study was to compare two N sources (Urea and CAN, 160 Kg N ha<sup>-1</sup> applied in 3 splits) and conventional tillage with tine cultivator (CT=0-15cm) and deep tillage with moldboard plough (DT=0-30cm) on soil biological properties, grain yield, and nitrogen use efficiency of winter wheat. A split-plot design was adopted in the winter wheat growing seasons of 2020-21 (S1) and 2021-22 (S2), with CT and DT performed in the main plots, and subplots were treated with two N sources (CAN and Urea) and a control with no-N. The results of the study showed that both N sources and tillage depths had a non-significant impact on agronomic parameters, except 1000-grain weight, which was significantly higher when urea was applied for both tillage practices. The recovery and agronomic efficiencies were high with urea and low with CAN fertilizer under both tillage depths in S2. The N uptake in plant parts increased with N sources regardless of tillage depths. The topsoil total N was higher in urea under CT, and the subsoil N increased by CAN under DT. The N sources increased the top and subsoil nitrate levels, and were significantly higher with CAN under DT tillage. The soil organic carbon and microbial biomass carbon contents decreased in the topsoil and increased in the subsoil, regardless of tillage depth, in response to different N sources. The  $\beta$ -glucosidase activity increased by N sources in both tillage depths, and chitinase increased by both N sources in DT. The aminopeptidase was decreased by N sources, irrespective of tillage depths. The study concluded that CT with urea is a viable approach for improving NUE and maximizing wheat productivity.

## Crop Recommendation Using Machine Learning with Soil and Environmental Data

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Agriculture plays a vital role in the economic development and food security of many countries, particularly in developing regions where a large proportion of the population depends directly on agricultural activities for their livelihood. Crop productivity is highly influenced by soil properties, climatic conditions, and the availability of essential nutrients in the soil. In general, farmers select crops based on personal experience, conventional practices, and general agronomic practices. However, such traditional approaches do not always result in optimal crop yield, resulting in 15-30% yield losses. Therefore, there is a strong need for intelligent systems that can assist farmers in making informed crop selection decisions. This presentation has been focused on developing a machine learning–based system capable of predicting the most suitable crop for a particular field using soil and environmental data. The system utilizes key soil parameters such as soil pH, soil moisture, and the concentration of essential nutrients, along with other relevant environmental factors. The proposed system generates crop recommendations tailored to specific soil and environmental conditions, with the potential to improve yield by 20–25% while reducing fertilizer misuse by approximately 15%. By integrating quantitative soil analysis with predictive analytics, the model provides a farmer-friendly decision support tool that enhances productivity, promotes efficient resource utilization, and supports sustainable agricultural practices.

## Comparative Effect of Various Organic Sources on Maize Yield, Soil Characteristics and Soil Carbon Stock

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The influence of added organic sources on soil characteristics, nutrient releases, buildup of soil carbon and ultimate effect on crop productivity varies with their sources. For this purpose, field and incubation studies were conducted in the Department of Soil and Environmental Sciences, The University of Agriculture Peshawar. The comparative influence of biochar, farmyard manure (FYM), crop residue (CR), poultry manure (PM) on soil carbon stock and maize yield was examined. The experimental design in the field was Split-Plot Randomized Complete Block Design (RCBD) with three replications main plots were maize crop and fallow whereas four organic sources and one control were applied to sub-plots. As compared to alone NPK application the integration of organic amendments significantly increased the maize yield, yielding attributes, nutrient concentration and improved the soil organic stock. The maximum plant height (183 cm), grains per cob (483.33), 1000-grain weight (316 g), biomass yield (13673 kg ha<sup>-1</sup>) and grain yield (4456.3 kg ha<sup>-1</sup>) were obtained using Poultry

manure. The biochar treated plots had significantly better plant N (2.04 %), C:N ratio (26.6) whereas poultry manure exhibited higher plant P (0.17 %), plant K (1.53 %). The postharvest soil analyses showed that biochar led to significant improvement of soil organic carbon (1.03%) and organic matter (1.77%). This implies that biochar has a high capacity to sequester carbon. Poultry manure was found to be very beneficial in maintain soil phosphorus (4.91 mg kg<sup>-1</sup>), whereas the FYM was found very helpful in K (111.45 mg kg<sup>-1</sup>). Incubation studies corroborates field study where less microbial activity, and higher soil C was recorded as compared to other manures. The results conclude that poultry manure was most useful in promoting the production of maize and biochar was better at promoting the long-term soil health and carbon stores. It is as well suggested that integrated application of organic amendments should be used in the production of maize and enhancement of soil fertility in a sustainable manner.

## Comparative Evaluation of Iron Fertilizer Sources and Fe-Enriched Compost on Growth, Yield and Fe Biofortification in Maize (*Zea mays* L.)

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Iron (Fe) deficiency in maize is a widespread problem that limits crop productivity and reduces nutritional quality, particularly in regions where maize is a staple food. To address this challenge, a field experiment was conducted to evaluate the comparative effectiveness of different Fe fertilizer sources and Fe-enriched compost on maize (*Zea mays* L.) growth, yield, and Fe biofortification. Six treatments were applied: T0 (control), T1 (Fe-solubilizing bacteria), T2 (Fe ash), T3 (iron sulfate), T4 (compost), and T5 (integrated application of compost (40 kg) + Fe ash (5 kg) + Fe-solubilizing bacteria). Growth parameters including plant height, shoot dry weight, root length, root dry weight, relative water content, and SPAD value were measured. Yield attributes such as cob length, cob diameter, cob dry weight, and grain yield were recorded, along with nutrient concentrations of N, P, K, Zn, and Fe in both grains and straw. Results demonstrated that compost and Fe-solubilizing bacteria significantly improved plant growth, physiological traits, yield components, and nutrient enrichment compared to the control and sole applications. Among all treatments, the integrated application (T5) was most effective, producing the highest grain yield and enhancing Fe concentration in grains and straw, while also improving uptake of N, P, K, and Zn. These findings highlight that combining organic amendments with mineral and microbial Fe sources offers a sustainable strategy to improve maize productivity and nutritional quality, while contributing to better soil fertility management and reducing micronutrient malnutrition.

## Characterization and Survival of Plant Growth Promoting Rhizobacteria in Biochar-Amended Bio-Compost

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Integrating biochar with bio-compost creates a synergistic soil amendment that enhances nutrient retention, improves soil structure, and increases crop productivity more effectively than either amendment alone. This combination stimulates microbial activity, reduces greenhouse gas emissions ( $\text{NH}_3$  and  $\text{CH}_4$ ), and immobilizes heavy metals in contaminated soils. The present study evaluated the efficacy of biochar–bio-compost mixtures as carrier materials for plant growth–promoting rhizobacteria (PGPR) and assessed their effects on rice growth, nutrient uptake, and rhizosphere colonization. An in vitro incubation experiment was conducted to examine the physicochemical properties and bacterial survival across twelve biocharbio-compost combinations. Biochar was produced from rice straw (RSB), mango leaves (MLB), and banana leaves (BLB) and blended with bio-compost at ratios of 100:0, 75:25, 50:50, and 25:75. The carrier formulations were analyzed for pH, electrical conductivity (EC), total organic carbon (TOC), organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), and PGPR survival over a 90-day incubation period. The results demonstrated that mixtures containing moderate biochar and higher proportions of bio-compost performed most effectively. The RSB 25% + BC 75% treatment exhibited the highest TOC (26.77%) and achieved maximum OM content (45.01%) at 90 days. The greatest bacterial survival ( $1.75 \times 10^8$  CFU  $\text{g}^{-1}$ ) was observed in MLB 25% + BC 75%, whereas sole biochar treatments showed significantly lower PGPR survival throughout incubation. The BLB 50% + BC 50% formulation produced moderate improvements in TOC, OM, and PGPR viability. In contrast, treatments containing 100% biochar consistently recorded the lowest microbial survival and elevated EC values, indicating limited nutrient availability. Overall, increasing the proportion of bio-compost enhanced nutrient content and stabilized pH, while high biochar content without compost reduced microbial persistence. These findings support the use of optimized biocharbio-compost mixtures as sustainable carrier systems to improve soil health, enhance microbial activity, and promote crop productivity.

## Assessment of Heavy Metals in Pumped Groundwater from Faisalabad City Area: A Case Study

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Poor quality and contaminated groundwater is a major threat to the health of masses because large number of human population uses groundwater as a source of drinking water. Groundwater quality is deteriorating day by day due to salinity and heavy metal contamination causing public health concern in Faisalabad. Therefore, the present study was conducted at Soil Chemistry Section to assess chemical parameters including pH, electrical conductivity EC, and total dissolved solids (TDS) along with toxic heavy metals (Pb, Cd, Cr, and Ni) in groundwater samples collected from city area including Nazimabad, Gobindpura, Afghanabad, Jinnah Colony, Ghulam Muhammadabad, and AARI. After collection, samples were analyzed on Atomic Absorption Spectrophotometer. The pH values ranged

from 7.01 to 7.89, remaining within the permissible range i.e 7.0-8.5. In contrast, TDS concentrations (333-3450 mg L<sup>-1</sup>) exceeded the recommended limit of 500 mg L<sup>-1</sup> in most sampling locations, particularly in Ghulam Muhammadabad (2061 ± 873 mg L<sup>-1</sup>) and Nazimabad (1877 ± 971 mg L<sup>-1</sup>), indicating elevated salinity levels and groundwater quality deterioration. Heavy metal concentration revealed marked spatial variability. The highest Pb contamination percentage of unfit samples exhibited in Ghulam Muhammadabad (57%), followed by Nazimabad (35%), Jinnah Colony (31%), AARI (28%), and Afghanabad (21%), while Gobindpura showed comparatively lower contamination (7%). Nickel (Ni) contamination was most prominent in Nazimabad (65%) and Jinnah Colony (31%). whereas cadmium (Cd) remained within safe limits across all study sites. Overall, elevated salinity, Pb and Ni dominance in groundwater of several urban areas suggested that quality of ground water was poor and contaminated. Therefore continuous monitoring of groundwater is a dire need of time to protect health of masses.

## Role of Organic and Chemical Phosphorus Amendments in Enhancing Wheat Productivity and Mineral Nutrition under Alkaline Calcareous Soils

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Poor soil fertility, declining organic matter and inefficient nutrient management are major constraints limiting wheat productivity under changing climate. Moreover, high phosphorus fixation threatens wheat productivity in alkaline calcareous soil of Pakistan. It lowers P availability, reduces grain size and crop yield. Organic fertilizers enhance P availability in soil through production of organic acids which lower soil pH and chelate calcium and reduces P fixation. Likewise, chemical fertilizers do same by supplying available P. In this context, a field study was conducted at Soil Chemistry Section, Faisalabad to evaluate the effect of organic and chemical amendments for improving crop productivity and mineral nutrition in wheat. Treatments T1: Control (No fertilizer), T2: Control P0 + RD NK, T3: Recommended P (DAP) + RD NK, T4: Recommended P (SSP) + RD NK, T5: Recommended P (20% FYM + 80% Fertilizer) + RD NK, T6: Recommended P (20% Poultry Manure + 80% Fertilizer) + RD NK, T7: Recommended P (20% Press Mud & 80% Fertilizer) + RD NK were used with three replications in Randomized Complete Block Design. Results revealed that maximum wheat production was obtained in T6 followed by T4. Maximum P in wheat grain was observed in T4 and maximum K was obtained from T5. The findings suggested that integrated use of organic and chemical P amendments enhance wheat productivity and mineral nutrient of soil.

# Integrated Impact of Organic Amendments and Gypsum for Enhancing Growth and Yield of *Pisum sativum* in Salt Affected Soil

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*Pisum sativum* (Pea) is a nutrient-dense source of protein, starch, and fiber. Its protein stands out as a sustainable, affordable, and hypoallergenic plant-based ingredient, making it vital for food and industrial uses. Salts affected soils (SAS) are amongst major reasons of losses in production of agricultural crops. Soil salinity imbalance harms food production by lowering crop yields and escalating agricultural management costs. Press mud (PM), a sugarcane industry by-product, reclaims salt-affected soils by enhancing nutrient uptake, soil structure, and salinity tolerance through improved water retention, solute potential, and sodium leaching. This experiment was comprised of twelve treatments with 3 replications. Experiment was performed under completely randomized design. The effect of individual and integrated application of organic amendments (Press mud and compost at 1%) and gypsum (at 2.5 t ha<sup>-1</sup>) along with control in normal as well as salt effected soil (having EC 7 ds m<sup>-1</sup> and SAR 15 mmol L<sup>-1</sup>) was evaluated on the growth and yield of pea plant. Plant growth and yield was negatively affected by salt stress while the organic and inorganic amendments improved growth and yield of pea. Among all treatments, the integrated application of compost and gypsum was found the most effective for enhancing plant growth and yield in normal as well as salt affected soil.

# Comparative Effect of Organic and Inorganic Fertilizers Integration on Spinach (*Spinacia Oleracea*) Growth, Soil Carbon and Nitrogen Concentration

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Many Pakistani soils, particularly dry and semi-arid areas, have relatively high nitrogen inputs and very low organic carbon. The soil's carbon and nitrogen content is disturbed when synthetic fertilizers are used excessively in the lack of enough carbon-rich organic matter. Soil aggregation, erosion, and reduced water-holding ability are caused by low carbon and nitrogen concentration. Soil fertility management is crucial for sustainable agriculture in order to maintain soil health and optimize

nutrient availability. Spinach (*Spinacia oleracea*) was used as a test crop in this study to examine how adding both inorganic and organic fertilizers affected the amounts of both carbon and nitrogen in soil. Compost, poultry manure and farm manure are examples of organic materials that was combined with urea, calcium ammonium nitrate and potassium nitrate. Integrated nutrient management (INM) is thought to be more effective than either fertilizer type alone at increasing soil fertility and organic carbon sequestration. A pot experiment was conducted under a completely randomized design (CRD) with sixteen treatments and three replications to evaluate the effects of inorganic and organic fertilizers on soil carbon and nitrogen soil. The experiment consisted of sixteen treatments: T<sub>0</sub> (Control); T<sub>1</sub> (Urea 100%); T<sub>2</sub> (KNO<sub>3</sub> 100%); T<sub>3</sub> (CAN 100%); T<sub>4</sub> (Compost 100%); T<sub>5</sub> (Farm manure 100%); T<sub>6</sub> (Poultry manure 100%); T<sub>7</sub> (Urea 75% + Farm manure 25%); T<sub>8</sub> (Urea 75% + Compost 25%); T<sub>9</sub> (Urea 75% + Poultry manure 25%); T<sub>10</sub> (Potassium nitrate 75% + Farm manure 25%); T<sub>11</sub> (Potassium nitrate 75% + Compost 25%); T<sub>12</sub> (Potassium nitrate 75% + Poultry manure 25%); T<sub>13</sub> (CAN 75% + Farm manure 25%); T<sub>14</sub> (CAN 75% + Compost 25%); and T<sub>15</sub> (CAN 75% + Poultry manure 25%). Fertilizers were applied at N (100 kg ha<sup>-1</sup>), P (50 kg ha<sup>-1</sup>), and K (50 kg ha<sup>-1</sup>). Integrated treatments significantly improved soil nitrogen and carbon compared to sole applications. The combination of 75% CAN + 25% poultry manure (T<sub>15</sub>) was the most effective. The study concluded that integrating inorganic and organic nitrogen sources enhances nitrogen use efficiency, improves soil carbon status, and supports sustainable soil fertility management.

## Inoculation Effect of Arbuscular Mycorrhizal Fungi on Yield, Zinc and Copper Uptake of Rice Crop

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Arbuscular mycorrhizal fungi have a symbiotic association with rice root systems, which improves efficiency of rice growth and development under nutrient deficient and lower input management systems by increasing access and assimilation of less mobile nutrients. Zinc is a major micronutrient in rice, which is deficient on a large scale in rice-wheat ecosystem of Khyber Pakhtunkhwa, Pakistan. Copper, a major micronutrient in rice influences photosynthesis, biosynthesis of lignin, growth and development. Deficiency and toxicity have both significant implications for rice metabolism and AMF function. Soil surveys performed in Swat, Peshawar, and D.I. Khan showed a marked spatial variability of AMF populations and micronutrient concentration in the region. The highest density of AMF spores (39 per 20 g soil), its colonization (62.4%) with high organic matter (1.9%) was noticed in Swat. The lower concentration of Zn than critical levels in all studied districts suggested requirement of Zn to rice crops. Greenhouse experiments proved that combination of AMF with Zn and Cu greatly improved growth, yield, and nutrient accumulation. Application of Zn (10 kg ha<sup>-1</sup>) + AMF showed a substantial increase in plant height (90.6 cm), number of tillers (11.2 plant<sup>-1</sup>), grain yield (43.5 g pot<sup>-1</sup>), biomass production (92.0 g pot<sup>-1</sup>), and Cu (2 kg ha<sup>-1</sup>) + AMF biomass production (89.5 g pot<sup>-1</sup>) indicating improved nutrient use efficiencies in rice. In Field Experiment, incorporating FYM (10 ton ha<sup>-1</sup>), Zn, Cu and AMF resulted in maximum plant height (91.0 cm), tillers (12 plant<sup>-1</sup>), panicle length (22.5 cm), biomass (10,800 kg ha<sup>-1</sup>), and grain yield (4900 kg ha<sup>-1</sup>), highlighting the synergistic effect of organic amendments on vegetative growth and nutrient accumulation. AMF spore density (80 per 20g) and

root infection (78%) was highest in combined treatments (Zn + Cu + FYM + AMF) demonstrating role of AMF in establishing symbiosis, enhanced nutrient absorption and growth promotion. Nutrient uptake analysis revealed that Zn+ Cu +AMF resulted in the highest Zn ( $0.25 \text{ kg ha}^{-1}$ ) and Cu ( $0.049 \text{ kg ha}^{-1}$ ) absorption, while single treatments (AMF alone or Cu + FYM) showed lower uptake, confirming advantage of integrated applications. The residual effects of treatments on wheat were equally pronounced. Treatments combination (Zn + Cu + FYM + AMF) consistently outperformed single-input treatments, demonstrating synergistic benefits of microbial, micronutrient, and organic amendments. These findings provided a strong basis for AMF along with FYM based strategies to improve crop productivity, micronutrient content, and sustainable agriculture in nutrient deficient regions of Khyber Pakhtunkhwa.

## Impact of Fine Grain Gypsum on Soil Properties During Reclamation of Saline-Sodic Soil (Lysimeter Study)

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Gypsum is popular non-renewable resource used during reclamation of saline-sodic soils. The efficiency of the process is dependent on particle size of gypsum. A lysimeter experiment was conducted to evaluate the efficiency of fine gypsum FG1 (0.595–2mm), FG2 (0.250-0.595mm) with commercial gypsum CG, at three application rates i.e. 100, 75, 50 % of soil gypsum requirement. The treatments were as T1 = Control (No Gypsum), T2= Commercial gypsum @100 % GR, T3= Commercial gypsum @75 % GR, T4= Commercial gypsum @50 % GR, T5= Fine gypsum1 @100 % GR, T6= Fine gypsum1 @75 % GR, T7= Fine gypsum1 @50 % GR, T8= Fine gypsum2 @100 %GR, T9= Fine gypsum2 @75 %GR, T10= Fine gypsum2 @50 %GR. The saline-sodic soil was collected, processed in the laboratory by standard procedures and filled in PVC column. Soil Pore volume was calculated as per method of Jury et. al.,1991. Canal water was used for leaching. Four leaching cycles were monitored. The leachates were analysed for sodium, calcium, chloride, and sulphate. Soil sampling was done from respective soil columns and analysed for physical (bulk density, infiltration rate) and chemical attributes (pHs, ECe, SAR). Results depicted that maximum volume of leachates were collected from soil columns in 2nd and 3rd leachate. Maximum sodium, calcium, chloride, sulphate leached out from the soil column in 2nd and 3rd leachate. FG2x100% increased cumulative sodium, calcium, chloride, sulphates in four leachates as compared to control. FG2 x100 % and FG2 x75% were statistically at par for decreasing soil bulk density, pHs , ECe ,SAR and increasing water infiltration rate but significantly better than other interactive values. Over all fine gypsum i.e. FG2 (0.250-0.595 mm size fraction) at 75 and 50% of soil gypsum requirement proved effective for improving physical and chemical properties of saline-sodic soil.

## Effects of Synthetic and Organic Fertilizers Integration on Improving Phosphorus Availability in Chili (*Capsicum* spp.) Crop

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Phosphorus (P) is crucial component for crop growth and development, particularly for chillies (*Capsicum* spp.). However, its availability is frequently constrained due to low mobility and fixation, particularly in soils with poor phosphorus retention. This study aimed to use both inorganic and organic fertilizers together to increase the availability of phosphorus in chili growth. While inorganic fertilizers supplied easily available phosphorus, organic fertilizers improved soil structure, encourage microbial activity, and aid in the gradual release of nutrients. It was observed that the application of these two types of fertilizers improved phosphorus bioavailability and enhanced the growth and yield of chili plants. Organic materials such as compost, poultry manure, and farmyard manure were combined with DAP for use in the study. This study evaluated the effect of integrated inorganic and organic fertilizers on phosphorus availability and chilli performance in a pot experiment conducted under a completely randomized design (CRD) with eight treatments and three replications: T0 (Control), T1 (DAP 100%), T2 (Farm manure 100%), T3 (Poultry manure 100%), T4 (Compost 100%), T5 (75% DAP + 25% Farm manure), T6 (75% DAP + 25% Poultry manure), and T7 (75% DAP + 25% Compost). Fertilizers were applied at N (100 kg ha<sup>-1</sup>), P (50 kg ha<sup>-1</sup>), and K (50 kg ha<sup>-1</sup>) at planting. Physical, physiological, and chemical parameters were recorded. Results showed that integrated treatments significantly enhanced phosphorus availability and chilli growth compared to sole applications. T6 (75% DAP + 25% Poultry manure) performed best, followed by T5 (75% DAP + 25% Farm manure). The study concluded that integrating synthetic and organic fertilizers, particularly 75% DAP with 25% poultry manure or farm manure, is an effective and sustainable strategy for improving phosphorus availability, and chilli productivity.

## Comparative Effect of Chemically Amended Plant Residues and Animal Waste on B-Glucosidase Enzyme Activity in an Alkaline Calcareous Soil

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The presence of glucosidase enzyme is crucial as it decomposes the plant's residue and soil organic matter (SOM). It acts as a catalysis for the hydrolysis of cellulose into simple sugars, increases in bacterial populations and substrate availability. Because of its role in carbon cycling, has become a standard soil quality indicator. It indicates the potential of the soil community to process cellulose, as it is crucial for the plant's growth. The aim of this investigation was to identify the activities of  $\beta$ -glucosidase in the soil, amended chemically with residues of plants and animal waste. An incubation study of 40 days was set up at 20 °C in the absence of light. Fourteen treatments include organically amended soil that was treated with urine (U), slurry (S), manure (M), wheat residues (WR), dicyandiamide (DCD), neem oil (NO), and elemental sulphur (ES) combinations. The  $\beta$ -glucosidase enzyme activities were analyzed by Fluorogenically labeled substrate methods at the microplate reader. The significant outcomes of this study were that animal waste combination with (i) M+WR (ii) U+NO (iii) S+DCD (iv) S+ES at day 40,40,10,2 respectively enhanced the activity of  $\beta$ -glucosidase enzyme while the animal waste combination with (i) S+NO+WR (ii) U+NO (iii) S+DCD (iv) U+ES at day 20,10,10,10 respectively enhanced the ammonium concentration. It was concluded that animal waste combination with wheat residue, neem oil, dicyandiamide and elemental sulphur enhanced the activity of  $\beta$ -glucosidase enzyme and ammonium concentration in an alkaline calcareous soil and improved soil health.

## Split Application of Diammonium Phosphate to Improve Phosphorus Use Efficiency in Pea (*Pisum sativum* L).

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Field pea is an important pulse crop widely cultivated and consumed across the world due to its high nutritional value and increasing demand in organic and health food markets. It is a vital part of sustainable food systems because of its high protein content, dietary fiber, vitamins, and minerals. The present research trial was conducted to investigate the effects of split doses of diammonium phosphate (DAP) on the growth, yield, and soil properties of field pea. Using several DAP application treatments, a field experiment was conducted under a Randomized Complete Block Design. Five treatments including control T1 (Control), T2 (Total recommended Phosphorus as a basal dose), T3 (Two equal splits of the recommended phosphorus), T4 (75% of the total recommended Phosphorus as basal dose), T5 (Two splits of 75% of the recommended phosphorus) with three replications was applied. The results revealed significant variations among treatments for yield and yield-related parameters. The highest fresh plant biomass and number of pods per plant were recorded in T2, the maximum fresh grain weight was observed in T4, while both maximum dry grain weight and overall grain yield were obtained in T1. Overall, T1 and T2 performed better in terms of yield and growth parameters, indicating their effectiveness in improving crop productivity.

## Investigating the Effect of Boron Tolerant Phosphorus Solubilizing Strains on Maize (*Zea Mays* L.) Growth

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Boron (B) deficiency in soil is a major constraint that adversely affects maize growth, nutrient uptake, and overall crop productivity. This study aimed to evaluate the potential of boron-tolerant phosphate solubilizing bacteria (PSB) in improving maize growth and nutrient uptake under B-applied conditions. Phosphate solubilizing bacteria enhance nutrient availability by solubilizing insoluble phosphorus and improving plant nutrient acquisition. A pot experiment was conducted using a completely randomized design (CRD) with nine treatments and three replications. Treatments included NPK alone (control), individual application of boron (as boric acid), and combinations of boron with different B-tolerant PSB strains. All treatments received recommended doses of NPK and B. The bacterial strains were previously isolated from rhizosphere soils and screened for boron tolerance using Minimum Inhibitory Concentration (MIC) testing, and only strains showing tolerance up to 300–350 mM B were selected. Maize plants were grown for 30 days, and agronomic, physiological, and chemical parameters were recorded. Results indicated that the combined application of boron and B-tolerant PSB strain 4 showed the best performance. Maximum shoot length (51.33 cm), shoot fresh weight (74.52 g), shoot dry weight (14.43 g), root fresh weight (12.3 g), and root dry weight (2.24 g) were observed under this treatment. Physiological parameters such as chlorophyll content (52.33 SPAD), relative water content (84.73%), and membrane stability index (71.40%) were also significantly improved. In terms of nutrient uptake, phosphorus content in shoots and roots reached 0.35% and 0.25%, respectively, while boron content was 36.0 mg kg<sup>-1</sup> in shoots and 19.0 mg kg<sup>-1</sup> in roots, representing increases of 68.75% and 67.65% over the control. The study concluded that boron-tolerant PSB strains, particularly strain 4, significantly enhance maize growth and nutrient uptake under B-applied conditions. Therefore, these bacteria have strong potential as sustainable biofertilizer candidates for improving crop productivity in boron-deficient soils.

## Mitigating The Harmful Effects of Salinity on The Growth and Yield of Wheat Through Individual and Combined Application of Si and Zn

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Salinity stress is one of the major abiotic stress factors limiting wheat productivity particularly in arid and semi-arid regions. High soil salinity causes the osmotic deregulation, specific ion toxicity, nutrient uptake decline and effects on physiological and metabolic functioning, leading to significant yield losses. As a result, there is a need to introduce sustainable nutrient management practices to improve the performance of crops in saline soils. Silicon (Si) is involved in structural strengthening and osmotic balance, whereas zinc (Zn) is an element responsible for the activation of enzymes and integrity of membranes. Recently, nanoparticle (NP) formulations of these elements are gaining momentum in research because of their increased bioavailability and controlled release kinetics. This study was conducted to determine the individual and combined effects of bulk and nano forms of Si and Zn on the growth of wheat under saline conditions. A pot experiment was conducted under controlled conditions using normal soil and saline soil ( $EC = 10 \text{ dSm}^{-1}$ ). A Completely Randomised Design (CRD) was used with seven treatment that included control, Si, Zn, Si + Zn, Si NPs, Zn NPs, and Si NPs + Zn NPs with three replications. All the treatments were applied in normal soil as well as saline soil. The application rate for Si and SiNPs was  $100 \text{ mg kg}^{-1}$  and for Zn and Zn NPs was  $15 \text{ mg kg}^{-1}$ . Growth parameters including plant height, chlorophyll content, and number of tillers per plant were recorded at the vegetative stage. Stress tolerance indicators such as relative water content (RWC) and membrane stability index (MSI) were also measured. Salinity significantly reduced plant height, chlorophyll content, and tillers per plant, compared with the non-saline control. These negative effects were reduced by the application of Si and Zn in bulk and nanoparticles. Under saline conditions, bulk and nano Si and Zn increased plant growth and yield. The combined treatment of Si NPs + Zn NPs showed the greatest improvement in plant growth and yield. In conclusion, the combined application of nano-silicon and nano-zinc appears to be an effective strategy for mitigating salinity stress and improving wheat productivity. Long-term sustainability should be supported by the field-based validation studies.

## Impact of Zinc Oxide-Nanoparticles and Salicylic Acid Foliar Application on Physiological Attributes and Wheat Productivity under Water Deficit Conditions

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Increasing frequency and intensity of drought events pose a serious threat to wheat production, necessitating the development of effective agronomic strategies to enhance drought tolerance. An experiment was conducted to evaluate the potential of foliar-applied zinc oxide nanoparticles (ZnO NPs) and salicylic acid (SA) to alleviate drought-induced stress in wheat (*Triticum aestivum* L.). Treatments included ZnO NPs (0, 75, and  $150 \text{ mg L}^{-1}$ ) and SA (0, 0.75, and  $1.50 \text{ mM}$ ) applied individually and in combination under two soil moisture regimes: well-watered (100% stored soil moisture) and water deficit condition (60% stored soil moisture). Foliar applications were performed at the tillering and booting growth stages. At three leaf stage drought stress was applied. Drought stress markedly reduced wheat growth and yield attributes; however, foliar supplementation with ZnO NPs and SA significantly mitigated these adverse effects. Both agents improved plant performance under water

deficit, with the combined application exhibiting a synergistic response. Notably, the combined application of ZnO NPs at 150 mg L<sup>-1</sup> and SA at 1.50 mM resulted in the most pronounced improvement in wheat performance under drought stress. This integrated treatment increased biological yield and grain yield by 9.10% and 7.42%, respectively, compared with the untreated control. Additionally, chlorophyll a and chlorophyll b contents were significantly enhanced by 16.8% and 19.1%, respectively, relative to the control. The same treatment also effectively modulated the antioxidative defense system, leading to increased activities of superoxide dismutase (12%), catalase (3.63%), and peroxidase (10.3%) in drought-stressed wheat leaves. These findings demonstrate that the combined foliar application of Zn NPs and SA is more effective in alleviating drought stress in wheat, highlighting its potential as a promising agronomic strategy to enhance crop resilience under limited water availability.

## Slow Released Biostimulant coated Urea for Enhancing Efficiency of Urea Utilization and Yield of Cotton

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Urea is a primary nitrogenous (N) fertilizer and an effective concentrated source of N (46%) worldwide. A major drawback of urea is that about 40% is lost in soil, especially in arid to semi-arid regions. Enhanced urea utilization efficiency can be achieved by reducing N losses from urea. An observational study was conducted to assess the efficacy of herbicide-polymer-coated urea (HPCU) in improving nitrogen use efficiency (NUE) and cotton development and productivity. Key findings from the study revealed significant differences in plant growth, yield, and nutrient efficiency among the treatments. The highest mean Plant height at 30 days since sowing, 60 days since sowing, 90 days since sowing, and 120 days since sowing, was observed in “HPCU + 50% chemical weed control”, “HPCU + 50% manual weeding + 50% chemical weed control”, “Conventional Urea + 100% manual weeding”, “HPCU + 50% manual weeding + 50% chemical weed control”. The treatment with HPCU + 50% manual weeding + 50% chemical weed control also produced the highest mean number of flowers per plant (6), square bolls per plant (12), and open square bolls per plant (14) at 60 DAS. This treatment continued to show superior performance, with the highest count of open square bolls per plant (12) at 90 DAS, and the peak counts of monopodial (11) and sympodial branches (19). Additionally, this treatment yielded the highest seed cotton yield (6 kg/plot) and seed yield (29 g/50g). Further, the HPCU + 50% manual weeding + 50% chemical weed control treatment exhibited the highest mean fiber length (27 mm), fiber strength (34 g/tex), and micronaire value (6%). It also has the highest GOT at (45%), chlorophyll content at (58), soil organic matter at (0.79%), soil extractable potassium at (273 mg/kg), soil nitrogen at (0.84%), shoot N content at (1.81%), shoot P content at (0.84%), shoot K content at (2.34%), WUE at (1.30  $\mu\text{mol mmole}^{-1}$ ), stomatal conductance at (14.20  $\text{mol m}^{-2} \text{s}^{-1}$ ), photosynthetic rate at (26  $\mu\text{mol m}^{-1} \text{s}^{-1}$ ), transpiration rate at (23.20  $\text{mmol m}^{-2} \text{s}^{-1}$ ), fresh weight at (198 g/plant), dry weight at (21 g/plant) and IE at (600 g g<sup>-1</sup>). The highest mean soil available phosphorus (8.7 mg/kg) was recorded, and the highest mean EC was found in the treatments with (3.0 dS/m). These findings demonstrate that HPCU, particularly when combined with 50% manual weeding

and 50% chemical weed control, significantly enhances plant growth, yield, and NUE in cotton cultivation.

## Impact of Organic and Inorganic Mulches on Growth and Yield of Green Chilli (*Capsicum annuum* L.)

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Mulching is an effective agronomical practice for conserving soil moisture, suppressing weeds, and improving crop productivity. A four-year field study was conducted at Kharala Village of Fateh Jang, District Attock, Pakistan, to evaluate the comparative efficacy of organic and inorganic mulching materials on the vegetative growth and reproductive yield of green chilli (*Capsicum annuum* L.). Four treatments were evaluated: T1 (Control/Farmer Practice, no mulch), T2 (Black polythene mulch BPM), T3 (White polythene mulch WPM), and T4 (Local grass clippings). The experimental design employed a Randomized Complete Block Design (RCBD) with three replications. Mulching increases soil water availability by reducing evaporation, managing soil temperature, or reducing crop irrigation requirements. Results indicated that black polythene mulch (BPM) significantly increased soil moisture content compared to other mulches. Growth parameters such as length & weight were significantly influenced by the diverse mulching treatments in comparison to the farmer practice/no mulch. Black polythene mulch (BPM) increased 23-25% fruit weight and about 18% fruit length compared with farmer practice/no mulch. Results showed that black polythene mulch (BPM) consistently produced higher yields, with the maximum yield observed in the black polythene mulch plot was 8346 kg/ha and the minimum yield recorded in the farmer practice/no mulch plot was 5744 kg/ha. The order of yield was as follows: black polythene mulch > local grass clippings > white polythene mulch > farmer practice/no mulch. These findings highlight the significant impact of mulching techniques on chillies growth and yield, providing valuable insights for sustainable agricultural practices and resource-efficient chilli cultivation. The study concludes that black polythene mulch (BPM) is a reliable option for enhancing chilli productivity in the agro-climatic conditions of Fateh Jang, while local grass clippings offer a cost-effective and environmentally friendly alternative.

## Effect of Climate Change on Vulture Movement and Diversity in Pakistan

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Vultures provide invaluable ecosystem services and play an important role in ecosystem balancing. Throughout the world, scavenger birds are declining rapidly with some populations already on the

brink of extinction. It is envisaged that ongoing climate crisis may further cause change in habitat suitability and impact the existing population. Change in carbon concentration as a result of anthropogenic activity is predicted to change the temperature and precipitation patterns in the years to come which could change the spread of vulture habitat. Pakistan covers nearly 900,000 sq. km, extending from the Arabian Sea to the Karakoram Mountain range. The avifauna of Pakistan includes eight vulture species, three of which are Critically Endangered: White-rumped Vulture (*Gyps bengalensis*), Indian Vulture (*G. indicus*), and Red-headed Vulture (*Sarcogyps calvus*). Between 2001 and 2007, rates of decline across the three largest White-rumped Vulture colonies in Pakistan ranged from 10% to an astounding 60% per year. The Gyps Vulture Restoration Project in Pakistan was launched in 2004 to conserve a viable population of White-rumped Vultures. The establishment of Vulture Safe Zones (VSZs) is one of the key activities of the SAVE partnership and the process aims to create large areas that are free of diclofenac. Rising temperatures and altered precipitation regimes are likely to render current 'Vulture Safe Zones' unsuitable, threatening the long-term recovery of these critically endangered scavengers.

## Climate-Driven Variation in Plant Community Composition along Altitudinal Gradients in the Hindu–Himalayan Region of Pakistan

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Pakistan occupies a unique biogeographic position where the Hindu Kush, Karakoram, and Himalayan mountain systems intersect, creating sharp altitudinal gradients over short spatial distances. These gradients generate pronounced variations in climatic conditions, particularly temperature, precipitation, snow cover, and moisture availability, which play a fundamental role in shaping vegetation patterns. As a result, mountain ecosystems in northern Pakistan support diverse plant communities ranging from subtropical forests at lower elevations to alpine and sub-alpine vegetation at higher altitudes. Several floristic and phytosociological studies conducted in northern Pakistan have demonstrated that altitude strongly influences plant species composition, richness, and community structure. Altitude functions as an integrated environmental variable, indirectly reflecting climatic stress, growing-season length, and soil moisture conditions. With increasing elevation, declining temperatures and increasing environmental harshness tend to limit species diversity, favoring stress-tolerant and specialized taxa. Recent concerns regarding climate change have further intensified the need to understand climate–vegetation relationships in Pakistan’s mountain regions. Rising temperatures and altered precipitation regimes have already been linked to shifts in vegetation zones and changes in the distribution of alpine and sub-alpine species. However, most existing studies remain descriptive, with limited integration of quantitative climate data and multivariate ecological analysis. Consequently, there is a clear need for systematic research that explicitly evaluates climate-driven variation in plant community composition along altitudinal gradients.

## Impact of Organic Amendment And

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Lead (Pb) contamination of agricultural soils has become a serious global environmental issue due to rapid industrialization, mining activities, excessive use of agrochemicals, and improper waste disposal. Lead is a non-biodegradable and persistent heavy metal that accumulates in soil and can easily enter the food chain through plant uptake, posing significant risks to ecosystem stability, crop productivity, and human health. Conventional remediation methods such as soil excavation, washing, and chemical stabilization are often costly and may cause further environmental disturbance. Therefore, environmentally sustainable and cost-effective remediation approaches are increasingly being explored. In recent years, the application of engineered nanoparticles and organic amendments has emerged as a promising strategy for the immobilization and stabilization of heavy metals in contaminated soils. Nanoparticles possess unique physicochemical properties including extremely small particle size, high surface area, and enhanced reactivity, which allow them to effectively adsorb and immobilize heavy metals. Materials such as iron oxide nanoparticles, nano-biochar, and other metal oxide nanomaterials have demonstrated strong binding affinity for Pb ions, thereby reducing their mobility and bioavailability in soil systems. In parallel, organic amendments including compost, farmyard manure, green manure, and biochar play an important role in improving soil structure, increasing cation exchange capacity, and enhancing microbial activity. These amendments also introduce functional groups such as carboxyl and hydroxyl groups that facilitate the formation of stable complexes with heavy metals, thereby reducing their solubility and toxicity. Recent literature indicates that the combined application of nanoparticles and organic amendments can create a synergistic effect that enhances lead immobilization while simultaneously improving soil fertility and plant growth. Organic materials can act as stabilizing agents for nanoparticles, reducing potential toxicity and promoting more efficient distribution within the soil matrix. Additionally, this integrated approach contributes to improved nutrient availability, enhanced microbial diversity, and better soil physicochemical properties. As a result, plant growth and productivity in lead-contaminated soils may be significantly improved. Despite these promising outcomes, further research is required to evaluate the long-term stability, environmental safety, and large-scale field applicability of nanoparticle-assisted remediation techniques. Understanding the interactions among nanoparticles, organic amendments, soil properties, and plant systems remains crucial for developing sustainable and effective strategies for managing lead-contaminated soils.

## Genomic and Proteomic Insights into a Novel Extremely Boron-Tolerant *Cytobacillus boracitolerans* sp. nov. Isolated from Sewage Sludge of Waste Water Treatment Pond

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Boron is an essential micronutrient but becomes toxic at elevated concentrations, posing ecological and agricultural challenges. In this study, we report the characterization of *Bacillus boracitolerans* sp. nov. NCCP-133<sup>T</sup>, an extremely boron-tolerant bacterium isolated from sewage sludge in Islamabad, Pakistan. Phylogenetic analysis based on 16S rRNA gene sequences revealed 99.7% similarity with closely related taxa, while DNA–DNA hybridization values confirmed its taxonomic distinctiveness. The strain exhibits remarkable boron tolerance, growing at concentrations up to 36.4% B. Chemotaxonomic analyses demonstrated unique cellular fatty acid profiles dominated by anteiso-C15:0 and anteiso-C17:0, menaquinone MK-7 as the major respiratory quinone, meso-diaminopimelic acid in the peptidoglycan, and a DNA G+C content of 42.0 mol%. Proteomic profiling under differential boron concentrations, performed through gel-free LC–MS/MS analysis, revealed that *B. boracitolerans* NCCP-133<sup>T</sup> exhibited a markedly broader proteomic response than the comparator strains. More than 250 proteins were differentially expressed under boron stress, including ion transporters, molecular chaperones, oxidative stress regulators, and metabolic enzymes. In comparison, *B. boroniphilus* showed fewer than 150 responsive proteins, while *B. subtilis* displayed a restricted stress profile with less than 80 changes. The abundance and diversity of responsive proteins in NCCP-133<sup>T</sup> underscore its capacity to remodel cellular physiology and maintain integrity under extreme boron stress. These integrated genomic and proteomic insights not only validate the taxonomic novelty of *Bacillus boracitolerans* but also unravel its molecular strategies to withstand metalloid toxicity. Collectively, this work broadens the understanding of microbial adaptation to boron and highlights the potential of *B. boracitolerans* sp. nov. for bioremediation of boron-contaminated environments.

## Potassium Role as Anti-Transpirant in Water Stress Condition: Effect on Growth and Biochemical Changes in Spinach.

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Drought is considered as a serious threat for sustainable crop production. Different chemical compounds which reduce transpiration are known as “antitranspirants”. Potassium plays key role in stress regulation. In view, the significance of antitranspirants, a pot experiment was conducted to evaluate the effect of potassium as an antitranspirant on spinach under different field capacity moisture regimes. Study involved completely randomized design-factorial included: Factor (A) Type of antitranspirants (ATs): ATC<sub>1</sub>: Water, ATC<sub>2</sub>: K<sub>2</sub>SO<sub>4</sub>, ATC<sub>3</sub>: Castor oil, Factor (B): Field capacity moisture level (FCML): FCML<sub>1</sub>: 50%, FCML<sub>2</sub>: 75%, FCML<sub>3</sub>: 100%. The ATs were applied at 1% after every 15 days of interval until harvesting of spinach. The results indicated that decreasing field capacity moisture levels, reduced most of growth parameters (plant height, fresh and dry weights of plant, number of leaves, stem girth, leaf area) and physiological parameters including relative growth rate and cell membrane stability index. Further, both ATs showed greater effect of K<sub>2</sub>SO<sub>4</sub> followed by castor oil as compared to water treatment. In case of nutrients (N, P and K) concentrations were followed similar

trend as of growth parameters. However, N and K concentrations were found in adequate range at 75% and 100 FCMLs in both ATs in plant tissue of spinach. It is concluded that the application of potassium K<sub>2</sub>SO<sub>4</sub> as an antitranspirant could help to mitigate drought effects on spinach plant.

## Organic Input Lability and Its Influence on Mineral-Associated and Particulate Organic Carbon Formation

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The stabilization of organic inputs into Mineral-associated organic carbon (MAOC) is one of the principal mechanisms that govern soil carbon persistence and it is therefore poorly known under contrasting soil organic carbon (SOC) conditions. This study tested the response of carbon fraction to increased lability of organic inputs, and investigated the possibility of a correction of initial SOC content. Two soils with different status of the carbon (C-rich and C-poor) were amended with wood chip alone or combined with 50 and 75% glucose and incubated under controlled lab conditions. Increasing the lability of substrate significantly increased microbial activities and N transformations. Nitrate concentrations increased by up to 419% in C-rich soil and 287% C-poor soil with 95% accumulation of ammonia in the C-poor soil. Similarly, there was a substantial increase in the beta-glucosidase activity that increased substantially under glucose amended treatments arriving at 117% in C-rich soil, while more than 200% for C-poor soil. Despite these vigorous responses from microbes, more pronounced increases in MAOC formation were observed in the C rich soil while microbial biomass and inorganic N accumulation were more pronounced in the C poor soil. These results demonstrate the significance of initial SOC on the fate of added labile carbon and the mineralization of carbon to stable mineral-associated pools or not. Overall, the stimulation of microbial processing following increased organic input lability depends strongly upon basement SOC conditions, but also on the efficiency of carbon stabilization in the form of MAOC.

## Synergistic Role of Melatonin-Primed PGPR in Lead Immobilization and Oxidative Stress Reduction in Oat (*Avena sativa* L.)

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Lead (Pb) contamination significantly affects crop growth by limiting nutrient uptake, photosynthetic processes and redox homeostasis. In the current study, a pot experiment was conducted to investigate the synergistic impact of melatonin-primed plant growth-promoting rhizobacteria (PGPR) on Pb

immobilization and mitigation of oxidative stress in *Avena sativa* (oat) grown in Pb-contaminated soil at a concentration of 400 mg/kg. Seeds of oat were treated with 100  $\mu$ M melatonin for 12 h prior to sowing and then inoculated with a Pb-tolerant PGPR consortium at a density of  $10^8$  CFU/mL. Results showed that the combined treatment significantly reduced Pb bioavailability by 38% mediated by an elevation in rhizospheric pH (0.6 units) and increased production of exopolysaccharides (EPS) and organic acids. Pb accumulation in roots and shoots decreased by 42% and 55%, respectively, accompanied by a reduced translocation factor from 0.71 to 0.39, indicating restricted Pb mobility. Furthermore, melatonin-primed PGPR significantly reduced oxidative stress by decreasing malondialdehyde (MDA) content by 47% and hydrogen peroxide ( $H_2O_2$ ) levels by 35% compared to Pb-stressed plants. Activities of antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) were also significantly increased by 52%, 44%, and 49%, respectively, compared to Pb-stressed oat plants. Chlorophyll content was also increased by 33%, accompanied by a 29% increase in biomass yield. This study concluded that melatonin-primed PGPR significantly enhanced phytostabilization of Pb and the antioxidant defense system of oat plants, demonstrating an eco-friendly and cost-effective strategy for sustainable oat cultivation under Pb-stressed soil conditions, thereby minimizing the risk of Pb entry into the food chain.

## Enhancing Zinc Biofortification in Tomato through Zinc-Solubilizing Bacteria

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Zinc (Zn) is an essential micronutrient that plays a crucial role in numerous physiological and biochemical processes in plants and is equally important for human nutrition. However, Zn deficiency in soils is a widespread problem, particularly in arid and semi-arid regions, where it limits crop productivity and reduces the nutritional quality of edible crops. In this context, the use of zinc-solubilizing bacteria (ZSB) has emerged as a promising and environmentally sustainable approach to enhance Zn bioavailability in the rhizosphere. This study aimed to evaluate the effectiveness of zinc-solubilizing bacteria in improving zinc availability, uptake, and biofortification in tomato (*Solanum lycopersicum*). A controlled pot experiment was conducted at Muhammad Nawaz Sharif University of Agriculture, Multan, using a Completely Randomized Design (CRD) with ten treatments. The treatments included control (no Zn application), zinc sulfate ( $ZnSO_4$ ) and zinc phosphate ( $Zn_3(PO_4)_2$ ) at recommended and elevated levels, applied alone and in combination with ZSB inoculation. Growth, physiological, and yield parameters were recorded, including plant height, shoot and root dry weight, leaf chlorophyll content, fruit yield, and plant zinc concentration. The results indicated that the combined application of ZSB and zinc fertilizers significantly improved plant growth, fruit yield, and Zn uptake compared with individual treatments. In particular, the integration of ZSB with the insoluble zinc source  $Zn_3(PO_4)_2$  enhanced Zn solubilization, leading to greater zinc biofortification in tomato fruits. Overall, the findings demonstrate that ZSB can serve as an effective bio-inoculant for improving

zinc bioavailability, crop productivity, and residual soil fertility. The integration of ZSB with zinc fertilizers offers a sustainable and biologically driven strategy to alleviate zinc deficiency in tomato cultivation and enhance the nutritional quality of crops grown in Zn-deficient soils.

## Effects of Different Zinc Levels on Growth, Yield and Physiology of Rice Genotype “SGM-ii”

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Although Zn micronutrient fertilizer require in trace quantity in rice plants but has a major role in rice productivity. Therefore, this field study was carried out to investigate the optimum and economical Zn level for the growth and yield of rice crop under agro-climatic conditions of Tandojam at Experimental Farm of Nuclear Institute of Agriculture (NIA), Tandojam (Longitude North 250, 26’0” and 680 32’0 East latitude), Sindh Pakistan. Rice variety “SGM-II” was tested during Kharif Season 2021, the experiment was laid out by RCBD (randomized complete block design) with three repeats. Five (05) Zn doses (03-, 06-, 09-, 12-and 15-kilogram zinc ha<sup>-1</sup>) were applied as Zingro fertilizer (33% Zn) was used as Zn source. The data regarding growth, yield, physiological and nutritional traits were statistically significantly varied. Growth parameters (plant height and tillers) of rice genotype significantly increased (18% and 44.6%) at 12 kg Zn ha<sup>-1</sup>over control. Yield attributes i.e panicle length, panicle weight, grain numbers per panicle, biomass production and paddy yield were highest percentile recorded 16.9%, 46.3%, 38.6%, 20.8%, 27% and 75.9% at Zn rate of 12 kg Zn ha<sup>-1</sup>, respectively. Similar trend was observed in nutritional traits i.e. Zn densities in paddy grains and hay and zinc accumulation in paddy grains and hay/straw showed 134.7% & 33.6%, 219.3% & 310.8%, at 12 kg Zn ha<sup>-1</sup>. Physiological traits (Chl a, Chl b, total Chl and carotenoid) revealed that maximum percentile of 59.4%, 79.4%, 97.9% and 78% at Zn applied at the rate of 15 kg Zn ha<sup>-1</sup>, respectively. It can be concluded from the above findings that the Zn application of 12 kg Zn per hectare is imperative to improve yield contributing traits and paddy harvest of rice genotype “SGM-II”. To achieve zinc biofortification objective of this genotype Zn analysis was carried, it revealed that 12 kg Zn ha<sup>-1</sup> is essential for Zn accumulation in paddy and its biomass for growing in Zn deficient areas of Sindh province.

## Remediating Lead Toxicity in Maize: Efficacy Ranking of Novel Organic Soil Amendments

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Due to heavy metal contamination, there are currently significant losses in agriculture and food security. Among these metals, lead (Pb), which is toxic and affects crop production, has emerged as a standout due to its severe toxicity and relatively obscure mode of action. Organic amendments have attracted attention because of their capability to improve soil fertility, soil carbon content as well as crop yield and productivity particularly under Pb contaminated soil conditions. Therefore, the present research was conducted to investigate the effect of farmyard manure, poultry manure, compost and biochar to enhance growth, yield, and quality of maize grown in Pb contaminated soil. To examine the effect of organic amendments, this pot experiment included farmyard manure, poultry manure, compost, and biochar at the rate of 1% and were tested in normal and Pb-contaminated soil (i.e., 400 mg Pb per kg soil) conditions. The pot experiment was conducted using a complete randomized design (CRD) with three replications of each applied treatment. Data was collected on various growth parameters, physiological responses, biochemical functions, ionic compositions and particularly Pb concentration, uptake, translocation. All the obtained data were analyzed statistically using the Analysis of Variance following Statistix 10 statistical package and differences among the treatment means were compared by the least significant difference test at 0.05 probability. The results revealed that the application of organic amendments had considerable impacts on maize growth and Pb concentration in plants were found to be reduced both under normal and Pb-contaminated soil conditions. Whereas, among all the tested amendments (i.e., farmyard manure, poultry manure, compost, and biochar), application of biochar and compost at the rate of 1% (10 g per kg) were found more effective in improving maize growth and physiological functions, and to reduce Pb concentration in maize both in normal and Pb-contaminated soils.

## Environmental Pollution Caused by Nitrogenous Fertilizer: A Case Study from Punjab, Pakistan

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There is serious misconception about environmental pollution caused by excessive use of nitrogenous fertilizers along with intensive irrigation practices which may cause nitrate contamination in groundwater of agricultural regions. In Pakistan, the fertilizer use according to recommendation is lacking due to farmer financial constraints and timely availability of nitrogenous fertilizer at their village level especially in case of wheat crop for its second dose application. Keeping in view this pollution threat in Punjab, a survey study was conducted by Soil Chemistry Section to estimate the threat of pollution by conducting profile sampling to assess the nitrate movement in soil profiles and its leaching potential under varying fertilizer and irrigation regimes. Soil and water samples were collected from various agro ecological zones of Punjab, Pakistan including, Okara, Sahiwal, Vehari, Multan, Chinnot, Hafizabad and Sialkot. The results indicated that nitrate (NO<sub>3</sub>-N) leaching was confined to the top 60 cm of soil, with the highest concentrations in the 0-30 cm and 30-60 cm soil profiles and then decreasing with increasing soil profile depths. The mean NO<sub>3</sub>-N contents were 19.75, 16.21, 8.46 and 5.12 mg kg<sup>-1</sup> at 0-30, 30-60, 60-90, and 90-120 cm, respectively. Water analysis from

tube wells across the studied areas indicated the presence of trace level of nitrate in all samples; however, concentrations were low and well below health hazard thresholds. The maximum NO<sub>3</sub> levels recorded were 9.53 and 11.25 ppm in Multan and Sahiwal, respectively, well below the FAO/WHO safe limit of 50 mg L<sup>-1</sup>. The NO<sub>3</sub>-N contents were found in each soil profile and the nitrate leaching trend was found up to the depth of 60 cm and then NO<sub>3</sub>-N contents were found in decreasing trend. This study clearly showed that nitrate leaching was found not found beyond the permissible limits beyond the depth of 90 cm. Moreover, the water analysis clearly indicated that NO<sub>3</sub>- N content were well below the WHO standards.

## Assessing Microplastic Contamination in Agricultural Soils Using GIS-Based Spatial Analysis for Enhancing Soil Resilience

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Soil resilience plays a significant role in maintaining important ecosystem services and sustainable agricultural productivity under changing climatic conditions. Recently, microplastic contamination has emerged as a threat to soil health and agricultural systems but it is largely overlooked too. Microplastics enter soils through plastic mulching materials, wastewater irrigation, application of sewage sludge and degradation of agricultural plastic residues. They have the ability to alter the physical properties of soil, affect the soil microbial activity and negatively effects the nutrient cycling processes. This ultimately influence the soil fertility and sustainability. Despite growing global concern, the spatial distribution of microplastics in agricultural soils remains poorly understood, particularly in developing regions. Geographic Information System (GIS) based spatial analysis offers a powerful tool for identifying the spots with contamination and assessing the spatial patterns of the microplastic accumulation in agricultural landscapes. The integration of land-use data, agricultural practices and input sources of microplastic can help in mapping and monitoring of microplastic pollution risks in soil. The spatial analysis provides valuable information for developing targeted soil management and pollution mitigation strategies. Soil science and geospatial technologies can support sustainable land management and strengthen soil resilience for environmental sustainability and food security.

## Harnessing PGPR and Microbial Metabolites for Climate-Resilient Canola Production

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Biofertilizers are emerging as advanced biotechnological inputs for promoting sustainable, organic, and climate-resilient agriculture. Excessive dependence on chemical fertilizers has resulted in environmental degradation, eutrophication, increased greenhouse gas emissions, depletion of soil organic matter, reduced microbial diversity, and potential risks to human health. In this context, biofertilizers offer a cost-effective, eco-friendly, and climate-smart alternative capable of mitigating the adverse impacts of climate change on agricultural systems. Biofertilizers comprise beneficial soil microorganisms and organic substrates that enhance soil fertility by improving nutrient availability, soil biological activity, and overall soil health. Plant growth-promoting rhizobacteria (PGPR) facilitate nutrient acquisition through biological nitrogen fixation and solubilization of essential nutrients, while also producing phytohormones such as auxins, cytokinins, biotin, and vitamins. Moreover, PGPR enhance plant tolerance to biotic and abiotic stresses, contributing to sustainable crop productivity under changing climatic conditions. A field experiment was conducted at the Agricultural Biotechnology Research Institute (ABRI), AARI Faisalabad, on low-fertility soil characterized by pH 8.01,  $E_{ce}$  2.3 dS  $m^{-1}$ , and organic matter content of 0.72%. Six treatments were evaluated: control (T1), PGPR–Azotobacter (T2), PGPR–Pseudomonas (T3), metabolite spray (T4), metabolite spray + PGPR–Azotobacter (T5), and metabolite spray + PGPR–Pseudomonas (T6) using randomized complete block design (RCBD) with three replications. Canola (*Brassica napus* L.) was used as the test crop, and all treatments received the recommended dose of NPK fertilizers. Growth and yield parameters including plant height, biomass accumulation, number of pods per plant, and seed yield were recorded. Results demonstrated that PGPR inoculation significantly improved growth and yield attributes compared to the control. However, the combined application of PGPR inoculation with microbial metabolite spray resulted in better yield compared to control. The highest seed yield (4036 kg  $ha^{-1}$ ) was recorded in treatment T6 (PGPR–Pseudomonas + metabolite spray), which was significantly higher than the control and statistically comparable with Azotobacter-based treatments. The findings highlight the potential of PGPR and microbial metabolites as innovative biotechnological tools for enhancing crop productivity, improving soil health, and ensuring sustainable agricultural production under climate change scenarios.

## Adsorption of Selected Azo Dye from Activated Carbon Derived from Black Permission.

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Azo dyes are used in different industrial applications in the textile, leather, paper, and food processing industries due to their attractive coloration, high tinctorial strength, and outstanding chemical stability. However, the disposal of wastewater containing azo dyes has turned out to be a major environmental problem in recent times due to the toxic, non-biodegradable, and stable nature of the dyes, which makes them resistant to conventional biological and physicochemical treatment processes used in wastewater treatment plants. Moreover, the presence of an intricate structure in the dyes makes them non-degradable in nature, leading to environmental pollution and posing risks to aquatic life and human beings as well. Hence, the development of inexpensive and eco-friendly adsorbent materials to remove azo dyes from wastewater is of great importance in maintaining a healthy environment. In the present study, activated carbon is prepared using the chemical activation

method with black persimmon fruit as the precursor and its adsorption potential to remove Indosol Violet 3B dye from aqueous solutions is evaluated. In this study, activated carbon is prepared with a porous structure and good surface morphology, which makes it more suitable as an adsorbent to remove dyes from wastewater. The presence of surface functional groups also contributes to enhanced interaction between dye molecules and adsorbent surfaces. Batch adsorption experiments are carried out to assess the impact of crucial process parameters such as pH, adsorbent dosage, contact time, temperature, and initial dye concentration on adsorption performance. The results revealed that adsorption performance is significantly dependent on environmental and process parameters. The optimized adsorption performance is observed at contact time of 120 minutes, pH of 3, adsorbent dosage of 0.3 g/50 mL, initial dye concentration of 50 mg/L, and temperature of 25°C. The enhanced adsorption performance is observed at lower pH values because of electrostatic attraction between negatively charged dye molecules and positively charged activated carbon surfaces. The achievement of adsorption equilibrium at 120 minutes of contact time validates the progressive adsorption of dye molecules and saturation of adsorption sites on adsorbent surfaces. The optimized parameters are chosen on the basis of adsorption equilibrium behavior, adsorption mechanisms, and economic considerations for ensuring adsorption performance and practicality. The results of this investigation revealed that activated carbon produced from black persimmon biomass is a highly efficient and sustainable adsorbent material for adsorptive removal of azo dyes from wastewater streams. The study demonstrates the potential of utilizing agricultural biomass wastes for developing high-performance adsorbent materials using simple and cost-effective preparation routes. Overall, the present research is helpful for developing 'green' wastewater treatment technologies and utilizing renewable biomass wastes for 'value-added' applications related to environmental remediation.

## Integrated Application of Iron Nanoparticles and Nano-Hydroxyapatite for Mitigating Cadmium Toxicity in Wheat (*Triticum Aestivum* L.)

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Heavy metal contamination of agricultural soils poses a significant challenge to sustainable crop production and food security. Cadmium (Cd), a highly toxic and non-essential transition metal, threatens plant growth and poses a serious health risk to humans through food chain transfer. Nanotechnology-based soil amendments, particularly iron nanoparticles (FeNPs) and nano-hydroxyapatite (nHAP), have emerged as promising materials for reducing Cd bioavailability in soil, thereby limiting its uptake by plants and sustaining growth and productivity under contaminated conditions. A pot experiment was conducted to evaluate the effects of FeNPs and nHAP, applied individually and in combination, on the growth and yield performance of wheat under Cd stress conditions. The experiment comprised twelve treatments: an uncontaminated control, a Cd-contaminated control, FeNPs (10 and 20 mg kg<sup>-1</sup>), nHAP (50 and 100 mg kg<sup>-1</sup>), nano-hybrids of FeNPs and nHAP (1:5 and 1:10 ratios @ 10:50 and 5:50 mg kg<sup>-1</sup>), Fe precursors (10 and 20 mg kg<sup>-1</sup>), and phosphoric acid (50 and 100 mg kg<sup>-1</sup>). Results indicated that combined application of FeNPs and nHAP

at a 1:10 ratio significantly increased the plant height (8.96%), shoot fresh weight (16.06%), root fresh weight (44.26%), root length (23.56%), shoot dry weight (14.39%), number of tillers (34.71%), spike length (20%), spike weight (40%) and 100-grain weight (26.82%) compared with untreated Cd-contaminated control. While comparing the individual nanoparticles, nHAP demonstrated greater effectiveness than FeNPs in improving yield attributes of wheat, recording an improvement of 15.11% compared to FeNPs treatments. Overall, the findings of the study demonstrated that nano-based soil amendments, particularly FeNPs-nHAP hybrids, can effectively mitigate Cd toxicity and enhance wheat productivity under Cd-contaminated conditions, offering a viable strategy for sustainable crop production.

## Comparative Effect of ZnO Nanoparticles and Zinc Sulfate on Growth, Chlorophyll and Yield of Wheat

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Zinc (Zn) deficiency in the calcareous soils of Punjab, Pakistan, is a major constraint to wheat productivity and grain nutritional quality. A field experiment was conducted at AARI, Faisalabad to evaluate the comparative efficacy of zinc oxide nanoparticles (ZnO NPs) and conventional zinc sulphate (ZnSO<sub>4</sub>) in improving chlorophyll content, grain Zn concentration and yield of wheat. The study was laid out in a randomized complete block design (RCBD) with three replications. Treatments comprised recommended NPK with soil-applied ZnSO<sub>4</sub>, foliar ZnSO<sub>4</sub> (0.2%), and foliar application of ZnO nanoparticles at varying concentrations (25, 50, 75 and 100 µg mL<sup>-1</sup>), applied at tillering, booting and grain filling stages. The results revealed that foliar application of ZnO nanoparticles significantly enhanced physiological attributes and yield performance of wheat compared with conventional Zn fertilization. Among the treatments, foliar application of ZnO nanoparticles at 75 µg mL<sup>-1</sup> resulted in the highest chlorophyll content (52.4 SPAD units), maximum grain Zn concentration (41.7 mg kg<sup>-1</sup>) and highest grain yield (5.48 t ha<sup>-1</sup>). Increasing the concentration to 100 µg mL<sup>-1</sup> did not produce a statistically significant increase over 75 µg mL<sup>-1</sup>, indicating a stabilization in response at higher nanoparticle concentration. The findings suggest that foliar application of ZnO nanoparticles at 75 µg mL<sup>-1</sup> is an effective approach to enhance wheat productivity and grain Zn bio-fortification under the agro-ecological conditions of Punjab, Pakistan.

## Effect of Rhizobium Inoculum Applied with Phosphorus Pre-Treated FYM Compost on Yield, N<sub>2</sub> Fixation and P Uptake by Mungbean

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Phosphorus complexation with Ca and Mg in alkaline soils could be reduced through pre-treatment of P with organic sources before application to soil. In this regard the effect of pre-treatment of rock phosphate and single super phosphate with farmyard manure was assessed on growth, yield and nitrogen fixation by mungbean (*Vigna radiata*) grown with and without rhizobium inoculum at The University of Agriculture, Peshawar during Kharif season 2023. The FYM was pre-treated with RP and SSP at 2% P and was let to decompose for almost 45 days in plastic covered cemented pits. Prepared composts were then applied to soil at 90 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> with and without rhizobium arranged in 2 (inoculum levels) x 5 (treatments) factorial randomized complete block design (RCBD) with three replications. Results showed that plant height, biomass and grain yield were increased with enriched composts applied with rhizobium irrespective of P sources. The plot receiving SSP enriched FYM compost with rhizobium has significantly higher plant height (61.53 cm), pods plant<sup>-1</sup> (36.17), grains pod<sup>-1</sup> (14.1), grain yield (1633 kg ha<sup>-1</sup>) and biomass (3633 kg ha<sup>-1</sup>) than control and plots receiving nontreated SSP or RP. This treatment also had significantly higher N<sub>2</sub> fixation (72.56 kg ha<sup>-1</sup>) and ndfa (63.52 %). Post-harvest soil study showed significant higher soil organic matter (1.01 %), mineral nitrogen (21.67 kg ha<sup>-1</sup>) in RP enriched FYM compost + rhizobium plots while extractable phosphorus (7.93 mg kg<sup>-1</sup>) was higher in SSP enriched FYM compost + rhizobium. Interestingly, the performance of RP significantly increased even better than soluble commercial SSP for all observed parameters when it was pre-treated with FYM. It is concluded that although the efficiency of SSP compost with rhizobium was better than RP FYM compost but still it is an optimal choice for pre-treatment of FYM compost based on its cost effectiveness. Pre-treatment of FYM compost with RP during composting is recommend with rhizobium inoculum for enhanced mung bean yield, N<sub>2</sub> fixation and P use efficiency with the additional benefit on soil health in low-input agro-ecosystems.

## Biodegradation of Phthalate-Contaminated Wastewater Using Microalgae and Biomass Production for Biolipid Extraction

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Phthalates are chemicals that are used owing to their properties of softening and making plastics flexible. They can be found in packaging, cosmetics, PVC pipes and medical products. Their non-strong attachment to the plastics makes them leech easily in water and soil, which makes them a serious pollutant. Phthalates are endocrine disruptors, which cause disruption of hormonal system in human beings and animals. This causes health issues such as infertility, developmental issues and even cancer as well as destroying aquatic life. The phthalates cannot be eliminated with the help of the conventional wastewater treatment plants, contributing to the threat of the environment and health. The objective of this research is to treat the phthalate contaminated wastewater using microalgae for removal of pollutant. Sample of algal water in freshwater lakes and wastewater plants, from freshwater lack sample we mix it with BBM media for the growth of algae ,first we get the mixed culture of algae than we get the isolation of pure strains, for the testing in water with phthalates. The conditions (pH, temperature, and the nutrient supply) optimize to learn which environment algae

can best degrade phthalates. Harvesting of algal biomass will be followed by growth. Such lipids is converted into biodiesel with the process of transesterification and this adds value to the process. It is expected that there will be a two-fold gain: the effective elimination of toxic phthalates in wastewater and the generation of renewable biodiesel at once.

## Impact of Green Manuring on Health of Low Fertility Calcareous Soils

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This study was conducted in a rice-based cropping scheme to investigate the impact of green manuring on soil health, considering soil physicochemical properties and sustainable crop production. A field experiment was started on 2 November and completed on 15 April under a rice–berseem (*Trifolium alexandrinum*) cropping system in calcareous soil. Two green manuring patterns, rice–berseem and rice–wheat–sesbania (*rostrata*), were compared with a commonly practiced rice–wheat (*Oryza sativa*–*Triticumaestivum*) cropping pattern. Green manuring of the berseem crop (last cutting) along with 50, 75, and 100% of the recommended fertilizer doses of nitrogen, phosphorus, and potassium (NPK) were compared with recommended NPK fertilization along with control (no fertilizer). The plant growth parameters of rice, including plant height, tillers per plant at maturity, and yield data, were recorded at harvest. The pre-sowing soil analysis revealed that the experimental soil was low in salts, and the nutrient (NPK) status was very low. The results indicated that green manuring substantially enhanced the grain and straw yield of rice crops. Green manuring combined with 75% of recommended NPK produced the highest grain yield (5.83 t ha<sup>-1</sup> in year III) compared to the other treatments. The soil analysis showed that the bulk density was reduced while soil porosity, organic carbon, and N, K, and P contents were significantly improved. From the results of this study, it is recommended that under calcareous soil conditions, the regular use of green manuring can significantly improve crop growth, yield, and physicochemical properties of soil and, therefore, should be adopted by farmers.

## Foliar Application of Silicon Can Alleviate Cadmium Contaminated Soils

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Cadmium (Cd) is one of the most mobile elements in soil-plant system and is considered as serious threat to health of soil, plants and humans. High mobility and toxicity of Cd warrants management option to minimize its accumulation in soil, plants and human. A pot experiment was conducted to study the influence of foliar application of silicon (Si) to decrease Cd in rice (*Oryza sativa* L.) grown in texturally different Cd contaminated soils. Treatments include three factors; two level of cadmium (0, 10 mg kg<sup>-1</sup> dry soil), four levels of Si (0.0, 0.25, 0.5 and 1.0 % Si applied to plant foliage and two soils varying in texture (clayey and loamy soil). The physiological parameters such water use efficiency, photosynthesis rate, transpiration rate and stomatal conductance were recorded. The crop growth parameters such as plant height, shoot dry weight and other parameters were also recorded. Results show that clayey soil at Si level 1 % without Cd showed the best results in terms of many plant growth and yield parameters. The plant tissue status of trace elements such as Cd, Mn, Zn, Cu and Fe concentration in soil, shoot, husk and grain were recorded. Under Cd contamination, application of Si at 1.0 % in the case of clayey soil showed significantly lower concentration of Cd in shoots and maximum levels of essential trace elements such as Fe, Mn, Cu and Zn concentration. However, at same levels of Cd contamination, maximum levels were recorded in loamy soils indicating role of texture in controlling amendment assisted mobilization/immobilization.



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