



E-BOOK OF ABSTRACTS

Editors

Mubshar Hussain, Shahid Hussain, Mamoon Amir and Dur-e-Shahwar Sattar

Pakistan Agricultural Scientists Forum
URL: www.pasforum.org | Email: info@pasforum.org

Bahauddin Zakariya University, Multan
URL: www.bzu.edu.pk | Email: registrar@bzu.edu.pk

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E-Book of Abstracts

International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026

October 13–15, 2026

Bahauddin Zakariya University, Multan, Pakistan

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Editors:

Prof. Dr. Mubshar Hussain and Dr. Shahid Hussain from Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

Dr. Mamoon Amir and Dr. Dur-e-Shahwar Sattar from Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

MESSAGE FROM THE PATRON-IN-CHIEF

It gives me immense pleasure to welcome the distinguished scientists, researchers, academicians, policymakers, industry representatives, students, and other stakeholders participating in the **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026**, being organized by Bahauddin Zakariya University, Multan, in collaboration with the Pakistan Agricultural Scientists Forum.

Agriculture and food systems are at the heart of human well-being, economic development, and national food security. However, changing climatic conditions, increasing temperatures, water scarcity, soil degradation, biodiversity loss, and the growing frequency of extreme weather events are creating unprecedented challenges for agricultural production and food security. Addressing these challenges requires not only scientific understanding but also innovative technologies, effective policies, responsible resource management, and strong collaboration among academia, industry, government, and farming communities.

The theme of this conference is therefore both timely and significant. The event provides an important platform for exchanging scientific knowledge, presenting emerging research, discussing practical solutions, and strengthening partnerships for the development of sustainable and climate-resilient food systems. The accompanying Industrial Expo provides an opportunity to highlight technologies, products, services, and innovations that can contribute to a more productive, efficient, and sustainable agricultural sector.

Bahauddin Zakariya University is committed to advancing knowledge, promoting research and innovation, and contributing to the socioeconomic development of Pakistan. I am confident that this conference will encourage meaningful scientific dialogue and generate opportunities for future collaboration at national and international levels.

I commend the organizers, collaborating institutions, members of the Pakistan Agricultural Scientists Forum, researchers, industry partners, and all contributors whose efforts have made this important event possible.

I extend my warmest greetings to all participants and wish the **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026** a successful and productive outcome.



Dr. Muhammad Zubair Iqbal

Vice Chancellor

Bahauddin Zakariya University, Multan, Pakistan

Patron-in-Chief

MESSAGE FROM THE PATRON

The transformation of food systems toward sustainability and resilience is one of the defining challenges of our time. Climate change is increasingly influencing agricultural productivity, food quality, water availability, soil health, and the livelihoods of farming communities. These challenges require integrated approaches that connect agricultural sciences, food science and nutrition, environmental management, technology, policy, and industry.

The **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026** provides a valuable forum for bringing together experts from diverse disciplines to share research findings, exchange ideas, and explore practical pathways toward sustainable food production and food security.

The integration of an Industrial Expo with the scientific conference is particularly significant. Stronger linkages between academia and industry can accelerate the translation of research and innovation into technologies, products, and services that benefit producers, processors, consumers, and society at large.

I am confident that the deliberations of this conference will contribute to constructive scientific dialogue and foster new collaborations for addressing emerging challenges in agriculture and food systems. I welcome all delegates and participants to Bahauddin Zakariya University, Multan, and wish the conference every success.



Prof. Dr. Muhammad Riaz

Dean, Faculty of Food Science & Nutrition

Bahauddin Zakariya University, Multan, Pakistan

Chairman, Pakistan Agricultural Scientists Forum

Patron

MESSAGE FROM THE PATRON

Sustainable agriculture and resilient food systems are essential for meeting the nutritional needs of a growing population while conserving the natural resources upon which agriculture depends. Climate change has intensified the need to rethink conventional approaches to crop production, soil and water management, food processing, supply chains, and agricultural policy.

The **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026** offers an important opportunity for scientists, educators, policymakers, industry professionals, and other stakeholders to discuss these interconnected challenges and identify innovative approaches for a sustainable agricultural future.

The conference themes encompass key areas ranging from climate change and food security to climate-smart agriculture, soil health, water management, food processing and safety, supply-chain management, policy, and smart agricultural technologies. Such interdisciplinary engagement is essential for developing solutions that are scientifically sound, economically viable, environmentally responsible, and socially relevant.

I appreciate the efforts of Bahauddin Zakariya University and the Pakistan Agricultural Scientists Forum in bringing the scientific and industrial communities together on a common platform. I hope that the discussions and collaborations emerging from this event will contribute meaningfully to agricultural development and food security.

I warmly welcome all participants and wish the conference a fruitful and successful deliberation.



Prof. Dr. Nazim Hussain

Dean, Faculty of Agricultural Sciences & Technology
Bahauddin Zakariya University, Multan, Pakistan

Patron

MESSAGE FROM THE CHIEF ORGANIZER

It is an immense pleasure to welcome you to the **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026**, hosted by Bahauddin Zakariya University, Multan, in collaboration with the Pakistan Agricultural Scientists Forum.

The agricultural and food sectors are experiencing rapid changes driven by climate variability, resource constraints, technological developments, changing consumer needs, and evolving national and international food-security priorities. Addressing these challenges requires multidisciplinary research as well as stronger connections between scientific knowledge and its practical application.

The conference has been designed to provide a platform for researchers, academics, students, policymakers, agricultural professionals, entrepreneurs, and industry representatives to exchange knowledge and share experiences. The seven thematic areas cover major dimensions of sustainable food systems, including climate change and food security, climate-smart agriculture, soil and water resources, food processing and value addition, supply-chain management and policy, and agri-industrial innovations and smart technologies.

The Industrial Expo complements the scientific program by providing an opportunity for industry and technology providers to showcase emerging solutions and engage directly with researchers and other stakeholders. We hope that this interaction will strengthen academia-industry linkages and encourage the development and adoption of innovative technologies.

I sincerely appreciate the support of the Vice Chancellor, the Patrons, the Pakistan Agricultural Scientists Forum, members of the organizing committee, participating institutions, industry partners, authors, reviewers, and all those who have contributed to the organization of this event.

I welcome all national and international participants to Bahauddin Zakariya University and hope that the conference provides an intellectually stimulating environment for scientific exchange, professional networking, and future collaboration.



Prof. Dr. Mubshar Hussain

Faculty of Agricultural Sciences & Technology
Bahauddin Zakariya University, Multan, Pakistan
Chief Organizer

ABOUT THE CONFERENCE

The **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026** is being organized by **Bahauddin Zakariya University (BZU), Multan, Pakistan**, in collaboration with the **Pakistan Agricultural Scientists Forum (PAS Forum)** from **October 13–15, 2026**.

The Pakistan Agricultural Scientists Forum promotes sustainable agricultural development by connecting research, education, industry, and farming communities to enhance food security and economic growth. In the context of accelerating climate change, agriculture and food systems face increasingly complex challenges, including rising temperatures, water scarcity, soil degradation, resource limitations, and extreme weather events.

The conference seeks to bring together researchers, academicians, policymakers, industry leaders, agricultural professionals, and other stakeholders to share scientific knowledge, discuss emerging challenges, and explore innovative solutions for sustainable and climate-resilient food systems.

The accompanying **Industrial Expo** provides a platform for industry and technology partners to showcase emerging technologies, products, services, and innovations relevant to agriculture, food production, processing, resource management, and sustainable food systems.

Through scientific presentations, technical discussions, networking, and academic-industry interaction, the event aims to facilitate knowledge exchange and encourage collaborations that can contribute to sustainable agricultural development, food security, and economic growth.

The conference provides a multidisciplinary forum in which scientific research, technological innovation, industrial development, and policy perspectives can be considered together in addressing the challenges facing future food systems.

Conference Objectives

The conference aims to:

1. **Review past and present climate change impacts on agriculture and food systems** and discuss projections and potential future scenarios.
2. **Promote food security** through sustainable, climate-smart, and resource-efficient agricultural practices.
3. **Integrate advances in food science and technology with agricultural production** to enhance food quality, safety, processing, value addition, and utilization.
4. **Strengthen academia-industry linkages** through scientific interaction, technology exchange, networking, and the Industrial Expo.

5. **Facilitate evidence-based policy dialogue** for climate-resilient agricultural practices and sustainable food systems.
6. **Encourage interdisciplinary and international collaboration** among researchers, academics, policymakers, industry professionals, and other stakeholders.
7. **Highlight emerging technologies and innovations** that can improve agricultural productivity, resource-use efficiency, food processing, and the resilience of food supply chains.

Conference Themes

Theme I. Climate Change and Food Security

Climate impacts on agriculture and food systems; climate variability; food availability and access; nutritional security; adaptation and resilience; and future food-system challenges.

Theme II. Climate-Smart and Sustainable Agriculture

Climate-smart crop and livestock production; sustainable intensification; resilient farming systems; conservation agriculture; sustainable agricultural practices; and adaptation strategies.

Theme III. Soil Health, Water Management & Resource-Use Efficiency

Soil health and fertility; soil conservation; water scarcity and management; irrigation efficiency; precision resource management; nutrient-use efficiency; and sustainable use of agricultural resources.

Theme IV. Food Processing, Safety & Value Addition

Food processing technologies; food safety and quality; postharvest management; preservation; food biotechnology; functional foods; value addition; waste utilization; and food loss reduction.

Theme V. Supply Chain Management and Food Security Policies

Agricultural and food supply chains; logistics; market systems; food security policies; trade; governance; risk management; and policy frameworks for resilient food systems.

Theme VI. Agri-Industrial Innovations and Smart Technologies

Precision agriculture; artificial intelligence; digital agriculture; automation; sensors and remote sensing; smart farming; biotechnology; agri-industrial technologies; and innovative solutions for sustainable agriculture and food systems.

Theme VII. Water, Sanitation and Hygiene

Sanitation across food value chains; hygiene in food handling and processing; wastewater treatment and reuse; water pollution prevention; food safety and contamination control.

ORGANIZING COMMITTEE

Patron-in-Chief

Dr. Muhammad Zubair Iqbal, Vice Chancellor, Bahauddin Zakariya University, Multan, Pakistan

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Prof. Dr. Muhammad Riaz, Dean, Faculty of Food Science & Nutrition, Bahauddin Zakariya University, Multan and Chairman, Pakistan Agricultural Scientists Forum

Prof. Dr. Nazim Hussain, Dean, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan

Chief Organizer

Prof. Dr. Mubshar Hussain, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan

Members of Organizing Committee

Dr. Abdul Rehman, Department of Agronomy, The Islamia University of Bahawalpur, Bahawalpur, and General Secretary, Pakistan Agricultural Scientists Forum

Prof. Dr. Saeed A. Asad, Department of Biosciences, COMSATS University, Islamabad, and Joint Secretary, Pakistan Agricultural Scientists Forum

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Prof. Dr. Muhammad Sana Ullah, Institute of Soil & Environmental Science, University of Agriculture, Faisalabad, and President, North Punjab PAS Forum

Organizers from the Host Institute (Bahauddin Zakariya University, Multan)

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Prof. Dr. Ijaz Randhawa, Institute of Agronomy, BZU, Multan

Prof. Dr. Tauqeer Ahmad Yasir, Institute of Agronomy, BZU, Multan

Prof. Dr. Naeem Sarwar, Institute of Agronomy, BZU, Multan

Dr. Khurram Afzal, Department of Human Nutrition, BZU, Multan

Dr. Tariq Ismail, Department of Food Science and Technology, BZU, Multan

Dr. Shahid Hussain, Department of Soil Science, BZU, Multan

Dr. Shabbir Hussain, Institute of Agronomy, BZU, Multan

Dr. Sami-ul-Allah, Department of Plant Breeding and Genetics, BZU, Multan

Dr. Amir Ismail, Department of Food Safety and Quality Management, BZU, Multan

Dr. Sajid Masood, Department of Soil Science, BZU, Multan

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The Organizing Committee of the **International Conference on Sustainable Food Systems in a Changing Climate & Industrial Expo 2026** gratefully acknowledges the support and contributions of all individuals and institutions who have made this event possible.

We express our sincere gratitude to the **Vice Chancellor, Bahauddin Zakariya University, Multan**, for providing leadership and institutional support for the conference. We are equally grateful to the Patrons and members of the **Pakistan Agricultural Scientists Forum** for their guidance and collaboration.

Our appreciation extends to the participating universities, research organizations, government institutions, industry partners, scientists, academicians, researchers, students, and professionals whose participation has contributed to the scientific and professional value of this event.

We also acknowledge the authors and reviewers whose research contributions form the foundation of this E-Book of Abstracts. Their efforts in sharing scientific knowledge and engaging with the conference themes are greatly valued.

The Organizing Committee appreciates the dedication of all members of the host-institute organizing team, volunteers, technical staff, and supporting personnel whose efforts have contributed to the planning and execution of the Conference and Industrial Expo.

We look forward to continued collaboration among academia, industry, policymakers, and farming communities in advancing sustainable, productive, and climate-resilient food systems.

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Farming the Future: Soil Health, Emissions, and Carbon Markets

Abdul Wakeel

Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Faisalabad, Pakistan

Corresponding author's e-mail: abdul.wakeel@uaf.edu.pk

Abstract

Pakistan's agricultural sector faces acute climate vulnerability and widespread soil degradation, underscoring the need for a shift toward low-carbon agriculture. This presentation examines the intersection of regenerative farming, climate resilience, and economic profitability in the Pakistani context, focusing on localized, high-impact strategies such as reduced tillage, Alternate Wetting and Drying (AWD) in rice cultivation, and sustainable nitrogen management to curb nitrous oxide emissions. It also addresses the widespread practice of crop residue burning, proposing biochar production and direct soil incorporation, together with optimized manure management, as sustainable alternatives. Healthy, carbon-rich soils act as biological buffers against extreme weather while sequestering atmospheric carbon, providing a foundation for long-term climate resilience. For these environmental gains to be sustained, they must also be economically viable: the presentation highlights how the transition to low-carbon practices can enable access to emerging carbon markets, allowing farmers to generate agricultural carbon credits and monetize soil stewardship, illustrated through case studies. Overall, the presentation argues that low-carbon agriculture functions simultaneously as an environmental safeguard and a viable economic strategy, with the potential to strengthen farm profitability, climate resilience, and long-term soil health in Pakistan.

Keywords: *Low-carbon agriculture; Alternate wetting and drying; Regenerative agriculture; Greenhouse gas emissions; Carbon markets; Nitrogen management*

Restoring Agrobiodiversity for Sustainable and Resilient Food Systems

Muhammad Farooq

Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al-Khoud, Muscat, Oman

Corresponding author's e-mail: farooqcp@squ.edu.om

Abstract

The accelerating erosion of agrobiodiversity threatens the resilience of food systems worldwide, with impacts especially visible in Pakistan, where agriculture relies heavily on a small number of staple crops. This narrowing of food diversity compromises nutritional quality, degrades soil health, and increases vulnerability to climatic stress. Neglected and underutilized crops, indigenous plant species, crop wild relatives, and traditional landraces hold considerable, largely overlooked potential to address these challenges, being often nutrient-dense, climate-resilient, and deeply embedded in local culture. When incorporated into breeding programs and sustainable practices such as crop rotation, intercropping, relay cropping, and cover cropping, these genetic resources can improve soil structure and fertility, reduce dependence on synthetic inputs, suppress weed pressure, lower greenhouse gas emissions, and support more efficient nutrient cycling within farming systems. Promoting these diverse crops also expands dietary choices, supports farmer livelihoods, and helps preserve cultural knowledge embedded in Pakistan's agricultural heritage. Restoring agrobiodiversity will require coordinated effort among farmers, researchers, policymakers, and local communities; embracing these underused genetic resources offers a practical, forward-looking path toward nourishing people, regenerating landscapes, and building food systems capable of thriving under a changing climate.

Keywords: *Agrobiodiversity; Crop wild relatives; Neglected and underutilized crops; Climate resilience; Soil health; Greenhouse gas emissions*

Functional Foods for the Prevention of Diet-Related Diseases: Bridging Food Science, Technology, and Nutrition

Tahir Zahoor*, Hamna Ikhtlaq, Moheet Khan

NUR International University, Lahore, Pakistan

*Corresponding author's e-mail: tahir.zahoor@niu.edu.pk

Abstract

Functional foods offer a promising approach to disease prevention by combining essential nutrition with physiologically beneficial components that may improve health and reduce disease risk. The rising global prevalence of obesity, type 2 diabetes, cardiovascular disease, hypertension, and other diet-related disorders has created an urgent need for innovative food-based prevention strategies. Advances in food science and technology provide new opportunities to develop nutritionally enhanced foods containing dietary fiber, probiotics, prebiotics, antioxidants, polyphenols, omega-3 fatty acids, vitamins, minerals, and other bioactive compounds. Emerging technologies, including fermentation, encapsulation, fortification, biotechnology, non-thermal processing, and precision formulation, can improve the nutritional value, stability, bioavailability, and sensory characteristics of functional foods derived from various fruit sources, including blackcurrant. Use of indigenous, underutilized, and climate-resilient food resources can further support sustainable nutrition and strengthen local food systems. Future development should emphasize evidence-based innovation supported by nutritional, biochemical, microbiological, clinical, and consumer research, with collaboration among food scientists, technologists, nutritionists, healthcare professionals, and industry essential to translating scientific discoveries into commercially viable products. Precision nutrition and nutrigenomics may further facilitate development of foods tailored to specific nutritional needs and disease-risk profiles.

Keywords: *Functional foods; Blackcurrant; Diet-related disease; Cardiovascular disease; Nutritional value*

Advancing Quality, Sustainability, and Innovation through Academia–Research–Industry Linkages: The Legacy and Future Vision of PSFST

Muhammad Atif Randhawa

*National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan
Pakistan Society of Food Scientists and Technologists, Pakistan; Punjab Knowledge and Nutrition Council, University of Agriculture, Faisalabad, Pakistan*

Corresponding author's e-mail: atifrandhawa@uaf.edu.pk

Abstract

Pakistan's food sector faces growing challenges related to food safety, quality, sustainability, technological advancement, and changing consumer demand, challenges that require stronger linkages among academia, research institutions, industry, regulatory bodies, and professional organizations. This presentation outlines a strategic vision for advancing quality, sustainability, and innovation through academia-research-industry linkages, building on the legacy and future direction of the Pakistan Society of Food Scientists and Technologists (PSFST). As a professional platform, PSFST can play a central role in connecting knowledge with practice, promoting industry-responsive education and research, facilitating technology transfer, supporting professional development, and strengthening evidence-based policy dialogue, with particular emphasis on emerging opportunities in food safety, sustainable food systems, value addition, digital technologies, and artificial intelligence. The presentation highlights the importance of transforming fragmented interactions into sustainable partnerships that generate measurable impact for the food industry and society, envisioning a connected food science ecosystem in which academia generates knowledge, research develops solutions, industry drives application, and PSFST serves as the bridge connecting them.

Keywords: *Academia-industry linkages; Food science policy; Technology transfer; Professional development; Food sector innovation*

The GCF Indus Basin Model for Smallholder Agribusiness Transformation: From Climate-Resilient Production to Market-Ready Cooperatives

Ruqia Khattak

Food and Agriculture Organization, Pakistan

Corresponding author's e-mail: Ruqia.Khattak@fao.org

Abstract

Smallholder farming systems across Pakistan's Indus Basin face compounding climate risks, including rising temperatures, water scarcity, soil degradation, and extreme weather, which threaten both crop production and the market systems on which smallholders depend. While climate-resilient agriculture (CRA) training has become a common response, production-side interventions alone are insufficient unless paired with institutional and market resilience. This presentation describes an operational model developed under the Green Climate Fund (GCF)-funded project "Transforming the Indus Basin with Climate-Resilient Agriculture and Water Management," implemented by FAO across eight districts of South Punjab and Sindh. The model centers on a staged pathway that moves farmer groups from climate-resilient field practices, through institutional and business readiness, to formal registration as Farmer Market Cooperatives (FMCs) under provincial cooperative law, with progression governed by an objective, six-dimension scoring framework covering institutional maturity, CRA adoption, business and financial readiness, market positioning, governance, and social inclusion. The pathway is supported by four operational pillars: a bilingual farmer business-planning workbook, harmonized legal and bye-law frameworks for Punjab and Sindh, market and value-chain linkage tools, and financial-inclusion mechanisms, alongside nine standardized bankable agribusiness investment cases and a village-level "business hub" model that extends benefits to non-member beneficiaries. Early field evidence — including trained facilitators, classified agro-technicians, and consolidated district action plans — demonstrates the pathway's operational readiness. Key lessons include the importance of sequencing institutional readiness before market linkage, treating business planning as a diagnostic tool, and harmonizing legal pathways across provinces. The model offers a replicable framework for climate-vulnerable river basins seeking to link production-side resilience with sustainable market institutions.

Keywords: *Climate-resilient agriculture; Agribusiness cooperatives; Indus Basin; Green Climate Fund; Farmer market institutions; Gender-responsive value chains*

Transforming Pakistan's Indus Basin: Evidence from a GCF-Funded Climate-Resilient Agriculture and Water Management Project

Noella Kamwendo

Food and Agriculture Organization, Pakistan

Corresponding author's e-mail: Noella.Kamwendo@fao.org

Abstract

Pakistan's Indus Basin is a critical food-producing region facing intensifying vulnerability due to its arid climate and dependence on a single river system. This abstract presents early evidence from the Green Climate Fund (GCF) project "Transforming the Indus Basin with Climate-Resilient Agriculture and Water Management," implemented by FAO with the provincial governments of Sindh and Punjab. The intervention promotes adoption of Climate-Resilient Agriculture (CRA) and On-Farm Water Management (OFWM) practices to shift the region from "business as usual" toward sustainable adaptation, using the Farmer Field School (FFS) approach together with CRA/OFWM demonstration plots. Operational evidence highlights the vital role of participatory learning in this transformation: the project has established a network of Farmer Field Schools, Climate Business Field Schools, and Women Open Schools, alongside CRA demonstration plots, to disseminate technical knowledge. To date, 1,535 extension workers have been trained in FFS and CRA/OFWM approaches, over 6,400 farmers have received direct training, and 43,160 farmers have engaged through Field Schools and CRA demonstration plots across Punjab and Sindh. Reports from 1,986 field schools, including pilot studies in tail-end communities, indicate promising improvements in irrigation reliability and agricultural productivity. Demonstration plots incorporating drip irrigation, mulching, and zero tillage have proven essential for allowing farmers to observe the tangible benefits of OFWM practices firsthand. By integrating these field-level demonstrations with institutional capacity building, the initiative provides scalable evidence that community-led, discovery-based learning can enhance resilience and livelihoods for an estimated 1.3 million vulnerable people across the basin.

Keywords: *Climate-resilient agriculture; On-farm water management; Farmer Field Schools; Indus Basin; Green Climate Fund; Irrigation efficiency*

RO-Reject Reuse for Water Conservation at Reverse Osmosis Plants

Muhammad Aqeel¹, Usama Nasir², Amna Iqbal³, Amir Ismail^{1*}, Umar Mushtaq Ahmad¹, Marium Waheed⁴

1 Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

3 Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

4 Fatima Jinnah Medical University, Lahore, Pakistan

***Corresponding author's e-mail:** amirismail@bzu.edu.pk

Abstract

Decentralized reverse osmosis (RO) systems are rapidly proliferating in water-stressed areas, generating significant volumes of reject water that are frequently discarded; Pakistan's per-capita water availability has fallen from roughly 5,600 m³ year⁻¹ in 1951 to below 1,000 m³, nearing the recognized 500 m³ absolute-scarcity threshold, so this practice compounds pressure on already stressed freshwater and groundwater resources. Unlike the hypersaline brine produced by seawater desalination, rejecting streams from inland RO systems treating low-TDS groundwater can retain moderate levels of salts and essential nutrients, offering potential for recovery and reuse. This study investigated whether this largely discarded stream could be safely redirected to beneficial use and developed a site-specific management framework, characterizing water from five community RO plants in Multan, Pakistan, and evaluating it through controlled irrigation experiments comparing tap water, RO permeate, and RO reject. Reject water contained higher levels of dissolved salts, sodium, and essential nutrients than permeate, with salinity varying widely between plants depending on source-water chemistry. Crop productivity under moderately mineralized reject water was 15–25% higher than under tap water and 35–50% higher than under RO permeate, while increasing salinity and sodium progressively reduced productivity; salinity and sodicity were the main limiting factors within a single cultivation cycle, with measurable post-harvest increases in soil salinity and sodicity, while trace-metal enrichment remained low to moderate. Drawing on the observed water-soil-crop relationships, a three-tiered fit-for-purpose framework is proposed, using irrigation-water TDS and EC together with resulting post-harvest soil SAR thresholds to identify which RO reject streams can be safely redirected to agricultural reuse. At the five plants studied, four of five reject streams met tier 1 or tier 2 quality thresholds, indicating that most of this currently discarded water is recoverable for irrigation; assuming comparable water quality across the wider network of community RO plants in the region, this framework suggests conservation potential on the order of billions of liters of freshwater equivalent annually. This approach reframes RO reject management from a disposal problem into a scalable water conservation strategy for water-stressed, decentralized RO regions worldwide.

Keywords: *Reverse osmosis; RO reject water; Water conservation; Water reuse; Circular water management; Irrigation water quality*

Climate Change and Food Security: A Nutrition and Dietetics Perspective

Wajeeha Habib, Umaima Mahmood*, Arisha Naeem

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan

***Corresponding author's e-mail:** umaimamehmood212@gmail.com

Abstract

Climate change is placing global food systems under severe strain by affecting both food production and diet quality. Rising temperatures, irregular rainfall, and extreme weather events are contributing to declines in major crops such as wheat, rice, and maize, alongside losses in animal farming and fisheries. This review examines the link between climate change and food security, with a specific focus on dietary diversity and nutrition from a dietetics perspective. Key drivers of this crisis include heat stress on crops, prolonged droughts that degrade soil, water shortages in arid regions, and ocean warming that reduces fish stocks. These pressures directly undermine the availability, access, utilization, and stability of food supplies, the core components of food security, leading to reduced output, rising prices that disproportionately affect low-income households, and narrower dietary diversity. Increased reliance on staple grains raises the risk of deficiencies in key micronutrients such as iron, vitamin A, and zinc, with the greatest impact on vulnerable groups, contributing to higher rates of child stunting, maternal anemia, and health risks for infants and the elderly. To address these challenges, this review recommends promoting heat-tolerant, nutrient-dense crop varieties; adopting soil-friendly, water-saving farming methods such as crop rotation and precision irrigation; developing nutrition-sensitive food policy; reducing postharvest losses through improved storage; and implementing community nutrition education programs. Protecting food security and nutrition under a changing climate requires an integrated approach combining adaptive farming with nutrition-focused policy to support healthier populations over the long term.

Keywords: *Climate change; Food security; Dietary diversity; Nutrition; Climate-resilient crops; Hidden hunger*

Development and Nutritional Evaluation of Value-Added Moringa-Fortified Biscuits

Ayesha Shahzain Noor*, Maniha Farman, Warisha Waheed, Umaima Farman, Nabia Rashid, Sadaf Javaria

Department of Food Science and Technology, Gomal University, Dera Ismail Khan, Pakistan

*Corresponding author's e-mail: shahzain2004006@gmail.com

Abstract

Malnutrition and micronutrient deficiency remain major public health concerns in Pakistan. Moringa oleifera leaves are a locally available, nutrient-dense resource rich in protein, iron, calcium, and antioxidants, yet remain underutilized in bakery products. This study aimed to develop nutritionally enhanced biscuits incorporating moringa leaf powder and to evaluate their nutritional and sensory properties. Biscuits were formulated at the Department of Food Science and Technology, Gomal University, by substituting wheat flour with moringa leaf powder at 0%, 3%, 5%, and 7% levels. Proximate analysis assessed moisture, protein, fat, ash, and fiber content, while sensory evaluation was conducted with 30 student panelists using a 9-point hedonic scale for color, flavor, texture, and overall acceptability. Protein content increased from 8.2% in the control to 11.6% in biscuits containing 7% moringa, with corresponding improvements in iron and calcium content across increasing incorporation levels. Sensory evaluation showed that biscuits with 5% moringa achieved the highest overall acceptability score (8.1), while those with 7% moringa exhibited a slightly bitter aftertaste; all fortified formulations remained acceptable for consumption. These findings indicate that moringa leaf powder can be incorporated into biscuits at up to 5% to improve nutritional value without compromising sensory quality, supporting its potential as an affordable functional snack to help address micronutrient deficiency and promote sustainable food systems in Pakistan.

Keywords: *Moringa oleifera*; Value addition; Nutritional evaluation; Biscuits; Functional food; Sensory evaluation

Trehalose-Mediated Drought Responses in Bread Wheat Reflect Genotypic Variation and Coordination of Growth and Redox Balance

Marwa Sulaiman Al Hinai^{1,2*}, Ibtisam Rashid Al Harrasi³, Mahmoud Yaish⁴, Muhammad Farooq^{1*}

1 Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al-Khoud, Oman

2 Directorate General of Agriculture and Livestock Research, Ministry of Agriculture, Fisheries and Water Resources, Al-Seeb, Oman

3 College of Applied Sciences and Pharmacy, University of Technology and Applied Sciences, Muscat, Oman

4 Department of Biology, College of Science, Sultan Qaboos University, Muscat, Oman

***Corresponding author's e-mail:** s121413@student.squ.edu.om; farooqcp@squ.edu.om

Abstract

Drought stress is a major constraint on wheat production in arid environments such as Oman. This study evaluated 20 bread wheat genotypes under well-watered (80% water-holding capacity, WHC), moderate drought (60% WHC), and severe drought (40% WHC) conditions to assess morphological, pigment, and biochemical responses. Drought significantly reduced plant performance, with substantial variation among genotypes. Under severe drought, trehalose content ranged from 2.50 to 60.63 $\mu\text{mol g}^{-1}$ fresh weight (FW) and showed a weak, non-linear association with shoot dry weight ($P \leq 0.05$), with an apparent optimum near 34.8 $\mu\text{mol g}^{-1}$ FW. Genotypes differed in their response patterns: Messani and WQ302 maintained higher growth and chlorophyll content with moderate trehalose accumulation, whereas Cooly and WQ229 accumulated high trehalose levels but showed reduced growth, and WQ231 and Saneen exhibited both low trehalose and poor growth. Trehalose was weakly negatively associated with malondialdehyde (MDA), and a model incorporating trehalose and antioxidant enzyme activity explained 29% of MDA variation. These findings indicate that drought tolerance in wheat is associated with coordinated regulation of carbon allocation, redox balance, and broader metabolic responses, rather than trehalose accumulation alone, and provide physiological indicators that may support selection of drought-resilient wheat genotypes for arid environments.

Keywords: *Trehalose metabolism; Antioxidant enzymes; Malondialdehyde; Oxidative stress; Water deficit; Bread wheat*

Adoption and Impacts of Climate-Smart Agricultural Practices for the Resilience and Productivity of Sustainable Food Systems

Nida Yousaf^{1*}, Ali Hamza², Nighat Raza²

1 Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan

2 Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** nidayousaf879@gmail.com

Abstract

Climate-smart agriculture (CSA) plays a significant role in strengthening global food security, improving living standards, and building resilience to climate change as part of sustainable agricultural development. Among small-scale farmers, adoption of CSA practices is shaped by a wide range of environmental, institutional, socioeconomic, and technological factors, including gender, age, education, risk perception, access to financial services, farm size, off-farm income, and local production conditions, which may influence adoption decisions either positively or negatively. Adoption is supported by agricultural training, access to technical assistance, participation in agricultural associations, support from non-governmental organizations, favorable climate conditions, and secure land tenure, and can be further strengthened through natural, institutional, financial, social, physical, and human capital, particularly via community-based organizations that improve access to technical and financial resources. The interlinked objectives of CSA include adapting to climate change, building community resilience, enhancing sustainable agricultural income and productivity, and reducing greenhouse gas emissions. Adoption of these practices can improve food security, household well-being, and dietary diversity while reducing climate-related risk, and can also increase crop production, farmer income, and overall economic activity. Integrating conventional agricultural methods with climate-smart technologies can further enhance soil quality and environmental sustainability. Combining CSA practices with stronger institutional support and international technology collaboration can promote the resilience and sustainability of agricultural food systems, supporting progress toward the United Nations Sustainable Development Goals, environmental protection, climate adaptation, and poverty reduction.

Keywords: *Climate-smart agriculture; Adoption decision; Sustainability; Food security; Farmer income; Sustainable Development Goals*

Green Banana Powder: An Emerging Plant-Based Excipient for Sustainable Nutraceutical Development

Allah Rakha^{1*}, Areej Munir¹

National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** arrehman_ft@uaf.edu.pk

Abstract

Pakistan's food supplements market was valued at USD 1.62 billion in 2024 and is projected to reach USD 3 billion by 2032, growing at a compound annual growth rate of 8% between 2026 and 2032. Excipients are widely used by industry in the manufacture of nutraceuticals and food supplements as carrier components that improve the appearance, stability, acceptability, and bioavailability of finished products. Despite this market growth, the sector remains heavily dependent on imported excipients such as lactose, whey solids, and maltodextrin, which together account for over 90% of local formulation use. This reliance results in significant foreign exchange loss and limits accessibility, since lactose-based excipients are unsuitable for a considerable proportion of Pakistan's lactose-intolerant population. Green banana powder (GBP) offers a locally available, cost-effective, and nutrient-rich alternative that remains unexplored within Pakistan's excipient landscape. Naturally lactose-free and gluten-free, and rich in resistant starch, GBP demonstrates strong functionality as a binder, bulking agent, and therapeutic enhancer, with additional prebiotic benefits for gut health. Beyond improving formulation performance, GBP adoption could stimulate rural economies, reduce post-harvest losses, lower the carbon footprint associated with current excipient use, and create new value chains for farmers and manufacturers. Rather than continuing to rely on imported, low-nutrient excipients, Pakistan can transform its agricultural surplus into a strategic excipient resource, fostering self-reliance and value addition within the nutraceutical supply chain.

Keywords: *Green banana powder; Nutraceuticals; Excipients; Food supplements; Resistant starch; Value addition*

Iron-Bio-Priming: A Smart and Sustainable Biofortification Technique for Iron-Rich Wheat Grain Production under Bed-Furrow Sowing and Drought Stress

Hamid Nawaz^{*1}, Basharat Ali², Nazim Hussain³, Azra Yasmeen³

1 Cholistan Institute of Desert Studies, Faculty of Agriculture & Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

2 Agronomic Research Station, Bahawalpur, Pakistan

3 Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** hamidnawaz@iub.edu.pk

Abstract

Meeting rising global food demand while addressing micronutrient malnutrition is a major challenge for agronomists: iron (Fe) deficiency affects more than half of the global population, with wheat as a primary staple crop. This two-year study (2023–24 and 2024–25) evaluated the effects of seed priming (dry-seed control, hydro-priming, bio-priming with moringa extract, iron priming with anhydrous FeSO₄, and combined iron-bio-priming), sowing method (line sowing versus bed-furrow sowing), and irrigation regime (normal irrigation, mild drought, severe drought) on wheat performance at the Agronomic Research Station, Bahawalpur, Pakistan. Iron-bio-priming combined with bed-furrow sowing produced the strongest interactive effects, improving fertile tillers (4%), grains per spike (23%), and 1000-grain weight (10%) relative to other treatments, with greater gains observed in the second year. This combination also increased grain yield (9%), biological yield (15%), and harvest index (7%) relative to iron priming, bio-priming, and hydro-priming, while producing the highest grain iron (1%) and zinc (11%) uptake and the lowest phytate content among treatments. Antioxidant activity was also enhanced under iron-bio-priming, with increases in superoxide dismutase (7%), peroxidase (12%), catalase (14%), ascorbic acid (2%), and total phenolic content (20%), particularly under drought stress. Economic analysis indicated that iron-bio-priming combined with bed-furrow sowing achieved the highest net income and benefit-cost ratio among treatments. These findings suggest that iron-bio-priming is an effective, low-cost agronomic approach for producing iron biofortified wheat under bed-furrow sowing, including under drought-stressed conditions.

Keywords: *Seed priming; Iron biofortification; Bed-furrow sowing; Drought stress; Wheat; Antioxidant enzymes*

From Climate Vulnerability to Resilience: Farmers' Perceptions and Pathways to Climate-Smart Agriculture in the Hindu Kush Himalaya

Saeed A. Asad^{1*}, Muhammad Abid², Gopal Thapa³, Tashi Dendup⁴

1 Department of Biosciences, COMSATS University Islamabad, Islamabad, Pakistan

2 Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Pakistan

3 Nepal Agroforestry Foundation, Nepal

4 College of Natural Resources, Royal University of Bhutan, Bhutan

***Corresponding author's e-mail:** saeed.asad@comsats.edu.pk

Abstract

The Hindu Kush Himalaya (HKH) is a global climate change hotspot, home to more than 200 million people, where extreme climate events have significantly affected ecosystems, agriculture, and food security. Ensuring sustainable agriculture and food security in this region requires identifying, upscaling, and validating climate-smart solutions at local and regional levels. This study investigated farmers' perceptions of climate change and identified climate-smart agricultural (CSA) practices suited to high-altitude farming areas in Pakistan, Nepal, and Bhutan, using surveys, focus group discussions, and key-informant interviews across three elevation-based study sites per country. A total of 360 households were surveyed (120 per country, 40 per elevation), alongside 20 key-informant interviews per country with community leaders and government officials. Farmers reported a significant rise in summer and winter temperatures over the past two to three decades, accompanied by changes in growing-season length and vegetation cover, driving a shift from monoculture to bi- and polyculture systems. Farmers in high-mountain areas faced direct effects on crop and livestock production, indirect socioeconomic consequences, and high adaptation costs, with smaller production units, limited financial resources, and weak institutional services constraining adaptation across all three countries. Uncertainty and reductions in crop and livestock yields were more pronounced in Pakistan than in Nepal or Bhutan. Adaptive measures included changes in crop type, variety selection, sowing dates, and land management, though decreasing and uncertain water availability, poverty, and limited institutional access continued to heighten vulnerability. The findings point to the need for capacity building on area-specific CSA practices and improved institutional outreach on climate risk and adaptation to support sustainable livelihoods across the Himalayan highlands.

Keywords: *Climate-smart agriculture; Farmer perception; Hindu Kush Himalaya; Climate adaptation; High-altitude farming; Food security*

Reviving Underutilized Indigenous Crops for Sustainable Dietary Diversification: A Climate-Resilient Approach to Food and Nutrition Security in Pakistan

Hira Iftikhar¹, Mubeen Naeem^{2*}

1 Institute of Home and Food Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Nutrition and Food Sciences (NIFSAT), University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** mubeennaeem345@gmail.com

Abstract

Climate change is posing significant challenges to food production and nutritional security in Pakistan through rising temperatures, water scarcity, and unpredictable weather patterns, threatening the availability of nutrient-rich foods and exacerbating micronutrient deficiencies and food insecurity. Promoting underutilized indigenous crops offers a sustainable pathway to building climate-resilient food systems and improving dietary quality. Crops such as pearl millet, sorghum, barley, chickpea, and moth bean are naturally adapted to harsh environmental conditions, require fewer agricultural inputs, and are rich sources of dietary fiber, protein, iron, zinc, calcium, and essential vitamins; their inclusion in daily diets can enhance dietary diversity, reduce hidden hunger, and strengthen food system resilience. Despite these nutritional and environmental benefits, utilization of these crops remains limited due to low consumer awareness, inadequate value addition, weak market access, and insufficient policy support. This review highlights the potential of indigenous crops to support sustainable nutrition, climate adaptation, and rural livelihoods in Pakistan, and argues that integrating these crops into nutrition programs, food product development, and agricultural policy could improve food security and public health while promoting environmentally sustainable agriculture. Future research should focus on consumer acceptance, innovative food product development, and effective policy interventions to increase the production and consumption of climate-resilient indigenous crops.

Keywords: *Climate change; Indigenous crops; Dietary diversification; Sustainable food systems; Hidden hunger; Food security*

Smart Bio-Adaptive Metal-Organic Frameworks for Sustainable Farming: Integrated Pest Management, Nutrient Delivery, and Rhizosphere Health

Khadija Zaman¹, Rukshar Rasool², Irtaza Hussain³, Mohammad Asif³, Sana Ashraf^{4*}, Ayesha Israr³, Bushra Jabeen⁵, Rabia Noreen⁶

1 Department of Material Sciences and Engineering, Hohai University, Nanjing, China

2 School of Natural Sciences, National University of Sciences and Technology, Islamabad, Pakistan

3 Faculty of Veterinary Sciences, Bahauddin Zakariya University, Multan, Pakistan

4 Department of Botany, University of Agriculture, Faisalabad, Pakistan

5 Department of Mathematics, Government College University, Faisalabad, Pakistan

6 Department of English, Government College University, Faisalabad, Pakistan

***Corresponding author's e-mail:** sanashraf254@gmail.com

Abstract

Modern agriculture is under increasing threat from climate change, agrochemical overuse, soil degradation, and disruption of beneficial soil microbial communities. Metal-organic frameworks (MOFs) have emerged as promising nano-carriers for precision farming owing to their responsive behavior, customizable pore structure, and strong loading capacity, yet most existing work treats MOFs as passive delivery vehicles with limited attention to their biological interactions and degradability. This review examines recent findings on degradable, bio-responsive MOFs for eco-friendly pest control, nutrient delivery, and soil microbiome engineering. Reported data indicate that MOFs can load 80–90% of pesticide payloads while preserving 79% of microbiome viability during encapsulation and can improve nutrient uptake by up to 64.4% through controlled release. Stimuli-responsive MOFs enable targeted chemical release during infection, triggered by changes in pH, reactive oxygen species, or pathogen-derived enzymes. Beyond current applications, this review proposes bioinspired, adaptive MOF designs for more holistic plant protection, including the use of polysaccharides, chitosan, pectin, and pathogen-responsive ligands to improve MOF binding to plant and fungal surfaces for targeted treatment. Embedding beneficial fungi such as *Trichoderma* within MOFs could enable gradual framework breakdown coupled with controlled agrochemical release and added biocontrol benefits, while encapsulating plant growth-promoting rhizobacteria (PGPR) in MOFs may protect them from environmental stress and support their survival and root colonization, contributing to more sustainable agricultural systems.

Keywords: *Metal-organic frameworks; Nanocarriers; Integrated pest management; Nutrient delivery; Soil microbiome engineering; Precision agriculture*

Reducing Food Waste through Sustainable Dietary Planning: A Nutrition-Based Approach to Strengthening Food Supply Chains and Food Security Policies in Pakistan

Mubeen Naeem^{1*}, Hira Iftikhar²

1 Institute of Home and Food Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Nutrition and Food Sciences (NIFSAT), University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** mubeennaeem345@gmail.com

Abstract

Food waste is a major challenge that threatens food security, nutrition, and the sustainability of food systems in Pakistan, with significant losses occurring throughout the supply chain, from production and storage to transportation, retail, and household consumption. These losses reduce the availability of nutritious food while increasing economic and environmental burdens. Sustainable dietary planning offers an effective, nutrition-based strategy to minimize avoidable food waste and promote efficient resource use. This review examines the role of evidence-based dietary practices, including meal planning, portion control, proper food storage, consumption of seasonal and local foods, and effective use of leftovers, in reducing household food waste, and discusses the importance of strengthening food supply chains through improved post-harvest handling, storage infrastructure, transportation systems, and food redistribution mechanisms. It further highlights the contribution of food security policy, nutrition education, consumer awareness, and multi-sectoral collaboration to sustainable food consumption. Integrating nutrition-focused dietary planning with efficient supply chain management and supportive policy frameworks can enhance food availability, improve dietary quality, and strengthen national food security, contributing to more sustainable and resilient food systems in Pakistan. Future research should evaluate the effectiveness of nutrition, supply chain, and policy interventions in reducing food waste and supporting long-term food security.

Keywords: *Food waste; Sustainable dietary planning; Supply chain management; Food security policy; Nutrition; Pakistan*

Integrating One Health System in Pakistan: A Strategic Approach to Combating Antimicrobial Resistance in the Food Chain

Irtaza Hussain, Mohammad Asif*, Ayesha Israr

Department of Pathobiology, Faculty of Veterinary Sciences, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** masifabbas5@gmail.com

Abstract

Antimicrobial resistance (AMR) is a pressing global health challenge, with the food chain serving as a significant pathway for the transmission of resistant pathogens. In Pakistan, irresponsible antimicrobial use in agriculture, particularly in livestock and poultry farming, has worsened the AMR crisis and poses risks to both public health and food safety. This study proposes a One Health-integrated framework to address AMR in Pakistan, linking human, animal, and environmental health to reduce the spread of resistant microorganisms. Unlike conventional sector-specific practices, the proposed framework promotes a coordinated cross-sectoral response through improved data-sharing, surveillance, and regulatory mechanisms. Recent scientific advances, including metagenomic sequencing for resistance surveillance, bacteriophage-based approaches, and innovative wastewater treatment technologies such as ozonation, UV treatment, and membrane filtration, are identified as key tools for detecting and managing AMR at the molecular level, while rapid point-of-care diagnostic kits for resistant pathogens offer promising routes for early detection and effective treatment. The development of vaccines and probiotics as alternatives to antibiotics in livestock is also highlighted as a means of reducing resistance transmission. Drawing on a synthesis of Pakistan's AMR surveillance data, agricultural practices, and international best practices, including Denmark's antibiotic-permission regulatory model, this framework presents actionable strategies for the early detection, prevention, and control of AMR in the food chain, including joint surveillance platforms, risk-based food safety monitoring, and collaborative policy implementation across health and agriculture ministries. This integrated approach aims to reduce AMR transmission at the farm-to-fork level, strengthening food safety and national public health resilience, with direct relevance to Pakistan's National Action Plan on AMR.

Keywords: *Antimicrobial resistance; One Health; Food chain; Surveillance; Public health; Food safety*

Gender-Responsive Climate Adaptation in Agri-Food Systems: A Framework for Equitable Innovation

Hira Iftikhar^{1*}, Kiran Raza²

1 Institute of Home Sciences, University of Agriculture, Faisalabad, Pakistan

2 National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** hira.iftikhar@uaf.edu.pk

Abstract

Climate change affects women in agricultural and food systems disproportionately relative to men, yet most current adaptation plans do not account for the distinct challenges and strengths women bring to these systems. This study examines how gender-responsive innovation can help close gaps in climate adaptation planning and digital farming tool design. Drawing on a review of policies and projects across South Asia, the study develops a three-part framework for equitable and inclusive innovation: (1) collecting disaggregated data to assess climate impacts across different groups, (2) co-developing climate-friendly technologies with input from women farmers, and (3) embedding gender equality within institutional structures supporting national climate plans. Early evidence indicates that programs incorporating women's local environmental knowledge achieve 25–40% greater adoption of climate-friendly farming practices than programs that do not consider gender, and that digital advisory services designed around women's literacy levels and technology access lead to improved farm-level decision-making and household food security. These findings suggest that gender-responsive adaptation is not only a matter of equity but also a strategic approach to building resilient, inclusive, and food-secure agricultural systems in climate-affected regions.

Keywords: *Gender-responsive adaptation; Climate-smart agriculture; Food security; Digital agriculture; Women's empowerment; Equitable innovation*

Integrated Innovations for Climate-Resilient Livestock Supply Chains

Kiran Raza^{1*}, Hira Iftikhar²

1 Institute of Home Sciences, University of Agriculture, Faisalabad, Pakistan

2 National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** kiran333raza@gmail.com

Abstract

Livestock supply chains are sensitive to disruptions caused by climate change, yet persistent barriers, including poor logistics, weak management, and limited access to financial resources, continue to constrain adoption of technologies that could improve their resilience. This study examines how combining multiple innovations can address these constraints simultaneously, proposing an integrated approach comprising: (1) solar- and renewable energy-powered cold storage to reduce post-harvest losses, (2) drought-tolerant feed and silage production to sustain animal nutrition during adverse weather, and (3) blockchain-based digital tracking and financial tools to improve supply chain transparency and expand smallholder access to credit. Evidence from process-level studies indicates that such combined interventions can reduce food loss by up to 35%, cut supply chain carbon emissions substantially, and increase smallholder income by 15–30% through improved market access. Realizing these gains requires government support, public-private collaboration, and targeted training for livestock producers. These findings indicate that climate adaptation in livestock systems requires a coordinated, multi-stakeholder effort rather than isolated technological interventions.

Keywords: *Livestock supply chains; Climate resilience; Solar cold chains; Digital traceability; Smallholder livelihoods; Blockchain*

Mitigation of Drought Stress in Maize Using Foliar-Applied Biostimulants Combined with Micronutrients

M. Waseem Hassan^{1*}, Rehab Noor¹, Khuram Mubeen²

1 Department of Soil and Environmental Sciences, MNS University of Agriculture, Multan, Pakistan

2 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** waseem.hassan@mnsuam.edu.pk

Abstract

Maize (*Zea mays* L.) is a globally important cereal crop whose growth is highly vulnerable to water deficit conditions. Drought stress disrupts water balance, limits nutrient assimilation, and induces oxidative damage, ultimately reducing plant growth and productivity. This greenhouse pot experiment, conducted in a Completely Randomized Design, evaluated the synergistic effects of foliar-applied biostimulants combined with zinc, iron, boron, copper, and manganese under optimal irrigation and drought stress. Under well-watered conditions, maize exhibited maximum shoot length (87.30 cm), leaf area (259.10 cm²), shoot fresh weight (33.40 g), and shoot dry weight (19.70 g), all of which were significantly reduced by drought stress. Among treatments, biostimulants combined with copper produced the highest stomatal conductance (102.60 mmol m⁻² s⁻¹) under normal conditions, while biostimulants combined with boron significantly improved leaf relative water content (74.25%) and reduced membrane damage under drought. Zinc-treated plants showed improved chlorophyll content (SPAD value 49.80), higher potassium concentration (3.05%), and reduced sodium accumulation, indicating enhanced ionic homeostasis under stress. Activities of key antioxidant enzymes, including peroxidase, superoxide dismutase, and catalase, were also markedly increased in treated plants. These findings indicate that combining biostimulants with micronutrients effectively mitigates drought-induced damage by improving plant water relations, antioxidant defense, and metabolic stability, offering a sustainable strategy to enhance maize resilience and productivity under limited water availability.

Keywords: Maize; Drought stress; Biostimulants; Micronutrients; Antioxidant enzymes; Stomatal conductance

Response of Cereal Crops and Associated Weeds to Moringa Aqueous Extract Application on Growth Metrics

Iqtidar Hussain^{1*}, Zuhair Hasnain², Sherheryar¹

1 Department of Agronomy, Faculty of Agriculture, Gomal University, Dera Ismail Khan, Pakistan

2 Department of Agronomy, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

***Corresponding author's e-mail:** iqtidarthussain453@yahoo.com

Abstract

Understanding the structural and functional characteristics of plant secondary metabolites (PSMs) is increasingly valuable in the context of environmental and climatic change, as Moringa leaf extract contains numerous secondary metabolites capable of stimulating or inhibiting plant growth, development, and germination. This study evaluated the allelopathic effects of a 20% (w/v) aqueous extract of Moringa oleifera leaves on the germination and early growth of five cereal crops and five common weed species. The extract produced species-specific responses, promoting growth in some cereals while inhibiting certain growth parameters in others: maize, sorghum, and millet generally showed improved biomass and leaf areas, whereas wheat and barley exhibited mixed responses. The extract also enhanced germination and early growth of the tested weed species, indicating that its effects were not crop-specific. These findings show that Moringa oleifera leaf extract has both growth-promoting and growth-inhibiting properties, suggesting that its agricultural application should be carefully optimized according to plant species and concentration, with further research needed to support its sustainable use.

Keywords: *Moringa oleifera; Allelopathy; Secondary metabolites; Cereal crops; Weed germination; Climate change*

Integrated Application of Chitosan and Silicon Enhances Salinity Stress Tolerance and Growth Performance of Pea (*Pisum sativum*)

Muhammad Bilal Javeed^{1*}, Rashid Hussain¹, Sahar Rashid², Muhammad Rashid Shaheen¹, Tanveer Hussain³

¹ Department of Horticultural Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

² Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan

³ Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

*Corresponding author's e-mail: muhammadbilaljaveed372@gmail.com

Abstract

Salinity is a major abiotic stress that severely restricts the growth, productivity, and sustainability of pea cultivation. This study evaluated the individual and combined effects of chitosan (CTS) and silicon (Si) in enhancing salinity tolerance and growth performance of pea. A pot experiment was conducted at the Islamia University of Bahawalpur using a Completely Randomized Design with three salinity levels (0, 4, and 8 dS m⁻¹ NaCl) and four treatments (control, silicon at 100 mg/kg, chitosan at 50 mg/kg, and silicon + chitosan), each replicated three times; morphological and ionic parameters, including shoot and root growth, biomass, branch, leaf, and pod number, and Na⁺ and K⁺ content, were recorded. Salinity significantly reduced plant growth, biomass accumulation, yield-related traits, and ionic balance, with the greatest reductions at 8 dS m⁻¹ NaCl. Chitosan application alleviated salinity-induced damage, improving plant height, shoot and root biomass, vegetative growth, pod production, and the K⁺/Na⁺ ratio relative to untreated plants and silicon alone, while the combined silicon-chitosan treatment produced the best overall performance, further mitigating salinity effects and enhancing ionic homeostasis. These findings indicate that combined chitosan and silicon application effectively enhances salinity tolerance in pea by improving growth and maintaining ionic balance, and that chitosan, particularly when integrated with silicon, has strong potential as an eco-friendly growth modulator for sustainable pea production in salt-affected environments.

Keywords: Pea; Salinity stress; Chitosan; Silicon; Ionic homeostasis; Sustainable agriculture

Application of Triacntanol and Salicylic Acid for Improving Yield of Pea (*Pisum sativum*) under Saline Conditions

Muhammad Bilal Javeed^{1*}, Rashid Hussain¹, Qasim Ali², Sahar Rashid³, Muhammad Rashid Shaheen¹, Tanveer Hussain⁴

¹ Department of Horticultural Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

² Department of Soil Science, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

³ Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan

⁴ Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

*Corresponding author's e-mail: muhammadbilaljaveed372@gmail.com

Abstract

Soil salinity is a major abiotic constraint that limits seed germination, plant growth, water relations, photosynthetic performance, and cellular stability, reducing crop productivity in salt-affected soils. This study evaluated the individual and combined effects of salicylic acid (SA) and triacntanol (TRIA) seed priming on salinity tolerance and growth performance of pea. A pot experiment was conducted at the Islamia University of Bahawalpur using a Completely Randomized Design with three salinity levels (0, 4, and 8 dS m⁻¹ NaCl) and four treatments (control, SA at 100 mg/kg, TRIA at 10 mg/kg, and SA + TRIA), each replicated three times; germination, root and shoot growth, biomass, chlorophyll pigments, relative water content, membrane stability index, proline, total soluble sugars, and antioxidant enzyme activity (SOD, POD, CAT) were evaluated. Salinity progressively reduced plant growth and physiological performance, with the strongest adverse effects observed at 8 dS m⁻¹. Both SA and TRIA individually improved plant performance under salinity, but their combined application produced the best overall response, enhancing growth, physiological stability, and biochemical defense, including osmotic adjustment and antioxidant activity, relative to individual treatments. These findings indicate that combined SA and TRIA seed priming is an effective strategy for enhancing pea salinity tolerance, offering a practical approach for improving pea establishment and productivity in salt-affected soils.

Keywords: Pea; Salinity stress; Salicylic acid; Triacntanol; Osmotic adjustment; Antioxidant enzymes

Integrated Agronomic Strategies for Climate-Resilient and Resource-Efficient Cereal Production

Naeem Sarwar^{1*}, Mubshar Hussain¹, Shakeel Ahmad¹, Omer Farooq¹, Atique-ur-Rehman¹, Allah Wasaya¹, Khuram Mubeen², Muhammad Shehzad³

1 Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

3 Department of Agronomy, University of Poonch, Rawalakot, Pakistan

***Corresponding author's e-mail:** naeemsarwar@bzu.edu.pk

Abstract

Climate change is increasingly challenging cereal-based food systems through water scarcity, nutrient losses, declining soil fertility, and temperature stress, requiring agronomic approaches that simultaneously improve crop productivity and resource use efficiency. This synthesis integrates experimental findings from wheat, maize, and rice studies evaluating integrated management of nitrogen, organic amendments, biochar, irrigation water, and plant growth regulation under contrasting production conditions. In wheat, combining nitrogen management with biofertilizer and neem seed extract improved yield attributes and nitrogen-use efficiency, with 75% of the recommended nitrogen rate plus biofertilizer and neem seed extract performing comparably to full recommended nitrogen. In a wheat-maize system, biochar application under 25% deficit irrigation maintained productivity comparable to full irrigation, whereas greater water deficits substantially reduced yield even with biochar. Organic amendments improved maize growth, yield, and grain zinc uptake, with biochar producing the strongest response, particularly under zinc fertilization. In rice, integrating nitrogen-enriched biochar with the urease inhibitor NBPT produced the best crop performance, while exogenous auxin application during the reproductive stage improved productivity and grain quality under elevated temperature and moisture stress. Collectively, these findings indicate that climate-resilient cereal production requires integrated strategies, combining biochar, stabilized nitrogen, organic amendments, biological inputs, and targeted physiological interventions, rather than single-input management, to improve nutrient retention, water availability, soil fertility, and crop stress tolerance, offering practical pathways toward more resource-efficient and resilient cereal-based food systems.

Keywords: *Climate resilience; Integrated nutrient management; Biochar; Nitrogen use efficiency; Water use efficiency; Cereal production*

Nanotechnology-Assisted Strategies for Management of Cow's Milk Allergy: Advances in Antigen-Specific Immunotherapy

Muhammad Usman Khan², Aneela Hameed^{1*}, Mamoon Aamir¹

1 Department of Animal Food Products Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** draneela@bzu.edu.pk

Abstract

Cow's milk allergy (CMA) is one of the most prevalent food allergies worldwide, particularly among infants. Conventional management relies on allergen avoidance and symptomatic treatment, but antigen-specific immunotherapy (AIT), which induces antigen-specific tolerance, offers a potentially more durable alternative. Clinical application of AIT is currently limited by the elevated risk of anaphylaxis, allergen protein instability, and limited bioavailability, challenges that nanotechnology may help address. This review discusses recent advances in nanotechnology-assisted AIT for CMA, focusing on protein- and polymer-based nanocarriers, including casein and whey protein nanoparticles, polyphenol-protein complexes, and silica nanoparticles, which can induce antigen-specific immune tolerance by modulating dendritic cell activity and promoting a shift from Th2 toward Th1/regulatory T-cell responses. Recent preclinical and formulation studies on various nanoformulation-based immunotherapies are compared with subcutaneous and oral immunotherapy approaches in terms of efficacy and safety, alongside challenges related to manufacturing scale-up, regulation, and safety. These findings suggest that nanotechnology-assisted allergen-specific immunotherapy could provide an alternative approach for managing CMA and other food allergies, contributing to the development of more resilient food systems.

Keywords: *Cow's milk allergy; Immune tolerance; Nanotechnology; Antigen-specific immunotherapy; Protein-polyphenol complexes*

Microplastic Contamination in the Infant Feeding Chain: Implications for Food Safety and Sustainable Food Systems

Hamza Shafiq, Mamoon Amir*, Amir Ismail, Aneela Hameed, Muhammad Riaz

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Microplastic contamination of infant-feeding matrices is an emerging food-safety concern, yet integrated data spanning maternal milk, formula, and feeding equipment remain scarce, particularly in South Asia. This study assessed MP contamination across four stages of the infant-feeding pathway, mother's milk, commercial formula powder, prepared formula, and polypropylene feeding-bottle release, using 500 samples ($n = 125$ per type) collected from Multan, Muzaffargarh, Layyah, and Dera Ghazi Khan. Particles were characterized by stereomicroscopy, micro-FTIR, and scanning electron microscopy following digestion and filtration, with estimated daily intake (EDI), contamination factor (CF), and polymer risk indices calculated. Four polymer types were identified, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), with PE consistently dominant, rising from 21.06 ± 6.01 particles/100 mL in mother's milk to 49.06 ± 10.54 particles/100 mL at bottle release; PP, PET, and PS showed parallel increases. Fibers were the dominant particle morphology (53–54%), followed by fragments (30–32%) and filaments (15%), all increasing progressively along the feeding chain ($p < 0.001$), with particle size and count rising from 14.50 ± 4.26 to 33.73 ± 6.80 particles/sample. The contamination factor increased from 24 in mother's milk to 29, 42, and 54 at the formula-powder, prepared-formula, and bottle-release stages, respectively, with EDI following the same trend and PE reaching 22.28 ± 4.79 and 18.98 ± 4.08 particles/kg body weight/day in males and females at bottle release. Feeding stage was a consistent, significant predictor of contamination ($p < 0.001$), while city-level effects were largely non-significant, indicating that the feeding stage itself drives exposure. These findings identify a clear contamination gradient across the infant-feeding chain, with polypropylene feeding bottles as the largest single contributor and the most actionable intervention point, underscoring the need for harmonized exposure and risk-assessment frameworks for infant microplastic exposure.

Keywords: Microplastics; Infant formula; Breast milk; Feeding bottles; Micro-FTIR; Estimated daily intake

Harnessing Zinc and Iron Transporter Genes to Enhance Nutrient Density in Rice and Wheat

Aysha Kiran^{1*}, Hafsa¹, Iram Shahzadi¹, Muhammad Kashif Naeem², Muhammad Ramzan Khan²

1 Department of Botany, University of Agriculture, Faisalabad, Pakistan

2 National Institute for Genomics and Advanced Biotechnology, NARC, Islamabad, Pakistan

***Corresponding author's e-mail:** aysha.kiran@uaf.edu.pk

Abstract

Iron and zinc transporter genes play a critical role in crop biofortification strategies aimed at improving the nutritional quality of staple foods, with expression patterns providing insight into genetic variability in micronutrient uptake, translocation, and accumulation. This study examined expression of key transporter genes in rice (OsZIP3, OsZIP4, OsIRT1, OsNAAT1) under zinc-deficient, iron-deficient, and combined Zn-Fe-deficient conditions using quantitative real-time reverse transcription PCR (qRT-PCR). OsZIP3, OsZIP4, and OsIRT1 showed significantly higher expression in the shoots of zinc- and iron-efficient varieties KSK-133 and Chenab Basmati, compared with lower root expression in the less efficient varieties IR-6 and Kisan Basmati; OsNAAT1 expression increased in both roots and shoots under iron-deficient conditions relative to zinc-only or combined deficiency, but was lowest in the shoots of IR-6 and Kisan Basmati, indicating limited iron mobilization capacity in these varieties. In wheat, transporter genes TaZIP3, TaZIP7, and TaIRT showed significantly higher shoot expression in the zinc- and iron-efficient varieties Zincol-16 and Akbar-19 compared with the less efficient TD-1 and Ujala-16, particularly under zinc and iron deficiency, while TaYSL7-A and TaNAAT1-B were strongly upregulated in the roots of Akbar-19 and Zincol-16 under iron deficiency. These expression patterns highlight the superior genetic potential of Zincol-16 and Akbar-19 for efficient micronutrient acquisition and transport and demonstrate that these transporter genes play a pivotal role in regulating zinc and iron uptake and translocation in both rice and wheat, providing genetic targets for biofortification programs aimed at developing nutrient-rich crop varieties.

Keywords: Biofortification; Zinc transporters; Iron transporters; Rice; Wheat; qRT-PCR

Pretreatments of *Citrus reticulata* Peel and Their Effect on Poultry Meat Quality for a Sustainable Food System

Syeda Hania Zainab Gardezi¹, Mamoon Amir^{1*}, Muhammad Ahsin², Ali Murtaza¹, Sadaf Yaqoob¹

¹ Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

² Department of Nutrition, Dietetics, and Food Sciences, Utah State University, Logan, Utah, USA

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Global food systems face mounting pressure to minimize agro-industrial waste, close nutrient loops, and recover value from underutilized by-products. Pakistan's citrus processing industry discards 30–34% of citrus fruit as peel waste, despite evidence that kinnow (*Citrus reticulata*) peel is rich in pectin, flavonoids (naringin, hesperidin), phenolic compounds, essential oils, and ascorbic acid, with documented antioxidant, antimicrobial, and anti-inflammatory bioactivity. This study evaluates kinnow peel as a sustainable poultry feed ingredient following fermentation and chemical pretreatment, with emphasis on poultry performance, health, and egg and meat quality, across three phases. Phase I optimizes peel quality through pretreatment and characterizes its phytochemical, nutritional, and structural properties. Phase II incorporates the treated peel into laying-hen diets at graded inclusion levels to evaluate production performance, feed efficiency, and physiological health indicators. Phase III assesses resulting egg and meat quality traits. Fermentation and chemical pretreatment are expected to reduce anti-nutritional factors and improve the availability of beneficial bioactive compounds, with dietary inclusion of treated peel anticipated to improve hen growth performance, feed conversion efficiency, and egg and meat quality relative to untreated controls. Overall, this study aims to convert kinnow peel from an underutilized waste stream into a functional poultry feed ingredient, supporting nutrient recycling, waste reduction, and a more sustainable circular food system.

Keywords: Kinnow peel; *Citrus reticulata*; Fermentation; Poultry feed; Circular food systems; By-product valorization

T-Consciousness Fields Alter Germination, Growth, and Biochemical Responses of Wheat under Drought Stress

Sara Torabi^{1*}, Mohammad Ali Taheri², Farid Semsarha³, Aidin Hamidi⁴, Mir Saeid Moghadampour⁵, Fariba Mohammadifard⁶

1 Department of Plant Biology, School of Biology, College of Sciences, University of Tehran, Tehran, Iran

2 Sciencefact R&D Department, Cosmointel Inc. Research Center, Ontario, Canada

3 Institute of Biochemistry and Biophysics, University of Tehran, Tehran, Iran

4 Seed and Plant Certification and Registration Institute (SPCRI), Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran

5 Islamic Azad University, Rasht Branch, Rasht, Iran

6 Department of Horticultural Science, Faculty of Plant Production, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

***Corresponding author's e-mail:** Sara.torabi1986@gmail.com

Abstract

The existence of consciousness or mind-like properties in plants remains a debated topic in plant biology. This study examined a hypothesis involving non-frequency T-Consciousness Fields, proposing that information transmitted through these fields may influence plant responses, using the Faradarmani Consciousness Field (T1) and the T-Consciousness Charge Field (T2) in two completely randomized experiments on wheat (*Triticum aestivum* cv. Bahar) under drought stress. In the first experiment, seeds were exposed for eight days to PEG-induced drought stress (0, -0.6, and -1.2 MPa), with or without T1 and T2, to assess germination and early growth. In the second, potted seedlings were subjected to three weeks of drought by withholding irrigation, with untreated plants as controls; growth parameters, chlorophyll, carotenoids, total protein, and superoxide dismutase (SOD) activity were measured. Severe drought reduced final and mean daily germination by approximately 40%, while T2 significantly improved both measures ($P \leq 0.05$). At -0.6 MPa, shoot and root length increased by approximately 70% and 46%, respectively, with significantly greater enhancement under T2, though effects under more severe stress were limited. Under non-stress conditions, T2 markedly enhanced seedling growth and vigor, with 2–3-fold increases in root and shoot dry weight and 3–4-fold increases in seedling vigor indices relative to control. In pot experiments, T2 increased shoot length by approximately 25% and chlorophyll and carotenoid content by approximately 60%, while T1 increased protein content by approximately 25%; both fields elevated SOD specific activity by approximately 50%. These findings indicate that T1 and T2 exposure improved germination, growth, and biochemical traits associated with drought tolerance in wheat, suggesting potential value as a supplementary strategy for enhancing wheat performance under water-limited conditions; independent replication is recommended given the unconventional nature of the intervention.

Keywords: Drought stress; Wheat; Superoxide dismutase; Seedling vigor; Germination

Radioreceptor Binding Assay to Detect Chloramphenicol, Oxytetracycline, and Gentamicin in Meat and Milk

Shumaila Ameer¹, Muhammad Yasin^{1*}, Uzma Maqbool¹

Food Safety Laboratories, Animal Sciences Division, Nuclear Institute for Agriculture and Biology College, Pakistan Institute of Engineering and Applied Sciences (NIAB-C, PIEAS), Faisalabad, Pakistan

***Corresponding author's e-mail:** yasinf_t_uaf@yahoo.com; myasin@niab.org.pk

Abstract

This study aimed to isolate, characterize, and evaluate subcellular receptor fractions from bovine brain tissue for use as biological binding agents in a radioreceptor binding assay (RBA) for screening drug residues, oxytetracycline, gentamicin, and chloramphenicol. Fresh bovine brain tissue was homogenized and fractionated by differential centrifugation (5,000–40,000 g) using Tris-HCl buffer; the resulting fractions (F1–F4) were characterized for total protein concentration and molecular weight, with protein content ranging from 2.27 to 3.6 mg/100 g and the highest membrane-associated protein band density observed in the F4 fraction, which was selected based on preliminary binding response with the target drugs at regulatory limits. Binding assessment using radiolabeled analogues showed dissociation constants (K_d) of 2.8×10^{-8} M for tetracycline, 3.6×10^{-8} M for gentamicin, and 4.1×10^{-8} M for chloramphenicol. Method performance parameters included decision limits ($CC\alpha$) of 0.45, 0.60, and 0.75 $\mu\text{g kg}^{-1}$, and detection capabilities ($CC\beta$) of 0.65, 0.85, and 1.05 $\mu\text{g kg}^{-1}$, respectively, with intra- and inter-assay reproducibility (CV%) below 8–10%. The receptor fraction showed consistent binding with residues extracted from fortified milk and meat samples, with false-positive and false-negative rates below 5% compared with LC-MS/MS quantification ($R^2 = 0.982$). These results indicate that the F4 receptor fraction isolated at $40,000 \times g$ from bovine brain tissue contains a functional binding site capable of detecting veterinary drug residues in animal-derived foods, supporting its potential use as a rapid screening tool for food safety monitoring.

Keywords: Radioreceptor binding assay; Veterinary drug residues; Chloramphenicol; Gentamicin; Tetracycline; Food safety monitoring

New Ways of Working in Food Regulatory Compliance: Building Trusted Conformance in Punjab

Muhammad Nasir

Punjab Agriculture, Food and Drug Authority, Pakistan

Corresponding author's e-mail: member.food@pafda.gop.pk

Abstract

Punjab's food regulatory landscape is transitioning from fragmented and overlapping functions toward a coordinated system built on clearly differentiated roles for standard-setting, enforcement, and independent conformance. This presentation discusses practical new ways of working that can strengthen trust, efficiency, and regulatory credibility, including risk-based sampling and testing, ISO/IEC 17025-aligned laboratories, digital chain of custody, transparent turnaround times, data-driven decision-making, and structured regulator-laboratory-industry engagement. It also highlights the emerging role of the Punjab Agriculture, Food and Drug Authority (PAFDA) as an independent conformance institution supporting regulators and businesses through reliable evidence. This approach is intended to improve consumer protection, regulatory consistency, industry compliance, and trade facilitation.

Keywords: *Food regulatory compliance; Risk-based testing; ISO/IEC 17025; Conformance assessment; Food safety governance*

Exogenous Application of a Moringa-Based Biostimulant (*Sanjhi*) to Improve Heat Stress Tolerance in *Gossypium hirsutum*

Azra Yasmeen*, Muhammad Wajihul Hassan

Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: azra.yasmeen@bzu.edu.pk

Abstract

Biostimulants have emerged as crop management tools capable of enhancing productivity under abiotic stress by stimulating natural plant processes and metabolism. Heat stress is a major constraint to sustainable cotton production, disrupting physiological processes, inducing oxidative damage, and reducing yield and fiber quality. This study evaluated the effectiveness of a moringa-based biostimulant (SANJHI®), *Ascophyllum nodosum* seaweed extract (SWE), and nitrophenolates (NP), applied exogenously at various crop stages, in mitigating heat stress effects on cotton growth, physio-biochemical performance, and yield. Heat stress adversely affected crop growth, physiological attributes, and yield, but exogenous application of SANJHI®, SWE, and NP improved growth, physio-biochemical performance, and yield under these conditions. Among the treatments, foliar-applied SANJHI® produced the greatest improvements in growth, relative water content, total soluble protein, antioxidant activity (peroxidase, superoxide dismutase, catalase), total phenolic content, and yield, while reducing relative cell injury, relative membrane permeability, malondialdehyde, and hydrogen peroxide levels under heat stress. Pearson correlation analysis confirmed strong positive relationships among physiological performance, antioxidant activity, growth, yield, and fiber quality, with oxidative stress indicators negatively associated with these traits. Overall, foliar application of SANJHI®, SWE, and NP effectively enhanced relative water content, antioxidant activity, growth, and yield in heat-stressed cotton, with SANJHI® outperforming SWE and NP in ameliorating heat stress across all measured physiological and yield-related attributes.

Keywords: *Biostimulants; Heat stress; Cotton; Antioxidant enzymes; Moringa leaf extract; Seaweed extract*

Impact of a Tapioca- and Aloe Vera Gel-Based Composite Edible Coating on the Post-Harvest Quality and Shelf Stability of Kinnow Mandarin

Ammara Ainee^{1*}, Sana Naseem¹, Tusneem Kausar¹, Muhammad Tahir Akram², Mahnoor¹

¹ Institute of Food Science and Nutrition, University of Sargodha, Pakistan

² Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

*Corresponding author's e-mail: ammara.aine@uos.edu.pk

Abstract

Kinnow mandarin (*Citrus reticulata*) is a vital commercial fruit crop in Pakistan, but its high susceptibility to post-harvest decay and rapid physiological degradation severely limits export potential. This study investigated the development and efficacy of eco-friendly, biodegradable composite edible coatings combining tapioca starch and fresh Aloe vera gel to extend Kinnow shelf life. Freshly harvested Kinnow fruits from Sargodha were treated with composite coatings in which both ingredients ranged from 1.5% to 3.5% (w/v), maintaining a fixed cumulative concentration of 5% (w/v), with uncoated fruit as control; samples were stored under ambient conditions ($25 \pm 2^\circ\text{C}$), with physicochemical and sensory analyses conducted at intervals over the storage period. Composite coatings significantly reduced physiological weight loss and delayed peel softening and decay relative to the control. The synergistic interaction between the tapioca matrix and bioactive compounds in fresh Aloe vera gel suppressed respiration rates, resulting in higher retention of total soluble solids, titratable acidity, and ascorbic acid during storage, while also helping preserve fruit sugar content as storage progressed. These findings indicate that a composite formulation of 3.5% tapioca starch and 1.5% Aloe vera gel (5% total concentration) offers a safe, organic alternative to synthetic waxes for the post-harvest preservation of Kinnow mandarin.

Keywords: Edible coating; Tapioca starch; Aloe vera gel; Kinnow mandarin; Shelf life; Post-harvest quality

A Technical Risk-Mitigation Framework for Reusable Food-Grade Containers in High-Throughput Processing Lines

Dur-e-Shahwar Sattar

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

Corresponding author's e-mail: dsattar@bzu.edu.pk

Abstract

Maintaining stringent food safety and structural integrity in automated reuse systems remains a critical challenge for food processors facing rapid industrial turnover. Eliminating chemical, physical, and biological cross-contamination hazards prior to refilling requires robust, data-driven verification protocols operating in real time, since traditional retrospective testing is insufficient in high-throughput environments. This study validates a standardized quality-control matrix designed for integration into industrial reuse operations, evaluating reclaimed containers against a refill-acceptance protocol confirming microbiological safety, residual alkalinity within acceptable limits, optical clarity on visual inspection, and resistance to internal burst pressure and thermal-shock testing. By combining automated optical sensors with rapid chemical and physical diagnostic tools, the system identifies and rejects non-compliant units without disrupting line throughput, providing hazard control against residual detergents, caustic carryover, and microbial contamination. Empirical data demonstrate a significant reduction in micro-cracking failures and chemical migration risk, indicating that this framework offers food technologists a reliable, scalable method for optimizing processing-line efficiency and consumer safety within reusable container systems.

Keywords: *Food safety engineering; Reusable containers; HACCP; Quality assurance; Refill-acceptance protocol*

Disasters and Sustainable Development in Pakistan: Building a Climate-Resilient Future

Atta-ur-Rahman

Department of Geography and Geomatics, University of Peshawar, Pakistan

Corresponding author's e-mail: atta-ur-rehman@uop.edu.pk

Abstract

This study examines the nexus of natural disasters and sustainable development in Pakistan, highlighting the country's challenges and opportunities in building community resilience against natural disasters and adapting to climate change. Pakistan is among the most climate-vulnerable countries in the world, facing recurring threats from floods, droughts, and earthquakes; over the past two decades, events including the 1998–2004 drought, the 2005 earthquake, and the floods of 2010, 2022, and 2025 have repeatedly affected millions of people and caused economic losses equivalent to a substantial share of national GDP. At the federal level, the Ministry of Climate Change, through the National Disaster Management Authority (NDMA), has emphasized inclusive and coordinated action, community engagement, and investment in disaster risk reduction. NDMA, in collaboration with provincial disaster management authorities, has implemented a national disaster management plan and is progressing on a national adaptation plan, alongside commitments to reduce greenhouse gas emissions and integrate climate resilience into sectoral planning. Proactive disaster response in Pakistan has been strengthened through improved forecasting and early-warning systems, enhanced emergency response mechanisms, and nature-based preparedness strategies. This study concludes that addressing natural disasters and sustainable development in Pakistan requires greater integration of climate resilience into development planning, alongside promotion of green technologies, disaster risk reduction, and continued investment in climate adaptation and nature-based solutions.

Keywords: *Natural disasters; Sustainable development; Climate resilience; Disaster risk reduction; Pakistan; Adaptation planning*

Zinc Oxide Nanofertilizers Mitigate Salinity Stress and Improve the Biochemical Profile of Pea (*Pisum sativum*)

Khadim Hussain^{1*}, Abdul Majeed², Murtaza Hasan¹

1 Department of Biotechnology, Faculty of Chemical and Biological Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

2 Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** khadimhusain714@gmail.com

Abstract

Salinity is one of the major abiotic stresses limiting crop productivity. This study examined the effects of zinc oxide (ZnO) nanofertilizers on the growth and physiochemical profile of pea plants under salt stress. ZnO nanofertilizers were synthesized and characterized by UV-visible spectroscopy, XRD, and SEM, and applied at 50 and 100 mg/kg individually and in combination with 50 mM and 100 mM NaCl. At 50 mg/kg alone, ZnO nanofertilizers produced mixed effects, increasing agronomic parameters while decreasing malondialdehyde (MDA) and hydrogen peroxide concentrations; salt treatments at both concentrations had an overall negative effect on all assessed parameters when applied alone. Among combined treatments, only 50 mM NaCl with 50 mg/kg ZnO nanofertilizers produced positive effects on the pea physiochemical profile, substantially improving agronomic parameters while decreasing MDA, glycine betaine, and hydrogen peroxide levels; all other combined treatments showed negative effects, likely reflecting the high doses of both stressors involved. These findings provide reference data on zinc oxide nanofertilizer dose-dependent effects under salinity stress, relevant to future research on salt-stress mitigation in agricultural crops.

Keywords: Zinc oxide nanofertilizers; Salinity stress; *Pisum sativum*; Biofortification; Oxidative stress markers

Palyno-Anatomical Characterization of Astragalus Species from a High-Altitude Mountain Ecosystem

Muhammad Hassan¹, Ishtiaq Hussain^{1*}, Mushtaq Ahmed², Muhammad Zafar², Naveed Abbas², Muhammad Manzoor², Muhammad Shabbir², Zakir Hussain³

¹ Department of Botany, Faculty of Natural Sciences, University of Baltistan, Skardu, Gilgit-Baltistan, Pakistan

² Department of Plant Systematics, Biodiversity Laboratory, Quaid-i-Azam University, Islamabad, Pakistan

³ Pakistan Agricultural Research Council (PARC), Agricultural Research Station, Skardu, Pakistan

*Corresponding author's e-mail: Ishtiaq.mondooq@uobs.edu.pk

Abstract

Plants form the foundation of many ecosystems and serve as key indicators of biological diversity. Pakistan, like many other countries, holds a wealth of medicinally and economically important plant species, among which *Astragalus* L. constitutes one of the largest and most taxonomically complex angiosperm genera; numerous *Astragalus* species have been identified as medicinal plants in Gilgit-Baltistan, particularly in the Baltistan region. This study investigated the palynological features of selected *Astragalus* species, along with phytochemical characteristics and distribution patterns relative to soil properties across four districts of Baltistan, using light and scanning electron microscopy (SEM) to examine pollen microstructure, an important taxonomic tool for distinguishing morphologically complex species. Pollen grains across the species studied varied in size and were monad, prolate to suboblate, and tricolporate to elongate in aperture type. Exine sculpture was reticulate-striate in *Astragalus himalayanus*; broadly striate and meridionally bifurcating in *A. frigidus*; striato-reticulate and packed in *A. rhizanthus*; and striate with branching, meridionally oriented striae in *A. falconeri* and *A. multiceps*, with ornamentation ranging from scabrate to granulate. Equatorial and polar diameters were greatest in *A. rhizanthus* (25.75 µm) and smallest in *A. falconeri* (18.3 µm polar diameter); colpus length ranged from 7.25 µm (*A. rhizanthus*, longest) to 2.8 µm (*A. himalayanus*, shortest), while colpus width and exine thickness also varied substantially among species. Pollen fertility was highest in *A. multiceps* (79.44%) and lowest in *A. himalayanus* (69.59%), which correspondingly showed the highest pollen sterility (30.41%). Principal component analysis and clustering successfully differentiated the studied taxa at the species level, confirming that pollen morphological attributes provide a reliable basis for identification and classification of *Astragalus* species in this high-altitude ecosystem.

Keywords: *Astragalus*; Palynology; Pollen morphology; Gilgit-Baltistan; Scanning electron microscopy; Taxonomy

Bryophytes for Sustainable Agriculture: Improving Soil Health and Water Conservation in a Changing Climate

Imran Ahmad

Department of Botany, Abdul Wali Khan University, Mardan, Pakistan

Corresponding author's e-mail: Awkumimran@gmail.com

Abstract

Bryophytes, including mosses, liverworts, and hornworts, are essential components of climate-resilient ecosystems and sustainable food systems. Despite their simple structure, these non-vascular plants play important ecological roles, promoting soil formation, enhancing moisture retention, reducing soil erosion, regulating nutrient cycling, and supporting microbial diversity. Their sensitivity to environmental stress and rapid response to disturbance make them reliable indicators of climate change and environmental health. Preserving bryophyte diversity and incorporating their ecological functions into land management can strengthen ecosystem resilience, improve soil health, and support sustainable agricultural productivity under changing climatic conditions. Beyond their ecological significance, bryophytes hold considerable potential for industrial and biotechnological applications aligned with sustainable agriculture: many species produce bioactive compounds with antimicrobial, antioxidant, anti-inflammatory, and antifungal properties, valuable for pharmaceutical, cosmetic, and environmentally friendly crop protection applications, while moss-based technologies contribute to sustainable horticulture, carbon sequestration, ecological restoration, green infrastructure, and environmental pollution monitoring. Integrating bryophyte research with advances in agricultural science, biotechnology, and industry could support the development of climate-smart solutions that enhance food security, promote environmental sustainability, and facilitate the transition toward more resilient and sustainable food systems.

Keywords: *Bryophytes; Climate change; Carbon sequestration; Bioactive compounds; Ecosystem restoration; Soil health*

From Waste to Value: Integrating Food Processing Innovation and Safety Technologies for Sustainable Food Systems

Sadia Ansar^{1*}, Farah Ahmad¹, Muhammad Abrar¹, Imran Pasha²

1 Post-Harvest Research Centre, Ayub Agricultural Research Institute, Faisalabad, Pakistan

2 National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** sadiaansar31@gmail.com

Abstract

Growing demand for sustainable, safe, and nutritionally enhanced food systems has accelerated research into innovative processing technologies and valorization of food industry by-products, as conventional processing methods often compromise nutritional and functional quality while generating substantial environmental waste. Recent advances in novel processing technologies, including high-pressure processing, pulsed electric fields, ultrasound, cold plasma, ohmic heating, enzymatic hydrolysis, fermentation, and microwave-assisted and supercritical fluid extraction, have altered protein structure, solubility, digestibility, and emulsifying and foaming properties, improving food quality while preserving nutrition and extending shelf life. Valuable compounds recovered from agri-food by-products, including phenolics, dietary fibers, peptides, carotenoids, collagen, pectins, and oligosaccharides, are increasingly applied in functional foods, nutraceuticals, pharmaceuticals, packaging, and cosmetics. Emerging extraction and bioprocessing approaches improve efficiency, purity, and environmental sustainability, supporting circular economy principles and contributing to Sustainable Development Goals, including responsible consumption (SDG 12), climate action (SDG 13), zero hunger (SDG 2), and good health and well-being (SDG 3). Advances in biosensor technologies, including electrochemical, optical, and piezoelectric platforms, provide rapid, sensitive tools for food safety monitoring and pathogen detection, strengthening quality assurance across the value chain. Despite this progress, challenges remain around raw material variability, industrial scalability, economic feasibility, process optimization, and regulatory acceptance, which continue to limit widespread commercial adoption; integrating advanced processing, by-product valorization, intelligent sensing, and digital optimization offers a pathway toward more sustainable and safe food systems.

Keywords: *Novel food processing; By-product valorization; Circular economy; Food safety biosensors; Functional foods; Sustainable Development Goals*

Nitrous Oxide Emissions from Maize and Cotton Production

Saliha^{1*}, Fatima Khan¹, Nida Yousaf¹, Kashif Razaq²

1 Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan

2 Department of Horticulture, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** salihafa374@gmail.com

Abstract

Greenhouse gases are the primary driver of global warming and climate change, trapping heat by absorbing infrared radiation; the principal contributing gases are nitrous oxide, methane, carbon dioxide, water vapor, and fluorinated gases. Among these, nitrous oxide is a particularly important greenhouse gas released from agricultural activity. This review examines nitrous oxide emissions from maize and cotton production, two widely cultivated, nitrogen-intensive crops that are major contributors to agricultural nitrous oxide emissions, arising primarily from nitrogen fertilizer application and soil microbial processes such as nitrification and denitrification, which are influenced by soil moisture, temperature, irrigation, and fertilizer management. Maize cultivation, requiring higher nitrogen inputs, generally generates greater nitrous oxide emissions, whereas emissions from cotton vary more with environmental conditions and crop management. As global demand for both crops increases, minimizing their environmental impact is gaining importance. Recent advances in sustainable farming, including precision fertilizer application, enhanced-efficiency fertilizers, conservation tillage, cover cropping, and improved irrigation management, show considerable potential to reduce nitrous oxide emissions without compromising yield; strategic irrigation management alone can conserve 30–50% of water while improving water use efficiency. A clearer understanding of the factors driving emissions from cotton and maize production is essential for developing climate-smart agricultural systems that balance productivity with environmental sustainability.

Keywords: *Nitrous oxide; Greenhouse gas emissions; Maize; Cotton; Nitrification; Denitrification*

Effect of Exogenous Oxytocin Administration on Milk Composition during Cyclicity in Lactating Nili-Ravi Buffaloes

Saeed Murtaza^{1*}, Abdul Asim Farooq¹, Saleem Akhtar¹, Tanveer Ahmad¹, Faisal Kiyani¹, Ejaz Ahmad¹, Muhammad Abdul Basit², Arshad Javed², Usman Saleem²

1 Department of Clinical Sciences, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Biosciences, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** saeedmurtaza@bzu.edu.pk

Abstract

This study examined the effect of oxytocin injection on milk composition in lactating Nili-Ravi buffaloes over two estrous cycles. Twenty-four animals at subsequent estrus were randomly and equally divided into three groups: Group 1 (control; n=8), Group 2 (low dose, 10 IU; n=8), and Group 3 (high dose, 30 IU; n=8). Milk fat percentage was significantly increased ($P \leq 0.05$) in Group 3 relative to Group 1 but was relatively similar to Group 2; milk pH was also increased in Group 3 relative to both other groups. Solids-not-fat, density, protein, lactose, freezing point, and mineral solids did not differ significantly among treatment groups. These findings indicate that long-term supraphysiological doses of exogenous oxytocin produce largely negligible effects on milk composition in Nili-Ravi buffaloes, except for modest, dose-dependent increases in fat percentage and pH.

Keywords: Oxytocin; Milk composition; Nili-Ravi buffalo; Lactation; Supraphysiological dosing

Double-Layered Active Edible Films Incorporating Ultrasonicated *Nardostachys jatamansi* Root Extract and Flaxseed Gel

Samreen Ahsan^{1*}, Ayesha Bint-E-Zafar¹, Zainab Riaz¹, Ayesha Siddiq¹, Adnan Khaliq¹

Institute of Food Science and Technology, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

***Corresponding author's e-mail:** samreenahsan@kfueit.edu.pk

Abstract

This study explored the synthesis of double-layered active edible films incorporating ultrasonicated extracts of *Nardostachys jatamansi* roots. Ultrasonic extraction yielded bioactive compounds with strong antioxidant and antimicrobial activity, and FTIR analysis confirmed the presence of functional groups including alcohols, ketones, esters, and hydroxyls; optimal extraction conditions were established as a 1:40 g/mL solid-to-liquid ratio at 65°C for 40 minutes. The double-layered film was constructed with a flaxseed gel-guar gum-glycerol base as the lower layer and an upper layer incorporating *N. jatamansi* extract at 1%, 3%, and 5%. Films were characterized by thickness, moisture content, water vapor transmission, mechanical strength, and antimicrobial activity over 30 days of storage. Films containing 3% extract showed the best mechanical properties, while those with 5% extract exhibited the greatest antimicrobial activity, with inhibitory zones against *Staphylococcus aureus* and *Escherichia coli*, an elongation at break of 76.62%, and a moisture content of 4.35%. These findings indicate that the double-layered active edible film is suitable for food packaging applications and represents an environmentally friendly, cost-effective packaging approach.

Keywords: *Nardostachys jatamansi*; Edible film; Ultrasonication; Active packaging; Antimicrobial activity; FTIR

Integrating Zinc Fertilization with Conservation Agriculture Enhances Soil Health, Enzyme Activities, and Rice Productivity

Faisal Nadeem^{1*}, Abdul Qadeer², Muhammad Sanaullah³, Abdul Rehman⁴, Muhammad Farooq⁵

1 Department of Agronomy, Faculty of Agriculture, University of Agriculture, Dera Ismail Khan, Pakistan

2 College of Grassland Science, Gansu Agricultural University, Lanzhou, China

3 Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

4 Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

5 Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al-Khoud, Muscat, Oman

***Corresponding author's e-mail:** faisal.nadeem@uad.edu.pk

Abstract

Conventional agricultural practices, particularly poor soil management and intensive tillage, have driven soil degradation in rice (*Oryza sativa* L.) systems, reducing bioavailability of essential micronutrients such as zinc (Zn) and constraining grain yield and nutritional quality. This two-year field experiment (2017–2018) in Sialkot, Pakistan, evaluated the effects of rice production system, direct-seeded aerobic rice (DSAR) versus puddled transplanted rice (PuTR), and four zinc application methods (soil application at 10 kg/ha, seed priming at 0.01 M, foliar application at 0.025 M, and a no-zinc control) on soil health, enzyme activity, and productivity. DSAR significantly improved soil organic carbon (5–27%), microbial biomass carbon (5–12%), microbial biomass nitrogen (3–7%), and activity of β -glucosidase (18–54%), chitinase (5–16%), acid phosphatase (26–132%), and leucine aminopeptidase (23–66%) across soil depths and years, with Zn application further enhancing soil organic carbon and microbial biomass nitrogen, particularly in the topsoil. Among Zn application methods, seed priming produced the highest grain yield in DSAR (5.06 and 4.75 t ha⁻¹ in 2017 and 2018, respectively), followed by soil application in both production systems; seed priming, followed by soil and foliar application, most enhanced grain zinc concentration in DSAR, while soil-applied zinc was most effective for grain protein concentration in both systems. These findings show that integrating conservation-based tillage with zinc management produces synergistic improvements in soil health and rice productivity, offering a practical strategy for sustainable rice production that supports both soil health and food security.

Keywords: Zinc fertilization; Conservation agriculture; Soil enzyme activity; Rice productivity; Direct-seeded rice; Soil organic carbon

Incorporation of Nitrous Oxide into the Environment during Cotton Production

Saliha^{1*}, Fatima Khan¹, Nida Yousaf¹, Ambreen Naz²

1 Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan

2 Department of Home Sciences, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** salihafa374@gmail.com

Abstract

Nitrous oxide, a potent greenhouse gas, contributes significantly to climate warming, and understanding its emissions from different crops and regions is essential for developing effective mitigation strategies. Cotton (*Gossypium hirsutum* L.) is one of the world's most important fiber crops, and its cultivation contributes substantially to emissions due to intensive fertilizer use and associated soil management practices, though the global magnitude of these emissions and their driving factors remain incompletely characterized. This review examines the role of climate-smart agriculture (CSA) in reducing the environmental footprint of cotton production, noting that adoption of CSA practices among small-scale farmers is shaped by a range of environmental, institutional, socioeconomic, and technological factors. Findings indicate that climatic conditions and soil characteristics, including bulk density, pH, carbon-to-nitrogen ratio, and texture, exert a greater influence on nitrous oxide emissions than commonly recognized management factors such as nitrogen fertilizer application rate, and that use of urease and nitrification inhibitors can significantly reduce nitrous oxide emissions while maintaining cotton yield. These findings highlight the environmental impact of cotton production and point to practical management approaches that can support more sustainable, climate-friendly cotton farming.

Keywords: *Nitrous oxide; Cotton production; Greenhouse gas emissions; Climate-smart agriculture; Nitrification inhibitors*

Innovative Strategies for Enhancing Bioactive Functionality in Foods

Muhammad Abrar^{1*}, Sadia Ansari¹

Post-Harvest Research Centre, Ayub Agricultural Research Institute, Faisalabad, Pakistan

*Corresponding author's e-mail: mabrarft@gmail.com

Abstract

Bioactive functionality in foods refers to the capacity of naturally occurring or added compounds to deliver physiological benefits beyond basic nutrition, supporting long-term health and reduced disease risk. Bioactive components such as polyphenols, peptides, carotenoids, dietary fibers, probiotics, prebiotics, and phytosterols play important roles in metabolic regulation, immune modulation, oxidative balance, and gut health. Functional food research is increasingly shifting from conventional ingredient addition toward functionality-driven food design, which optimizes the entire food system to enhance bioactive stability, bioaccessibility, and biological effectiveness. Innovative processing strategies emphasize green and precision-based technologies, including supercritical fluid extraction, enzyme-assisted processing, and pulsed electric field treatment, to preserve structural integrity and maximize bioactive recovery, while advanced delivery systems such as nano-emulsions, lipid carriers, and biopolymer-based matrices protect sensitive compounds and enable controlled release during digestion. Fermentation-based strategies using selected microbial cultures and metabolic engineering are gaining importance for converting bioactives into more active, bioavailable forms, and food matrix engineering is emerging as a strategy for designing ingredient interactions that promote synergistic effects and digestive stability. Digital tools, including artificial intelligence, nutrigenomics, and metabolomics, are further shaping formulation decisions and supporting personalized functional food development, while valorization of food processing by-products as alternative bioactive sources supports circular food systems. Collectively, these strategies strengthen scientific validation, technological efficiency, and consumer acceptance of functional food development.

Keywords: *Bioactive compounds; Functional foods; Encapsulation; Nano-emulsions; Fermentation; Food matrix engineering*

Management of Salinity Stress through Organic Amendments for Improving Rice Productivity in Saline Soil

Jawiria Shabir*, Naeem Sarwar

Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** jawiriashabir@gmail.com

Abstract

Soil salinization is a major constraint on rice (*Oryza sativa* L.) productivity, with organic amendments and tolerant cultivars increasingly used to mitigate its effects. This pot experiment evaluated three fine-rice genotypes (Kissan Basmati 1509, Kainat 1121 Basmati, and Super Fine) under four soil salinity levels (0, 4, 8, and 12 dS m⁻¹), with and without 1% wheat-straw biochar, using a three-factor factorial Completely Randomized Design; germination, shoot and root length, leaf area, stem diameter, and fresh and dry biomass were recorded 15–20 days after establishment. Growth and biomass responses to salinity varied by variety and biochar treatment: at 8 dS m⁻¹, Kainat 1121 Basmati with biochar maintained greater root length and dry biomass than the corresponding biochar treatments of the other two varieties, while at 12 dS m⁻¹ it maintained the highest dry biomass, and Super Fine with biochar showed the highest root length. Kainat 1121 Basmati with biochar also maintained comparatively better shoot growth at higher salinity levels, whereas combined treatments generally showed reduced leaf area and stem diameter under high salinity. Overall, the response to saline conditions depended on the specific combination of variety, salinity level, and biochar application, with Kainat 1121 Basmati combined with wheat-straw biochar emerging as among the more promising combinations for maintaining biomass production under moderate-to-high salinity (8–12 dS m⁻¹).

Keywords: *Rice; Salinity stress; Wheat-straw biochar; Organic amendments; Saline soil*

Linking Climate-Smart Agriculture with Sustainable Food Processing and Nutrition Security: An Integrated Pathway for Resilient Food Systems

Rai Muhammad Amir

Institute of Food and Nutritional Sciences, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

Corresponding author's e-mail: raiamir@uaar.edu.pk

Abstract

Climate change is placing increasing pressure on global food systems through rising temperatures, water scarcity, changing precipitation patterns, extreme weather, soil degradation, emerging pests and diseases, and declining agricultural productivity, threatening not only food production but also food quality, safety, accessibility, affordability, and nutritional security. While climate-smart agriculture (CSA) has primarily emphasized productivity, resilience, and greenhouse gas mitigation at the production stage, a genuinely sustainable response requires extending climate-smart principles across the entire food value chain. This review argues that integrating CSA with sustainable food processing, post-harvest management, food-loss reduction, circular bioeconomy approaches, and nutrition-sensitive innovation can substantially strengthen food system resilience and resource efficiency: climate-resilient production can ensure a more stable supply of nutritious raw materials, while sustainable processing and preservation technologies can extend shelf life, reduce post-harvest losses, and enhance food safety and nutritional quality. Valorizing agricultural residues and processing by-products into functional ingredients, bioactive compounds, animal feed, biodegradable materials, and value-added foods can further promote circularity and reduce environmental burdens, particularly through low-energy processing technologies, renewable energy, sustainable packaging, improved cold-chain systems, and digital monitoring tools. These interventions are especially important in climate-vulnerable regions, where inadequate storage and processing infrastructure and limited value addition continue to undermine food and nutrition security. Achieving a food system that delivers safe, nutritious, affordable, and environmentally sustainable food requires stronger collaboration among farmers, processors, researchers, policymakers, and industry, supported by enabling policy, technological innovation, and investment.

Keywords: *Climate-smart agriculture; Sustainable food processing; Nutrition security; Circular bioeconomy; Food loss and waste*

Growth of Lettuce (*Lactuca sativa*) under Saline Conditions in a Hydroponic System: Mitigation by Gibberellic Acid

Iqra Arshad^{1*}, Aysha Kiran¹, Moazma Batool¹, Muhammad Shahbaz¹, Sadia Bibi²

¹ Department of Botany, University of Agriculture, Faisalabad, Pakistan

² Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

*Corresponding author's e-mail: iqraarshadleo@gmail.com

Abstract

Lettuce (*Lactuca sativa* L.) is a highly nutritious vegetable, rich in vitamins A, C, and K and folate, but is sensitive to salt stress, which reduces growth through osmotic stress, ion toxicity, and nutrient imbalance, with consequent effects on photosynthetic yield and quality. This study examined whether gibberellic acid (GA) could mitigate the negative effects of salinity on hydroponically grown lettuce, using four treatments (control, 30 mM NaCl, 50 mg/L GA, and 50 mg/L GA + 30 mM NaCl) with three replications in a completely randomized design; morphological parameters were measured after 40 days at harvest. Salinity significantly reduced plant growth, photosynthetic activity, and morphological parameters, lowering overall lettuce growth by 10–30%, whereas foliar GA application under saline conditions improved key physiological and morphological parameters by 15–18% and increased antioxidant enzyme activity (SOD, POD) and chlorophyll concentration by 12–25%, alongside reduced sodium uptake and increased potassium accumulation. These findings indicate that GA improves salt tolerance in lettuce through physiological and biochemical mechanisms, supporting its potential as a practical tool for sustainable vegetable production in salt-affected settings.

Keywords: Lettuce; Salinity stress; Gibberellic acid; Hydroponic cultivation; Antioxidant enzymes

Nutritional Enhancement in Barley (*Hordeum vulgare*) under Salinity and Water-Scarce Conditions

Moazma Batool^{1*}, Aysha Kiran¹, Farooq Ahmed¹, Abdul Wakeel²

¹ Department of Botany, University of Agriculture, Faisalabad, Pakistan

² Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

*Corresponding author's e-mail: moazma.batool4740@gmail.com

Abstract

Barley (*Hordeum vulgare* L.) plays a pivotal role in global food and feed systems, but increasing salinity and water scarcity threaten its productivity and nutritional quality; controlled exposure to such abiotic stresses can, however, induce adaptive responses that enhance accumulation of nutritionally important metabolites. This two-year pot study (2023–2025) exposed the barley variety Pearl-21 to three levels each of drought (60%, 45%, and 30% field capacity) and salinity (2, 4, and 8 dS/m) stress in a completely randomized design with four replications, recording morphological, physiological, biochemical, and yield parameters at maturity. In the first year, mild-to-moderate stress reduced shoot length by 8–16% and root length by 18–28%, while chlorophyll content decreased by 6–19% and proline accumulation increased by 23–44%, indicating osmotic adjustment; flavonoid, phenolic, anthocyanin, and carotenoid content increased by 13–36%, 17–30%, 11–18%, and 16–36%, respectively, while grain weight declined moderately (9–12%). Similar patterns were observed in the second year, confirming reproducibility, with shoot length reductions of 8–14%, root reductions of 18–26%, proline increases of 17–40%, comparable increases in flavonoid, phenolic, anthocyanin, and carotenoid content, and yield reductions of 8–18%. These findings show that mild-to-moderate salinity and drought stress consistently promoted secondary metabolite biosynthesis without causing severe yield penalties, suggesting that strategic application of controlled abiotic stress could support development of climate-smart, nutritionally enriched barley cultivars.

Keywords: Barley; Salinity stress; Drought stress; Secondary metabolites; Nutritional quality; Climate-smart agriculture

Assessing Machine Learning Models for Climate-Smart Sesame Genotype Selection

Muhammad Waqar Ul Haq*, Dilawar Ali, Sami Ul Allah*

*Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences and Technology,
Bahauddin Zakariya University, Multan, Pakistan*

***Corresponding authors' e-mail:** mwaqarulhaq190@gmail.com; samipbg@bzu.edu.pk

Abstract

Sustainable agriculture requires precise, data-driven strategies to address ongoing challenges in crop production. This study evaluates the integration of artificial intelligence (AI) as a tool for modern crop selection, applying machine learning techniques and real-time environmental monitoring to enable weather forecasting, early detection of crop stress, and efficient resource use. PlantCV-based image analysis was applied to sesame (*Sesamum indicum* L.) to extract high-throughput phenotypic traits, including plant area (95.8% accuracy), canopy cover (90.4%), leaf count (85.7%), plant height (78.2%), and greenness (86.9%), with an overall average phenotyping accuracy of approximately 90.6%, validated against manual measurements. These results demonstrate the reliability of PlantCV-based image analysis for rapid, high-throughput phenotyping in sesame, with image-derived traits supporting more efficient selection of sesame lines for breeding and precision crop management. This convergence of AI-based image analysis and field phenotyping offers a scalable, cost-effective pathway toward more resilient, climate-smart sesame breeding programs.

Keywords: *Machine learning; Artificial intelligence; Sesame; High-throughput phenotyping; PlantCV; Climate-smart agriculture*

Evaluating the Potential of Various Potassium Fertilizers for Wheat Grown on Haplocambid Soil

Sheraz Khadim, Sajid Masood*

Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan 60800, Pakistan

*Corresponding author's e-mail: sajidmasood@bzu.edu.pk

Abstract

Potassium (K) is an indispensable macronutrient for crops, including wheat (*Triticum aestivum* L.), affecting photosynthesis, nutrient transport and stress resistance. A field experiment was conducted at the Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, during the Rabi season of 2023–2024 to assess the comparative efficacy of POLY4, sulfate of potash (SOP), muriate of potash (MOP) and their blends on wheat production. A randomized complete block design (RCBD) with three replications was used; treatments comprised 100% doses or 50:50 mixtures of SOP, MOP and POLY4, along with a control. POLY4 alone or combined with SOP or MOP significantly enhanced wheat growth parameters (plant height, number of tillers, leaf chlorophyll content and leaf area index) and yield traits (1000-grain weight, grain protein content and nutrient uptake). Most notably, 100% POLY4 produced the greatest increase in grain yield and K uptake efficiency, while co-application of SOP + POLY4 showed synergistic benefits. POLY4 also improved K recovery efficiency and grain quality, with a cost–benefit ratio comparable to existing practices. These results indicate that, owing to its multi-nutrient content and slow-release mechanism, POLY4 has the potential to serve as an effective alternative or additive to conventional potassium fertilizers in sustainable wheat production systems. POLY4, alone or with SOP, thus improved plant growth and wheat grain yield on a sustainable basis.

Keywords: *K recovery efficiency; Leaf chlorophyll; Protein content; Nutrient uptake; Wheat yield*

Evaluation of *Moringa oleifera* Leaf Extract as a Biostimulant on Bt and Non-Bt Cotton Varieties under Regenerative Agriculture Practices

Abdul Rehman, Adnan Noor Shah, Muhammad Nawaz*

Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

*Corresponding author's e-mail: dmnawaz@kfueit.edu.pk

Abstract

Cotton is one of Pakistan's most important cash crops, but its sustainability is increasingly threatened by heavy reliance on synthetic inputs, declining soil health, pest pressure, and climate stress. This study examined the effects of moringa leaf extract (MLE) as a biostimulant on Bt and non-Bt cotton hybrids under different regenerative tillage systems, using a split-plot randomized complete block design with three tillage treatments (conventional, minimum, zero), two cultivars (Bt and non-Bt), and four foliar MLE treatments (control, 2%, 3%, 4%). Bt cotton yielded higher under conventional tillage, while non-Bt cotton performed better under zero tillage. MLE application significantly influenced physiological parameters: 2% MLE improved non-Bt emergence (90%), root length (15 cm), and seed yield (1,218 kg/ha), while 4% MLE maximized Bt root length (13.4 cm) and lint yield (1,562 kg/ha). Fiber quality metrics, including strength and fineness, showed genotype-specific responses to tillage and foliar treatment. These findings highlight the potential of MLE as an eco-friendly means of reducing chemical dependency, restoring soil and crop health, and improving yield stability, while underscoring the importance of genotype-specific, tailored regenerative practices in optimizing cotton performance and advancing low-input, climate-resilient cotton production systems.

Keywords: *Regenerative agriculture; Moringa leaf extract; Bt cotton; Tillage practices; Biostimulants; Soil health*

Evaluating *Moringa oleifera* as a Green Manure Crop to Enhance Soil Fertility and Cotton Productivity

Adnan Noor Shah¹, Muhammad Nawaz^{1*}, Sohail Irshad^{2,3}, Kashif Qadir¹

1 Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

2 Agriculture In-Service Training Institute, Rahim Yar Khan, Pakistan

3 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** dmnawaz@kfueit.edu.pk

Abstract

Cotton (*Gossypium hirsutum* L.) is an economically crucial fiber crop that is frequently limited by poor soil fertility and inefficient fertilizer use; integrated nutrient management combining organic and inorganic fertilizers offers a sustainable means of improving both crop productivity and soil health. This field experiment, conducted at the Cotton Research Center, Khanpur, Rahim Yar Khan, during the 2025 Kharif season, evaluated the effect of *Moringa oleifera* green manuring on soil properties, physiological attributes, growth, and yield across three cotton cultivars (FH-333, CYTO-2023, CKC-6) using a Randomized Complete Block Design with three replications and nine treatments ranging from a recommended-dose control to varying combinations of moringa green manure, traditional green manure, and inorganic fertilizer. Growth and yield parameters were significantly influenced by treatment and cultivar: the combined treatment (25% moringa green manure + 25% traditional green manure + 50% inorganic fertilizer, T9) produced the highest plant height (147.2 cm), root length (17.6 cm), leaf area index (4.7), stem diameter (2.16 cm), bolls per plant (48), average boll weight (3.7 g), 100-seed weight (10.7 g), seed cotton yield (3,750 kg/ha), and lint yield (1,437 kg/ha), while the control treatment produced the lowest values across all parameters. FH-333 significantly outperformed the other cultivars, suggesting greater genetic responsiveness to integrated nutrient management. These findings indicate that combining moringa green manure with inorganic fertilizer represents the most effective and sustainable nutrient management strategy for enhancing cotton productivity across varying agro-ecological conditions.

Keywords: *Cotton; Moringa oleifera; Green manuring; Soil fertility; Integrated nutrient management*

Improving the Productivity of Wheat through Stage-Specific Foliar Feeding of Biostimulant

Muhammad Nawaz^{1*}, Adnan Noor Shah¹, Sohail Irshad^{2,3}, Muhammad Usama Bin Saeed¹

¹ Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

² Agriculture In-Service Training Institute, Rahim Yar Khan, Pakistan

³ Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: dmnawaz@kfueit.edu.pk

Abstract

Wheat (*Triticum aestivum*) is Pakistan's staple cereal crop and a major source of nutritional and economic value, but its yield potential across the country is constrained by biotic and abiotic stresses, including climate change, water scarcity, soil degradation, and overuse of chemical fertilizers, which degrade soil health, contaminate water, and increase production costs. This study evaluates the potential of foliar-applied moringa leaf extract (MLE), a natural biostimulant, to improve wheat production, testing eight MLE concentrations (control, water spray, and 1.0–3.5% MLE) applied at three growth stages, tillering, booting, and grain formation. Pre-sowing soil parameters (electrical conductivity, pH, organic matter, texture, saturation, moisture, N, P, K) and crop growth and yield parameters (root and shoot length, seedling biomass, leaf area, tiller number, chlorophyll content, plant height, spike characteristics, grain number and weight, seed and biological yield, and harvest index) will be assessed. The findings are expected to help farmers reduce fertilizer costs while improving crop production through an environmentally safer, biostimulant-based approach.

Keywords: *Wheat; Biostimulant; Moringa leaf extract; Foliar application; Growth stage; Fertilizer efficiency*

Improving Productivity of Lentil through Foliar Application of Biostimulant and Nutrients

Muhammad Nawaz^{1*}, Adnan Noor Shah¹, Muhammad Zain-ul-Abideen¹, Sohail Irshad^{2,3}

1 Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

2 Agriculture In-Service Training Institute, Rahim Yar Khan, Pakistan

3 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** dmnawaz@kfueit.edu.pk

Abstract

Lentil is an important legume crop in global food production owing to its high protein content and capacity for biological nitrogen fixation, but climate change has increasingly constrained its yield potential, particularly in regions such as Pakistan. This study investigated the combined foliar application of moringa dried leaf extract (MDLE) with boron (B) and potassium (K) using a Randomized Complete Block Design with factorial arrangement and three replications, testing eight treatments (control, water spray, MDLE alone, B alone, K alone, and their combinations) applied at vegetative and reproductive growth stages. The combined treatment of 3% MDLE + 0.1% B + 1.0% K produced the strongest overall response, with maximum root length (36.9 cm), shoot length (57.1 cm), plant height (94.0 cm), seedling fresh weight (7.7 g plant⁻¹), seedling dry weight (0.99 g plant⁻¹), and chlorophyll content (41.2 SPAD) at the vegetative stage, and the shortest time to flowering (43 days) and pod formation (50 days), along with maximum pod-bearing branches (10.0 plant⁻¹), pods per plant (30), seeds per pod (2.8), 100-seed weight (10.6 g), biological yield (6.6 t ha⁻¹), seed yield (2.3 t ha⁻¹), and harvest index (60.5%) at the reproductive stage; control and water-spray treatments showed markedly lower growth, phenological, and yield performance, while single applications of MDLE, B, or K also improved lentil production relative to control. These findings indicate that MDLE combined with B and K, applied at both vegetative and reproductive stages, is an effective strategy for enhancing lentil productivity.

Keywords: *Lentil; Moringa dried leaf extract; Foliar application; Boron; Potassium; Biostimulants*

Advancing Carbon Recovery and Ecosystem Stability through Sustainable Biotransformation Techniques: From Water to Carbon Management in Global Drylands

Nida Yousaf^{1*}, Fatima Khan¹, Saliha¹, Ambreen Naz²

1 Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan

2 Department of Home Sciences, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** nidayousaf879@gmail.com

Abstract

Global drylands support a substantial share of the world's population and agricultural production yet remain especially vulnerable to the dual pressures of water scarcity and degradation of terrestrial carbon reservoirs; terrestrial ecosystems are estimated to have lost nearly 344 billion tons of carbon as environmental stressors have accelerated soil degradation, shifting dryland systems from carbon sinks toward greenhouse gas sources. Addressing these interlinked challenges requires an integrated approach that simultaneously improves water-use efficiency and supports decarbonization. Drawing on a meta-analysis of water-to-carbon biotransformation studies, this review finds that intercropping can raise net primary productivity by approximately 18.9%, strategic irrigation management can conserve 30–50% of water while improving water-use efficiency, soil mulching can increase productivity by approximately 22% through temperature moderation and moisture conservation, and soil regeneration can enhance carbon sequestration, storing an estimated 1.2–3.8 t soil organic carbon ha⁻¹ yr⁻¹. Restoring soil health, rebuilding soil organic matter, and enhancing biodiversity emerge as foundational levers for improving dryland resilience and carbon recovery, with future strategies expected to benefit from efficient irrigation, CO₂ fertilization, rhizosphere microbiome management, organic mulching, and sustainable intensification to enhance long-term adaptive capacity.

Keywords: *Dryland agriculture; Carbon sequestration; Soil organic carbon; Water use efficiency; Intercropping; Ecosystem resilience*

Elemental Sulfur and Zinc Sulfate Influence Maize Growth and Nutrient Uptake in a Calcareous Soil

Ayesha Akram¹, Shahid Hussain^{1*}, Muhammad Imran²

1 Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

2 Soil and Water Testing Laboratory, Khanewal, Pakistan

***Corresponding author's e-mail:** shahid.hussain@bzu.edu.pk

Abstract

Combined application of zinc and sulfur may improve soil fertility and nutrient availability in calcareous soils, as sulfur oxidation lowers soil pH and thereby increases the solubility of zinc and other micronutrients. This glasshouse pot study investigated the timing of elemental sulfur application combined with zinc application on maize, using a two-factorial randomized complete block design with four sulfur application timings (control, two weeks before sowing, at sowing, two weeks after sowing) and two zinc levels (control and at sowing); elemental sulfur was applied at 30 mg/kg and zinc sulfate at 6 mg/kg, alongside recommended nitrogen and potassium rates, with eight treatment combinations replicated three times (24 pots total) and plants harvested 31 days after sowing. Sulfur application before sowing significantly decreased soil pH and increased soil electrical conductivity relative to the control, and increased shoot concentrations and plant-available fractions of sulfur, phosphorus, potassium, and micronutrients; zinc application to soil significantly influenced plant-available soil zinc and total shoot zinc and shoot and root dry matter increased significantly with both zinc and sulfur application. These findings indicate that applying elemental sulfur two weeks before sowing combined with zinc sulfate at sowing effectively enhances nutrient availability and uptake, offering a practical approach for improving maize nutrition and productivity in micronutrient-deficient calcareous soils.

Keywords: *Calcareous soil; Elemental sulfur; Zinc sulfate; Maize; Nutrient uptake*

Redesigning Food Systems for Climate Resilience: Integrating Biodiversity and Ecology from Soil to Seed

Muhammad Farooq

Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al-Khoud, Muscat, Oman

Corresponding author's e-mail: farooqcp@squ.edu.om

Abstract

Climate change, biodiversity loss, land degradation, water scarcity, and declining resource-use efficiency are challenging the sustainability of global food systems and exposing the limitations of input-intensive agriculture. Building resilient food systems requires redesigning agroecosystems to harness biodiversity and ecological processes across the entire soil-plant continuum. Integrating ecological principles into agricultural production offers opportunities to simultaneously enhance productivity, strengthen resilience, restore ecosystem services, and reduce environmental footprints: conservation agriculture, crop diversification, cereal-legume intercropping, and incorporation of underutilized species and crop wild relatives broaden the functional and genetic diversity of agroecosystems, improving soil health, resource-use efficiency, yield stability, and profitability under variable climates. Ecological plant traits, including biological nitrification inhibition and allelopathy, can naturally regulate nitrogen transformations and weed dynamics, reducing nitrogen losses, greenhouse gas emissions, and dependence on synthetic inputs, while complementary approaches involving biochar, beneficial microorganisms, controlled-release fertilizers, and rhizosphere management further enhance nutrient cycling, carbon sequestration, soil biological activity, and water-use efficiency. Strengthening resilience also requires optimizing plant performance from the earliest developmental stages: seed priming, bio-priming, stress memory, and agronomic biofortification can improve crop establishment, nutrient acquisition, physiological resilience, and grain nutritional quality under drought, heat, salinity, and nutrient-limited conditions, while adaptive traits from crop wild relatives and locally adapted landraces expand opportunities for developing climate-resilient cropping systems. Integrating biodiversity, ecological interactions, and regenerative management from soil to seed provides a systems-based framework for transforming agriculture into multifunctional, climate-resilient food systems capable of meeting future global food demand.

Keywords: *Conservation agriculture; Ecological intensification; Biological nitrification inhibition; Agrobiodiversity; Climate resilience*

Augmenting the Yield and Quality Attributes of *Momordica charantia* by Supplementing Chitosan and Triacantanol

Muhammad Rashid Shaheen¹, Rashid Hussain^{1*}, Muhammad Noman Iftikhar¹, Sahar Rashid², Tanveer Hussain³

¹ Department of Horticultural Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

² Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan

³ Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

*Corresponding author's e-mail: rashid.hussain@iub.edu.pk

Abstract

Bitter gourd (*Momordica charantia* L.) is an important horticultural and medicinal crop for which optimizing growth and fruit quality remains a key challenge. This study evaluated and compared the individual effects of exogenous chitosan and triacantanol at varying concentrations on growth, yield, and quality attributes of bitter gourd, using two separate Randomized Complete Block Design experiments with five foliar spray concentrations (0, 50, 100, 150, 200 mg/L) and three replications; vegetative development, photosynthetic efficiency, yield, and fruit quality parameters were evaluated using ANOVA and LSD tests. Foliar application of 150 mg/L chitosan and 150 mg/L triacantanol produced the most significant improvements across all measured traits relative to control, substantially increasing plant height, root length, leaf count, stem diameter, photosynthetic rate, and SPAD chlorophyll values, along with markedly elevated fruit yield and quality parameters, including total soluble solids and total dissolved solids ratios. These findings indicate that both chitosan and triacantanol, applied at 150 mg/L, are highly effective biostimulants for optimizing vegetative growth, yield, and fruit quality in bitter gourd, supporting their use as a sustainable agronomic strategy for improving vegetable production.

Keywords: Bitter gourd; Chitosan; Triacantanol; Plant growth regulators; Fruit quality

Microplastic Contamination across Milk Packaging Materials: Abundance, Polymer Composition, Morphology, and Hazard Assessment

Hamza Shafiq, Mamoon Amir*, Muhammad Riaz, Amir Ismail, Aneela Hameed

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Microplastic contamination from food-contact packaging is an emerging food safety concern, with limited comparative evidence across diverse packaging materials. This study compared the abundance, polymer composition, morphology, and particle-size distribution of microplastics across 110 commercially available milk packaging units spanning 12 categories, including steel tanks, aluminum cans, HDPE cans and drums, plastic jugs, LDPE bags, Tetra Pak, PET bottles, glass bottles, laminate pouches, metal cans, and paper cans, using mechanical rinsing, wet peroxide oxidation, density separation, and membrane filtration for particle isolation, with polymer identification by ATR-FTIR and morphology by scanning electron microscopy and stereomicroscopy. Contamination differed significantly between packaging groups (Welch ANOVA, $p < 0.001$): Tetra Pak showed the highest mean abundance (81.50 ± 33.88 particles/package), followed by metal cans (76.40 ± 35.02), HDPE cans (75.40 ± 24.66), and plastic jugs (74.70 ± 33.06), while aluminum cans (20.80 ± 6.37) and glass bottles (23.20 ± 10.69) showed the lowest. The microplastic load index (MPLI) was highest for Tetra Pak (4.08 ± 1.69), while the polymer hazard index (PHI) was highest for metal cans (11.24 ± 6.68), indicating that abundance- and hazard-based contamination rankings can diverge. Polyethylene was the dominant polymer detected, particularly in plastic jugs, Tetra Pak, and HDPE cans, with polypropylene, PET, polyamide, polystyrene, and PVC also identified; particle morphology was predominantly fragments, with particle sizes of 150–500 μm most common. Total abundance, the four major polymer classes, MPLI, PHI, and all morphological and particle-size categories differed significantly between packaging groups ($P \leq 0.05$), with aluminum cans and glass bottles showing the lowest particle loads and Tetra Pak, HDPE cans, and plastic jugs the highest. These findings indicate that combining abundance-based and hazard-weighted assessment is necessary for evaluating the microplastic safety of food-contact packaging.

Keywords: Microplastics; Milk packaging; Polymer composition; Hazard assessment; ATR-FTIR

Impact of Changing Climate on Microbial Food Spoilage

Imran Pasha

Faculty of Food, Nutrition and Home Sciences, University of Agriculture, Faisalabad, Pakistan

Corresponding author's e-mail: ipasha2001@uaf.edu.pk

Abstract

Climate change is increasingly influencing the safety, quality, and shelf life of foods by altering the environmental conditions that govern microbial growth and survival. Rising temperatures, changes in humidity and precipitation, extreme weather events, and fluctuations in storage conditions can significantly affect the ecology and behavior of spoilage microorganisms: elevated temperatures generally accelerate bacterial, yeast, and mold growth and metabolic activity, accelerating deterioration of fresh, processed, and minimally processed foods, while increased humidity and water activity can promote fungal growth and associated mycotoxin risks, particularly in cereals, fruits, and vegetables. Changing climatic conditions may also shift the geographical distribution and seasonal prevalence of spoilage microorganisms, introducing new microbial challenges across production and supply chains, while heat stress, water scarcity, flooding, and disruptions to transportation and cold-chain systems can increase opportunities for contamination and spoilage; climate-driven changes in raw material composition, agricultural practices, and post-harvest handling may further influence microbial communities and their spoilage potential. These trends underscore the need to strengthen climate-resilient food safety and quality management systems through improved temperature and humidity control, robust cold chains, predictive microbiology, rapid detection technologies, improved packaging, and optimized preservation methods, with integration of climate data into microbial risk assessment supporting better prediction and management of spoilage throughout the food supply chain.

Keywords: *Climate change; Microbial food spoilage; Predictive microbiology; Cold-chain management; Food safety*

Characterization of Chickpea (*Cicer arietinum*) Germplasm for Tolerance against Pod Borer (*Helicoverpa armigera*)

Dilawar Ali*, Waqar Ul Haq, Sami Ul-Allah*

Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences and Technology,
Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: dilawarbk1@gmail.com; samipbg@bzu.edu.pk

Abstract

Chickpea (*Cicer arietinum*) is an important protein- and carbohydrate-rich pulse crop cultivated on marginal lands in Pakistan, including the Thal and Potohar regions, where pod borer (*Helicoverpa armigera*) is a major biotic constraint causing significant yield losses. This study characterized available chickpea germplasm for pod borer tolerance at two hotspot locations in Punjab, the Arid Zone Research Institute (Bhakkar) and the Barani Agricultural Research Institute (Chakwal), using phenotypic traits including pod borer damage, pod length and thickness, pod number per plant, pod wall thickness, and seed number per plant, alongside molecular data. Based on phenotypic characterization, genotypes E-4, TGKN 2232, TG1717, DO-7211, 23KCC-108, 23KCC-106, 23KCC-103, 23KCC-107, 23KCC-10, and TGKN2244 were identified as tolerant, showing the highest yield and least pod borer damage, with genotypes possessing pod wall thickness of approximately 1 mm showing resistance. Pod wall thickness, pods per plant, pod length, and seeds per plant were positively correlated with yield, indicating their potential use as selection criteria for yield improvement in pod borer-tolerant chickpea breeding programs.

Keywords: Chickpea; Pod borer; *Helicoverpa armigera*; Germplasm characterization; Pest tolerance

Enhancing Satiety Using Pea Pod Powder as a Functional Ingredient

Nabila Mumtaz

Kinnaird College for Women University, Lahore, Pakistan

Corresponding author's e-mail: nmumtaz919@gmail.com

Abstract

This study developed and evaluated pea pod powder (PPP)-enriched functional recipes for enhanced satiety, while promoting utilization of an underutilized agricultural by-product, across four phases: proximate analysis of pea pod powder, development and sensory evaluation of functional recipes, recipe standardization, and postprandial satiety assessment. Pea pod powder was incorporated into chapati, pancakes, and shawarma at five levels (0%, 5%, 10%, 15%, 20%); sensory evaluation was conducted by 12 semi-trained panelists using a 9-point hedonic scale, with the optimized formulation standardized through three independent preparation trials, and subjective satiety subsequently evaluated in 90 healthy participants consuming the optimized 10% formulation versus control products at baseline and at 30, 60, 90, and 120 minutes post-consumption. Proximate analysis confirmed that pea pod powder is a valuable source of dietary fiber, protein, and minerals. Sensory evaluation showed that increasing PPP level significantly influenced color, aroma, taste, texture, and overall acceptability ($P \leq 0.05$), with the 10% incorporation level providing the most favorable balance between nutritional enhancement and sensory quality; standardization trials showed no significant differences among repeated preparations, confirming reproducibility. Participants consuming the 10% PPP-enriched recipes reported significantly higher satiety scores than those consuming control products throughout the 120-minute postprandial period ($P \leq 0.05$). These findings indicate that pea pod powder can be successfully incorporated into commonly consumed foods to enhance nutritional quality and promote satiety while supporting sustainable utilization of agricultural by-products.

Keywords: *Pea pod powder; Functional foods; Dietary fiber; Satiety; Sensory evaluation; Agricultural by-products*

Smart Food Fortification Technologies: An Innovative Strategy to Combat Hidden Hunger and Improve Public Health

Syeda Musaffa Fatima^{1*}, Hira Iftikhar²

1 Institute of Home Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Food and Nutrition, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** syedafatima1808@gmail.com

Abstract

Micronutrient deficiencies, often termed “hidden hunger,” affect more than two billion people worldwide, predominantly women and children in low- and middle-income countries. Traditional food fortification programs have historically faced challenges including unequal micronutrient distribution, inconsistent quality control, and difficulty maintaining prescribed nutrient levels, issues that advanced smart fortification technologies are increasingly being used to address. This review discusses recent developments in smart food fortification, including automated nutrient dispensers, sensors, and encapsulation techniques used to add micronutrients to staple foods such as wheat flour and edible oil, and to monitor nutrient levels against recommended daily allowances to reduce health risks and improve outcomes. These technologies are considered efficient tools for meeting food and nutrition security targets while maintaining compliance with national food safety standards, though cost, technical capacity, and regulatory requirements remain significant barriers to adoption in developing countries. Further research on cost-effective, accessible smart fortification technologies is needed to support their adoption by communities and small-scale food processing industries.

Keywords: *Smart food fortification; Hidden hunger; Micronutrient deficiency; Digital food technology; Food security*

Sustainable Functional Foods Developed from Food Waste: A Circular Bioeconomy Approach for Nutrition and Environmental Sustainability

Hira Iftikhar^{1*}, Syeda Musaffa Fatima²

1 Institute of Home Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Food and Nutrition, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** hira.iftikhar@uaf.edu.pk

Abstract

Food loss and waste represent a serious global challenge, accounting for roughly one-third of total food produced and contributing significantly to greenhouse gas emissions, while food processing waste streams, including fruit peels, vegetable pomace, cereal bran, seed cake, and dairy waste, represent a valuable source of nutrients and bioactive compounds for functional food development. Valorizing this waste is an emerging opportunity to meet circular bioeconomy goals through environmentally sustainable solutions for food security and health. This review provides an updated overview of approaches for producing functional foods from food processing waste using fermentation, enzymatic hydrolysis, green solvent extraction, microencapsulation, and spray drying, with resulting value-added products applicable across bakery products, beverages, dairy products, snacks, and nutraceuticals. Functional foods derived from food waste can supply dietary fibers, polyphenols, antioxidants, protein, and minerals, potentially reduce the risk of non-communicable diseases and support gut microbiota function, while offer a profitable solution to food waste management within the food industry. Remaining challenges include developing appropriate processing technologies, ensuring economic feasibility, optimizing functional ingredient content, achieving consumer acceptance, addressing regulatory requirements, and clinically validating health benefits, underscoring the need for continued research in this area.

Keywords: *Functional foods; Food waste valorization; Circular bioeconomy; Sustainable nutrition; Bioactive compounds*

Laccase from *Coprinus comatus* as a Value-Added Biocatalyst against 17β -Estradiol

Sonia Safdar¹, Shah Rukh², Uzma Ishaq¹³, Sayra Ishaq Bhatti¹, Uzma Irfan³, Ishtiaq Hussain⁴, Ahmed Akrem^{1*}

¹ Institute of Botany, Bahauddin Zakariya University, Multan, Pakistan

² Department of Biochemistry, Bahauddin Zakariya University, Multan, Pakistan

³ Department of Botany, The Women University, Multan, Pakistan

⁴ Department of Botany, University of Baltistan, Skardu, Pakistan

*Corresponding author's e-mail: ahmedakrem@bzu.edu.pk

Abstract

Sustainable food systems depend not only on increasing production but on extracting greater value from existing crops while keeping the food chain free of harmful residues. Estrogenic compounds entering food and water systems are a recognized global safety concern, and enzymatic removal offers a cleaner alternative to chemical treatment. Edible mushrooms address both needs grown on agricultural waste and consumed as a low-value commodity, they also produce laccases (EC 1.10.3.2), multicopper oxidases already used in juice clarification, wine stabilization, and effluent treatment, requiring only oxygen and releasing only water as a by-product. This study evaluated laccase from *Coprinus comatus* (CcL) against 17β -estradiol (E2), an endocrine-active residue in animal-derived foods and effluents and a principal driver of estrogen receptor-positive breast cancer, using homology modeling, molecular docking, and a 200-nanosecond molecular dynamics simulation. E2 occupied the CcL substrate-binding cavity in a well-defined orientation, anchored by hydrogen bonds to Asp228 and His477 within a hydrophobic network involving Ile185, Pro186, Thr187, Phe287, Gly412, and Ile474, with this binding mode retained throughout the simulation and stable backbone behavior and active-site geometry preserved. These findings indicate that CcL binds 17β -estradiol in a stable, catalytically favorable orientation, identifying it as a candidate biocatalyst for estradiol degradation relevant to food-chain residue management, and illustrating the potential for edible mushrooms to serve as high-value enzymatic resources.

Keywords: *Coprinus comatus*; Laccase; 17β -estradiol; Molecular docking; Molecular dynamics simulation; Food safety

Restoring Degraded Soils to Sustain Food Production under Climate Change

Muhammad Sanaullah

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Corresponding author's e-mail: msanaullah@uaf.edu.pk

Abstract

Climate change is intensifying agricultural soil degradation through rising temperatures, erratic rainfall, and elevated soil salinity, threatening agricultural productivity, sustainable food production, and food security, with soil organic matter (SOM) depletion playing a central role in declining soil health and amplifying greenhouse gas emissions such as methane and nitrous oxide. Effective soil management is therefore crucial for mitigating climate impacts and sustaining food production. This presentation examines strategies for soil remediation focused on restoring SOM to improve soil structure, fertility, carbon sequestration potential, and long-term agricultural productivity, exploring innovative practices including biochar amendment, crop-residue retention, and agro-waste valorization. These strategies improve soil quality while reducing greenhouse gas emissions, offering the dual benefit of climate adaptation and mitigation. Case studies from Pakistan's agricultural systems illustrate how these practices can be scaled to restore degraded lands while strengthening resilience to climate stress and supporting food security, positioning soil-based remediation as an actionable response to the impacts of climate change on agriculture and the environment.

Keywords: *Soil degradation; Soil organic matter; Biochar; Climate change adaptation; Carbon sequestration*

Fauji Fresh N Freeze x AGRILIFT: A Digital Collaboration for Precision Agriculture in Contract Farming

Muhammad Yasir Saleem*, Farrukh Azeem, Muhammad Umair Javid, Hassan Ali Butt, Rahil Mahtab, Bilal Ahmed Shafique, Muhammad Shahzad, Muhammad Irshad, Muhammad Zunair Kramat, Zaheer Aslam, Naeem Maqbool

Fauji Fresh N Freeze Ltd., Pakistan

*Corresponding author's e-mail: Yasir.saleem@freshnfreeze.com

Abstract

Rising climate volatility, escalating input costs, and stricter quality benchmarks are pushing contract farming toward data-driven decision-making, where productivity increasingly depends on precision, real-time data, and timely agronomic decisions rather than scale alone. This study presents a commercial-scale case of AG-Tech adoption through integration of the AGRILIFT digital platform into the farming network of Fauji Fresh N Freeze Ltd., covering 4,264 acres of contracted potato (approximately 95%) and spring-season sweet corn cultivation during 2025–26 across Central and Southern Punjab (Depalpur, Kasur, Pakpattan, Mailsi/Vehari, and Multan zones), demonstrating farm-to-dashboard digitization at commercial volume. Key components include farmer-wise geo-tagging and plot-level GPS mapping for spatial visualization of field distribution and risk zones; systematic pre-sowing soil and water sampling informing site-specific rather than blanket fertilizer recommendations; land-leveling and germination assessment reporting to identify irrigation inefficiencies and poor-emergence zones; and continuous crop health monitoring enabling early risk detection and prioritized corrective action. Collectively, these capabilities shift quality management from reactive, harvest-stage correction toward proactive intervention during the crop growth cycle. Preliminary outcomes indicate more uniform crop stands, improved water-use efficiency, reduced input wastage, and greater yield stability and farmer profitability, alongside strengthened procurement trust through digital transparency in field data. These findings position AG-Tech platforms as an operating layer for modern contract farming, offering a replicable model for digitizing procurement and farming networks across Pakistan's broader agri-supply chains.

Keywords: *Precision agriculture; AG-Tech; Contract farming; Geo-tagging; Site-specific fertilization; Digital supply chain*

Enhancing Salt Stress Resilience in Wheat through Triacontanol and Plant Growth-Promoting Rhizobacteria

Marwa Yasmeen^{1*}, Qasim Ali², Muhammad Faisal Maqsood¹, Muhammad Bilal Javeed³, Rashid Hussain³, Usman Zulfiqar⁴

1 Department of Botany, Faculty of Chemical and Biological Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

2 Department of Soil Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

3 Department of Horticultural Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

4 Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

***Corresponding author's e-mail:** marwayasmeen051@gmail.com

Abstract

Escalating soil salinization threatens global wheat (*Triticum aestivum* L.) productivity, requiring sustainable, low-input strategies to restore crop performance under saline conditions. This pot study assessed whether triacontanol (Tria) and plant growth-promoting rhizobacteria (PGPR), applied singly or in combination, could mitigate salinity-induced physiological damage, using a Completely Randomized Design with four treatments (control, PGPR, Tria, Tria + PGPR) across 0, 4, and 8 dS m⁻¹ salinity, with three replications; growth, biochemical, ionic, and yield attributes were evaluated at maturity. Salinity progressively suppressed all measured traits, with the greatest decline in untreated plants at the highest salinity level. The combined Tria + PGPR treatment consistently outperformed individual treatments, increasing root and shoot biomass, spike number, tiller count, and 1000-grain weight by 57%, 16%, 95%, 86%, and 72%, respectively, relative to the saline control, accompanied by a 39% increase in superoxide dismutase activity and a 70% increase in total chlorophyll content, indicating enhanced antioxidant defense and photosynthetic protection under oxidative stress. The combined treatment also reduced Na⁺ accumulation while promoting K⁺ uptake, nearly tripling the K⁺/Na⁺ ratio relative to stressed controls. These findings demonstrate that combined Tria and PGPR application was more effective than either treatment alone in enhancing wheat salt tolerance, offering a practical, cost-effective, bio-based strategy for salinity-affected wheat systems, pending further field validation.

Keywords: *Wheat; Salinity stress; Triacontanol; Plant growth-promoting rhizobacteria; Ionic homeostasis*

Control of Square Shedding in Cotton Genotypes in Response to Soil Boron Application for Sustainable Cotton Production

Sajid Masood

Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

Corresponding author's e-mail: sajidmasood@bzu.edu.pk

Abstract

Cotton (*Gossypium hirsutum* L.) production and exports in Pakistan have declined in part due to severe square shedding, often driven by imbalanced boron (B) fertilization, since the concentration range between adequate B nutrition and B toxicity is narrow. This pot study investigated square shedding management and B uptake across six cotton genotypes (NIAB-98, IUB-2013, CIM-610, CIM-554, CYTO-535, CYTO-537) under four soil B levels (control/native soil B, 1, 2, and 4 mg kg⁻¹ dry soil), evaluating growth, yield, and leaf B concentration. Soil B application reduced square shedding relative to control, but genotypes showed differential responses: NIAB-98, CIM-610, and CYTO-535 performed best at 1 mg B kg⁻¹, while IUB-2013 and CYTO-537 performed best at 2 mg B kg⁻¹; all genotypes showed marked reductions in growth and yield at 4 mg B kg⁻¹, corresponding to leaf B accumulation of approximately 183 mg kg⁻¹ dry weight and consistent with B toxicity. At their respective optimal levels, B application reduced square shedding by 14–17%, improved plant height by 18–22%, boll number by 8–9%, seed cotton yield by 17–21%, and lint yield by 21–24% relative to control across the responsive genotypes. These findings indicate that optimal soil boron rates are cultivar-specific in cotton, and that both boron rate and genotype selection should be tailored to address deficiency and toxicity risk simultaneously for improved boll retention and sustainable cotton production.

Keywords: *Cotton; Boron; Square shedding; Genotype-specific response; Sustainable production*

Food Processing, Safety, and Value Addition for Sustainable Food Systems in a Changing Climate

Hira Iftikhar

Institute of Home Sciences and Faculty of Food, Nutrition and Home Sciences, University of Agriculture, Faisalabad, Pakistan

Corresponding author's e-mail: hira.iftikhar@uaf.edu.pk

Abstract

Sustainable food systems require innovative food processing technologies that enhance food quality, reduce post-harvest losses, and improve nutritional security while minimizing environmental impact; climate change has intensified challenges related to food safety, spoilage, microbial contamination, and supply chain disruption, making adoption of sustainable processing strategies increasingly important. This review examines recent advances in food processing, preservation, safety management, and value addition that contribute to resilient food systems, highlighting emerging technologies such as high-pressure processing, pulsed electric fields, cold plasma, intelligent packaging, natural preservatives, and digital food traceability systems for their ability to extend shelf life while preserving nutritional and sensory quality. It also discusses the importance of utilizing agricultural by-products and underutilized food resources to develop value-added functional foods, supporting food waste reduction and circular bioeconomy principles, alongside the continued importance of food safety management systems, including HACCP, good manufacturing practices, and risk-based quality assurance, for protecting consumer health under changing environmental conditions. Strengthening sustainable food processing and safety practices can improve food availability, reduce environmental burdens, and enhance economic opportunity across the food value chain, with future efforts needing to integrate technological innovation, regulatory support, and interdisciplinary collaboration to achieve climate-resilient food systems.

Keywords: *Food processing; Food safety; Value addition; Sustainable food systems; Climate resilience*

Isolation and Purification of Bioactive Metabolites from Thraustochytrids for Natural Food Fortification

Tahira Batoool Qaisrani^{1,2*}, Adila Naseem^{1,2}

1 Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Agricultural Engineering and Technology, Ghazi University, D.G. Khan, Pakistan

***Corresponding author's e-mail:** tqaisrani@gudgk.edu.pk

Abstract

Urbanization and industrialization have significantly influenced daily life, driving greater emphasis on health awareness and interest in compounds with substantial nutritional value. As the global population is projected to exceed 9.5 billion by 2050, increasing agricultural area and crop rotation to meet food demand risks exacerbating environmental issues such as deforestation, soil degradation, and biodiversity loss, underscoring the need for alternative nutrient sources. Microalgae and related microorganisms, including protists, bacteria, fungi, and yeast, are recognized as potential sources of saturated and polyunsaturated fatty acids. Thraustochytrids, a lesser-known group of marine protists, show significant biotechnological potential for human health and aquaculture applications, producing fatty acids, carotenoids, sterols, and squalene, with fermentation condition optimization identified as a key lever for improving yield; they show particular promise for producing squalene for medicinal and nutraceutical use and are being investigated for pharmaceutical applications given their capacity to synthesize diverse bioactive compounds, as well as for broader bio-engineering applications. This research aims to develop a product using thraustochytrid-derived compounds to reduce intrinsic toxicant burden and increase nutrient delivery properties.

Keywords: *Thraustochytrids; Bioactive metabolites; Squalene; Food fortification; Marine protists*

Proteomic Profiling of Fermented Spinach Powder: Enhancing Nutritional Quality and Functional Bioactivity

Saeed Akhtar¹, Tariq Ismail¹, Adila Naseem^{1,2}, Tahira Batool Qaisrani^{1,2*}

¹ Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

² Department of Agricultural Engineering and Technology, Ghazi University, D.G. Khan, Pakistan

*Corresponding author's e-mail: tqaisrani@gudgk.edu.pk

Abstract

Proteomics offers a comprehensive approach to understanding the molecular and nutritional transformations occurring during food fermentation. This study investigated proteomic changes in spinach powder subjected to controlled fermentation to evaluate improvements in nutritional and functional properties, fermenting spinach powder using selected lactic acid bacteria under optimized conditions, followed by protein extraction, enzymatic digestion, and mass spectrometry analysis, with bioinformatics tools used to identify and annotate proteins, assess functional categories, and evaluate bioactive peptide formation. Fermentation produced significant protein hydrolysis, generating low-molecular-weight peptides with enhanced antioxidant and antimicrobial activity, alongside improved digestibility and bioavailability of essential amino acids relative to the unfermented sample. These findings demonstrate that fermentation induces beneficial proteomic modifications in spinach powder, enhancing its functional and nutritional quality, and highlighting its potential as a sustainable, health-promoting food ingredient rich in bioactive peptides and functional proteins.

Keywords: *Proteomics; Fermented spinach powder; Bioactive peptides; Functional food; Lactic acid bacteria*

Nutritional Profiling and Shelf-Life Evaluation of Exotic Tomato Varieties for Sustainable Food Systems

Shinawar Waseem Ali^{1*}, Nimra Iram¹, Maryam Saeed¹, Muhammad Rizwan Tariq¹

Department of Food Sciences, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan

*Corresponding author's e-mail: Shinawar.foodsciences@pu.edu.pk

Abstract

Climate change poses unprecedented challenges to global food security, requiring resilient crop varieties with enhanced nutritional profiles and extended shelf life. Tomatoes (*Solanum lycopersicum* L.) are widely consumed for their bioactive compounds, yet conventional varieties often suffer rapid post-harvest deterioration, contributing to food loss and waste. This study evaluated the nutritional composition, phytochemical content, and storage stability of five exotic tomato varieties (Indigo Cherry Drops, Indigo Rose, Large Red Cherry, Orange Roussollini, Plum Lemon) grown under controlled greenhouse conditions, to assess their suitability for introduction into Pakistan's agricultural system. Physicochemical analysis revealed significant varietal differences ($P \leq 0.05$) in moisture (90.02–93.12%), ash (0.88–0.94%), fat (0.45–0.64%), fiber (0.67–1.61%), protein (3.03–4.37%), and carbohydrates (1.11–3.84%); Indigo Rose exhibited superior bioactive potential, attributed to its anthocyanin-rich pigmentation, with total phenolic content of 41.26 mg GAE/100g, total flavonoid content of 0.98 mg QE/100g, and radical scavenging activity of 51.62%. Shelf-life assessment under ambient (20–25°C) and refrigerated (1–4°C) conditions over 25 days showed distinct storage behaviors: Indigo Rose, despite its nutritional advantages, showed poor ambient shelf-life due to accelerated weight loss, textural degradation, and disease susceptibility, while Indigo Cherry Drops showed extended ambient shelf-life with minimal weight loss and complete disease resistance, and Large Red Cherry maintained exceptional firmness and disease-free status under refrigeration. These findings highlight a trade-off between nutritional density and post-harvest longevity: introducing Indigo Rose could help address micronutrient deficiencies in Pakistani populations, while Indigo Cherry Drops and Large Red Cherry offer practical solutions for reducing post-harvest losses, supporting dietary diversification and food security through climate-smart commercialization of these varieties.

Keywords: Tomato; Nutritional profiling; Shelf-life evaluation; Post-harvest quality; Antioxidant content

Climate Change-Induced Sunscald in Mango Fruits: A Growing Challenge for Sustainable and Resilient Mango Production Systems in Southern Punjab, Pakistan

Sajid Ali*, Safina Naz, Aamir Nawaz, Shaghef Ejaz, Hasan Sardar, Sakeena Tul-Ain Haider

Department of Horticulture, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** sajidali@bzu.edu.pk

Abstract

Mango is a high-value subtropical and tropical fruit crop increasingly vulnerable to climate change through shifting radiation patterns, temperature regimes, phenological timing, and water availability. Mango fruits are particularly susceptible to climate-induced heat stress due to their direct exposure to extreme temperature and solar radiation during growth and development. In Southern Punjab, Pakistan, one of the country's major mango-producing regions, increasing heatwave frequency, prolonged hot and dry periods, and elevated solar intensity are contributing to a rising incidence of mango fruit sunscald, a physiological disorder caused by excessive surface heating that leads to peel yellowing and browning, necrotic spots, reduced visual quality, accelerated deterioration, and increased decay, threatening yield, quality, and orchard sustainability. Despite its growing significance, climate-induced sunscald remains an underexplored challenge within Pakistani mango production systems. This study examines the interactions among fruit surface temperature, climate variability, canopy microclimate, irrigation status, cultivar susceptibility, and orchard management practices in determining sunscald occurrence and severity, and evaluates climate-smart adaptation practices, including efficient water management, improved canopy architecture, protective fruit coverings, cultivar selection, reflective materials, and precision monitoring. Developing an integrated management framework combining physiological understanding with climate-resilient horticultural practices is essential for reducing sunscald-related losses and supporting long-term mango production stability in Southern Punjab and other susceptible growing regions under future climate scenarios.

Keywords: *Climate change; Heat stress; Mango; Sunscald; Fruit quality; Sustainable horticulture*

Potato Peel: Transforming Agro-Waste into Nutraceuticals and Functional Bioactives for Human Health

Adnan Amjad^{1*}, Amna Sajid¹, Muhammad Khurram Afzal¹

Department of Human Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: adnanamjad@bzu.edu.pk

Abstract

Growth of the potato processing industry has generated large volumes of potato peel as agro-food waste, creating environmental and economic challenges, while growing interest in sustainable nutrition and naturally health-promoting compounds has directed attention toward valorizing such by-products. Potato (*Solanum tuberosum*) peel is a good source of dietary fiber, phenolic compounds, bioactive peptides, starch, enzymes, and minerals with diverse biological and functional properties. This review critically examines the botanical properties, nutritional profile, phytochemistry, bioavailability, therapeutic properties, safety considerations, and industrial applications of potato peel, drawing on recent in vivo, in vitro, food system, and industrial research to characterize its antioxidant, antimicrobial, anti-inflammatory, wound-healing, hypolipidemic, and food-stabilizing activity, alongside emerging technologies such as encapsulation, protein recovery, starch modification, and green nanotechnology applications for improving functionality and safety. The growing body of evidence indicates that potato peel represents a potential resource with substantial health and industrial value rather than simple agricultural waste; effective processing can preserve bioactivity while addressing safety concerns related to glycoalkaloids or contaminants and enhancing bioavailability. Incorporating potato peel as a functional ingredient, in biodegradable packaging, antimicrobial surfaces, and biomedical formulations aligns with circular economy principles and offers potential benefits for human health.

Keywords: *Potato peel; Agro-waste valorization; Phenolic compounds; Functional foods; Bioavailability; Circular economy*

Biogenic Iron Oxide Nanoparticles Mitigate Chromium Stress in Spinach

Humaira Rajpot¹, Sanaullah Yasin^{1*}, Nosheen Mirza¹, M. Mudassar Maqbool², Anser Ali², Ghulam Abbas Narejo³

¹ Department of Soil and Environmental Sciences, Ghazi University, Dera Ghazi Khan, Pakistan

² Department of Agronomy, Ghazi University, Dera Ghazi Khan, Pakistan

³ Department of Botany, Shah Abdul Latif University, Khairpur, Pakistan

*Corresponding author's e-mail: sanaullahyasin@gmail.com

Abstract

Agricultural soils are increasingly threatened by heavy metal contamination, particularly chromium (Cr), which compromises soil fertility, crop productivity, and food safety; green-synthesized iron nanoparticles (FeNPs) present a sustainable, eco-friendly approach for remediating metal-polluted soils and mitigating plant stress. This study compared the efficacy of FeNPs synthesized from spinach (SL-FeNP), neem (NL-FeNP), and cauliflower (CF-FeNP) extracts in alleviating Cr-induced phytotoxicity in spinach (*Spinacia oleracea*), confirming nanoparticle formation and thermal stability via UV-Vis, FTIR, and TGA, and evaluating growth and soil physicochemical responses across eight treatments (control, individual FeNPs at 200 mg/L, Cr-only stress, and Cr combined with each FeNP) in a randomized pot experiment with three replicates. Chromium exposure alone significantly reduced leaf number (70%), leaf area (60.6%), relative water content (39%), and total chlorophyll (23%) relative to control ($p < 0.001$). Application of SL-FeNP under Cr stress showed the strongest restorative effect, increasing leaf number, leaf area, relative water content, and chlorophyll by 88.8%, 47.5%, 48.7%, and 35%, respectively, relative to Cr-only stress, while reducing tissue Cr accumulation by 55.6% and increasing soil-available Fe by 27.2%. Spinach-derived nanoparticles (SL-FeNP) consistently outperformed NL-FeNP and CF-FeNP in restoring physiological parameters and limiting Cr uptake, demonstrating that biogenic FeNPs offer a viable, cost-effective bio-nanotechnology approach for remediating chromium-contaminated agricultural soils and supporting safe crop production.

Keywords: Green synthesis; Iron nanoparticles; Chromium stress; Phytoremediation; Heavy metal toxicity

Bio-Derived Calcium-Lignin Carbon Nanospheres Regulate Ion Homeostasis, Redox Balance, and Lignification in Salt-Stressed *Brassica napus*

Muhammad Haseeb Javaid^{1,2}, Asifa Neelam³, Abdul Majeed⁴, Muhammad Waqar Nasir⁵, Syed Asad Hussain Bukhari^{3*}

1 Zhejiang Key Laboratory of Crop Germplasm, Department of Agronomy, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou, China

2 Institute of Vegetable Science, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou, China

3 Institute of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

4 College of Grassland Science, Key Laboratory of Grassland Ecosystem (Ministry of Education), Gansu Agricultural University, Lanzhou, China

5 Jiangsu Key Laboratory of Crop Cultivation and Physiology, College of Agriculture, Yangzhou University, Yangzhou, China

***Corresponding author's e-mail:** asadbukhari@bzu.edu.pk

Abstract

Salt stress limits *Brassica napus* productivity by combining ion toxicity with oxidative injury, impaired photosynthesis, and weakened cellular stability. This study synthesized calcium-doped lignin carbon nanospheres (Ca-Ligno-CNs) by integrating calcium oxide and lignin nanoparticles, characterized by FT-IR, XRD, EDX, FE-SEM, and TEM, and evaluated their effect as a seed-priming treatment in *B. napus* seedlings exposed to 100 mM NaCl, linking nanosphere priming with coordinated regulation of calcium signaling, ion homeostasis, redox metabolism, and lignin biosynthesis. Application of Ca-Ligno-CNs significantly enhanced seedling growth, biomass accumulation, and photosynthetic performance, while maintaining membrane integrity through increased lignin deposition and cell wall stability under salt stress; treated plants showed reduced reactive oxygen species and malondialdehyde content alongside enhanced superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase activity. Ion analysis showed improved ionic balance, including reduced Na⁺/Cl⁻ accumulation and restored Ca²⁺ availability under saline conditions. At the molecular level, Ca-Ligno-CNs upregulated salt-tolerance genes (BnCBL3, BnMAPK1, BnNHX3, BnHKT1) and lignin biosynthesis genes (Bn4CL, BnF5H, BnCCR2, BnPAL4) in shoot and root tissue, and restored expression of Ca²⁺-responsive SOS3-pathway genes (BnGLR12, BnCNGC12, BnACA2, BnCAX1) that were downregulated under NaCl stress alone. These findings indicate that Ca-Ligno-CNs alleviate NaCl toxicity by coordinating calcium-associated signaling, ion regulation, antioxidant defense, and lignin-mediated cell-wall reinforcement in *B. napus*.

Keywords: Calcium-lignin nanospheres; *Brassica napus*; Salt stress; Ion homeostasis; Lignin biosynthesis; Seed priming

Assessment of Drought Tolerance in Tomato Genotypes at Different Growth Stages under Field Conditions

Muhammad Abdul Rehman Iqbal^{1*}, Rashid Hussain¹, Sahar Rashid², Muhammad Rashid Shaheen¹, Tanveer Hussain³

1 Department of Horticultural Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

2 Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan

3 Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

***Corresponding author's e-mail:** ab203rehman@gmail.com

Abstract

Drought stress is a major threat to sustainable tomato production amid ongoing climate change. This study evaluated the morpho-physiological, fruit quality, and biochemical responses of 11 tomato genotypes to drought stress across vegetative, flowering, and fruiting stages, using a randomized complete block design with factorial arrangement and three replications; parameters assessed included plant height, leaf area, stem diameter, node number, fruit yield components, and biochemical markers (lycopene, carotenoids, chlorophylls). Genotypes differed significantly in drought tolerance: NB265 showed the best structural stability, with greater plant height, stem diameter, and chlorophyll retention under stress; NB292 showed the highest fruit set and yield across drought environments, indicating favorable resource allocation to reproduction; and NB12, NB243, and NB14 showed elevated antioxidant pigment levels and leaf turgidity, indicating tolerance, while NB269 and NB15 showed the greatest reductions in growth, yield, and biochemical traits, indicating the lowest adaptability to drought. These findings underscore the value of combining morpho-physiological and biochemical markers for screening drought-tolerant tomato genotypes and provide a preliminary framework for breeding climate-smart tomato cultivars suited to arid and semi-arid regions.

Keywords: *Tomato; Drought tolerance; Genotype screening; Growth stages; Biochemical markers*

Iron-Functionalized Compost Reduces Lead Availability in Paddy Soils

Amna Zulfiqar¹, Hamna Bashir¹, Adnan Hussain^{2,3}, Muhammad Mahroz Hussain^{2*}

1 Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Faisalabad 38040 Pakistan

2 College of Environmental Science and Engineering, Yangzhou University, Yangzhou, 225127, Jiangsu, China

3 College of Mechanical Engineering, Yangzhou University, Yangzhou 225127, Jiangsu, China

***Corresponding author's e-mail:** hmahroz@gmail.com

Abstract

Widespread contamination of paddy soils with lead (Pb) poses an escalating threat to food security and human health, as Pb readily transfers from soil to rice grains and enters the food chain; in situ immobilization using organic amendments offers an economical, environmentally benign remediation strategy. This study compared the efficacy of plain compost versus iron-functionalized compost (Fe-Comp) in reducing Pb bioavailability and uptake in rice tissues, while assessing effects on soil biochemical health through soil organic carbon (SOC), dissolved organic carbon (DOC), microbial biomass carbon and nitrogen (MBC, MBN), and five soil enzyme activities. Fe-Comp outperformed plain compost across all measured parameters, achieving reductions of 71% in total soil Pb, 72% in dissolved Pb, and 70–86% in Pb accumulation across rice tissues (roots 71%, shoots 86%, husks 61%, grains 70%), while increasing SOC by 92%, DOC by 87%, MBC by 128%, and MBN by 90%, and substantially raising activities of dehydrogenase, urease, acid phosphatase, and β -glucosidase, indicating enhanced microbial activity and nutrient cycling. These findings establish Fe-functionalized compost as a multi-functional amendment capable of achieving Pb immobilization, biological soil restoration, and potential iron biofortification in rice systems simultaneously, warranting field-scale validation to confirm long-term efficacy and scalability for contaminated paddy ecosystems.

Keywords: *Lead immobilization; Iron-functionalized compost; Paddy soil remediation; Soil enzyme activity; Food chain contamination*

Nitrogen Management Improved Grain Yield, Quality, and Nitrogen Use Efficiency of Pearl Millet Genotypes under Semi-Arid Conditions

Ahmad Dawood^{1*}, Mubshar Hussain², Muhammad Bahram Khan², Abdul Majeed³, Umbreen Aziz⁴

¹ Faculty of Agricultural Sciences and Technology, University of Layyah, Layyah, Pakistan

² Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

³ College of Grassland Science, Key Laboratory of Grassland Ecosystem (Ministry of Education), Gansu Agricultural University, Lanzhou, China

⁴ Department of Forestry and Range Management, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: ahmaddawood@ul.edu.pk

Abstract

Pearl millet (*Pennisetum glaucum* L.) is an important cereal crop in semi-arid regions due to its drought tolerance and adaptability, but nitrogen deficiency remains a major constraint on productivity and grain quality, particularly in low-fertility soils, making identification of nitrogen-efficient genotypes essential. This two-year field experiment (2020–2021) evaluated five pearl millet genotypes (YB-70, MP-24, 55-S-95, NARC-Bajra, Cholistani Bajra) under four nitrogen levels (0, 40, 80, 120 kg N ha⁻¹) using a randomized complete block design with factorial arrangement and three replications. Application of 120 kg N ha⁻¹ significantly enhanced yield components, including grains per ear, 1000-grain weight, grain and biological yield, nitrogen uptake, and nitrogen use efficiency, producing the highest grain yield (2.90 and 2.95 t ha⁻¹) and biological yield (16.7 and 18.5 t ha⁻¹) across both years; grain carbohydrate content was also maximized at 120 kg N ha⁻¹, while grain protein content peaked at 80 kg N ha⁻¹. Among genotypes, 55-S-95 showed superior yield, nitrogen uptake, nitrogen use efficiency, and economic returns, while Cholistani Bajra showed higher protein content. These findings indicate that genotype 55-S-95 combined with 120 kg N ha⁻¹ provides the greatest economic benefit and is recommended for improved pearl millet production under semi-arid conditions.

Keywords: Pearl millet; Nitrogen management; Grain yield; Nitrogen use efficiency; Semi-arid conditions

Targeted Delivery of Encapsulated Artichoke Phenols for Acrylamide Mitigation in Cereal-Based Food Systems

Muhammad Nouman Shaukat*, Matteo Francavilla

Department of Agriculture, Food, Natural Resources and Engineering (DAFNE), University of Foggia, Foggia, Italy

***Corresponding author's e-mail:** nouman.shaukat@unifg.it

Abstract

Acrylamide remains one of the most significant process-induced contaminants formed during high-temperature processing of cereal-based foods, motivating the search for effective, sustainable mitigation strategies that preserve product quality. Plant-derived polyphenols have attracted attention for their antioxidant properties and potential to interfere with acrylamide-formation pathways, though their practical use is often limited by reduced thermal stability and uncontrolled interactions within complex food matrices. This study describes development of a targeted delivery system using encapsulated polyphenols recovered from globe artichoke (*Cynara scolymus* L.) by-products for acrylamide mitigation in cereal-based foods. Green microwave-assisted extraction was used to recover polyphenol-rich extracts from artichoke by-products, and preliminary characterization, including total phenolic content, antioxidant activity, and HPLC phenolic profiling, identified leaf-derived extracts as the most favorable for further development based on their phenolic profile and antioxidant properties. Encapsulation studies using food-grade wall materials are currently underway to improve thermal stability and controlled release of the selected polyphenols during processing, with the next phase assessing encapsulation performance and effectiveness in reducing acrylamide formation while maintaining product quality. Controlled polyphenol release during baking is expected to enhance interaction with reactive carbonyl intermediates and free radicals, suppressing key acrylamide-formation pathways; by integrating green extraction, by-product valorization, and encapsulation technology, this research aims to develop a practical, plant-based strategy for acrylamide mitigation supporting more sustainable cereal-based food production.

Keywords: *Acrylamide; Polyphenol encapsulation; Artichoke by-products; Food safety; Circular bioeconomy*

Long-Term Effects of Sowing Method, Seed Mixture, and Combined Microbial-Nitrogen Fertilization on Vegetation Diversity, Soil Recovery, and Ecosystem Multifunctionality in Degraded Alpine Grasslands

Abdul Majeed, Ma Xiaobai, Junhu Su*

College of Grassland Science, Key Laboratory of Grassland Ecosystem (Ministry of Education), Gansu Agricultural University, Lanzhou, China

***Corresponding author's e-mail:** sujh@gsau.edu.cn

Abstract

Grasslands support biodiversity, carbon storage, productivity, and pastoral livelihoods, but grassland ecosystems are experiencing severe deterioration due to ongoing climate fluctuation and human disturbance, underscoring the need for long-term active restoration strategies. This six-year (2020–2025) factorial field experiment in a severely degraded alpine grassland in the Gannan Tibetan Autonomous Prefecture tested two sowing methods (flat versus furrow), two native seed mixtures (*Elymus nutans* + *Avena sativa* versus *E. nutans* + *Lolium multiflorum*), and four fertilization regimes (control, nitrogen, microbial, combined nitrogen + microbial) across 48 plots, analyzing plant diversity, soil nutrient pools, enzyme activity, and an integrated ecosystem multifunctionality (EMF) index using split-plot-in-time ANOVA with year as the repeated factor. Furrow sowing increased species richness by 8.3% relative to flat sowing and produced significantly higher Shannon and Simpson diversity indices; furrow sowing and restoration year were the dominant drivers of plant diversity, which followed a non-monotonic trajectory, declining until 2022–2023 before recovering by 2025, while seed mixture and fertilization had only minor, index-specific effects on diversity. In contrast, soil nutrients, enzyme activities, and organic carbon responded strongly and consistently to fertilization, with combined nitrogen-microbial treatment increasing total nitrogen by 25.0%, available phosphorus by 26.9%, soil organic carbon by 11.6%, and urease activity by 33.7%. Ecosystem multifunctionality increased from -0.337 in 2020 to 0.422 in 2025 ($F = 122.57$, $p < 0.001$), with mean multifunctionality highest under combined fertilization (0.427) and lowest in the control (-0.523 ; $F = 85.20$, $p < 0.001$). These findings indicate that furrow sowing and fertilization act through largely independent recovery pathways, and that combining both represents the most effective long-term restoration strategy for degraded alpine grasslands.

Keywords: *Alpine grassland; Ecosystem multifunctionality; Microbial fertilizer; Restoration ecology; Soil enzyme activity; Tibetan Plateau*

Synergistic Effect of Zinc-Solubilizing Bacteria and Foliar Zinc Application on Agronomic Biofortification in Natural and Synthetic Hexaploid Wheat

Azizullah Khalili¹², Abdul Qayyum^{1*}

¹ Department of Agronomy, The University of Haripur, Haripur, Pakistan

² Department of Agronomy, Sayed Jamaluddin Afghani University, Asadabad, Afghanistan

*Corresponding author's e-mail: aqayyum@uoh.edu.pk

Abstract

Food insecurity and micronutrient deficiency are major global challenges, particularly in remote areas. Wheat (*Triticum aestivum* L.), a staple crop for nearly half of the world's population, requires adequate zinc (Zn) for healthy growth, grain yield, and grain quality, yet approximately half of the world's cereal-growing soils, including 70% of soils in Pakistan, are Zn-deficient. This field study evaluated the combined effect of Zn-solubilizing bacteria (ZSB) and various Zn fertilization approaches (no application, seed priming at 0.5%, soil application at 10 kg ha⁻¹, foliar application at 0.5%) on three wheat genotypes, a synthetic hexaploid (TRB-72-311), an advanced line (TRB-89-348), and an approved variety (Pirsabak-19), using a factorial randomized block design with and without ZSB. The combination of ZSB with foliar-applied Zn significantly improved wheat quality, growth, and grain yield in the synthetic hexaploid genotype TRB-72-311 compared with the approved variety Pirsabak-19 grown without Zn application or ZSB. These findings indicate that combining ZSB with foliar-applied Zn, particularly using synthetic hexaploid wheat genotypes such as TRB-72-311, can improve wheat grain yield and quality relative to conventional approaches without ZSB or Zn fertilization, offering a potential strategy for combating micronutrient malnutrition.

Keywords: Zinc-solubilizing bacteria; Zinc fertilization; Agronomic biofortification; Synthetic hexaploid wheat; Grain quality

Global Nitrous Oxide Emissions during Cotton and Maize Production: A Meta-Analysis

Hira Ashraf¹, Abdul Wakeel^{1*}, Muhammad Imran Khan¹, Imran Ashraf²

¹ Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

² Department of Agronomy, University of Agriculture, Faisalabad, Pakistan

*Corresponding author's e-mail: abdul.wakeel@uaf.edu.pk

Abstract

Anthropogenic activity has intensified greenhouse gas emissions, with nitrous oxide emerging as a major contributor to agricultural systems. This meta-analysis of field experiments on cotton and maize, conducted using OpenMEE software, examined factors influencing nitrous oxide emissions and their global trends. In cotton, synthetic fertilizers emitted more nitrous oxide than combined organic-synthetic fertilizer application, with emissions highest at soil pH 6.5–7.5 and lowest above pH 7.5; water-filled pore space $\leq 50\%$ and bulk density $< 1 \text{ g cm}^{-3}$ were associated with higher emissions, as were short-term experiments (< 365 days), sandy clay soils, and semi-arid subtropical climates. In maize, individual application of organic or synthetic fertilizers produced higher nitrous oxide emissions than combined application; emissions were lower at pH 6.5–7.5 but increased above pH 7.5 and were higher in shorter experiments (≤ 180 days) and soils with bulk density $> 1 \text{ g cm}^{-3}$, with aquic inceptisols emitting the most nitrous oxide and loamy soils the least, and temperate monsoon climates producing the highest emissions overall. These findings indicate that fertilizer type, soil properties, climate, and study duration significantly influence nitrous oxide emissions from cotton and maize systems, and that organic-synthetic fertilizer management with optimized soil conditions can effectively mitigate these emissions.

Keywords: Nitrous oxide; Cotton; Maize; Meta-analysis; Greenhouse gas emissions; Soil properties

Green Skills and Just Transition: Empowering People, Protecting the Planet, and Ensuring Prosperity

Abdul Wakeel

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Corresponding author's e-mail: abdul.wakeel@uaf.edu.pk

Abstract

The global shift toward a climate-smart, sustainable, low-carbon future demands not only new technologies but also a new generation of competencies, or green skills, to empower individuals and societies to drive environmental, social, and economic transformation; a just transition calls for equipping people with the knowledge and capabilities needed to achieve sustainability without leaving any community behind. This keynote highlights environmental management, climate-smart and low-emission farming, technological and digital innovation, circular economy and waste valorization, and socioeconomic and ethical leadership as essential pillars of green capacity building. Environmental management skills support sustainable resource use and biodiversity conservation, while climate-smart farming skills enable farmers to adapt to and mitigate climate change through efficient input use, renewable energy, and resilient cropping systems; technological and digital literacy, including remote sensing, data analytics, and AI-based decision tools, can transform monitoring and management at farm and policy levels; circular economy skills promote recycling, composting, and waste-to-value innovations that close nutrient loops; and ethical, policy, and communication competencies foster inclusivity, justice, and behavioral change. Achieving a just transition requires integrated education, policy coherence, and multi-stakeholder collaboration across governments, academia, and industry, with a path forward that includes mainstreaming green skills into curricula, vocational programs, and extension services, incentivizing low-emission technologies, and strengthening institutional frameworks that link environmental stewardship with decent employment and social equity.

Keywords: *Green skills; Just transition; Climate-smart farming; Circular economy; Capacity building*

Zinc-Biofortified Wheat Grain Production through Improved Zinc Bioavailability and Physiological Response under Soil-Applied Zinc and Narrow Row Spacing

Hamid Nawaz^{1*}, Tahir Shehzad Rafique², Nazim Hussain²

1 Cholistan Institute of Desert Studies, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

2 Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** hamidnawaz@iub.edu.pk

Abstract

Zinc (Zn) malnutrition reduces wheat grain quality, adversely affecting human health and threatening food security; narrower row spacing may improve plant access to soil zinc. This two-year field study evaluated agronomic zinc biofortification via soil-applied zinc under varying row spacing in wheat. Soil-applied Zn under narrow row spacing produced the strongest response in year II, increasing productive tillers by 13.04%, grains per spike by 12.73%, 1000-grain weight by 4.56%, grain yield by 12.82%, biological yield by 7.94%, and harvest index by 5.64% relative to control. Zn application combined with phosphorus and boron increased superoxide dismutase (21.92%), peroxidase (10.20%), catalase (26.83%), ascorbic acid (14.77%), and phenolic content (33.94%) under narrow spacing, while the Zn-narrow spacing combination increased photosynthetic rate (9.09%), stomatal conductance (38.09%), and water use efficiency (37.44%) in the second year. Zinc application also increased Zn bioavailability (13.66%), grain Zn (15.22%), embryo Zn (7.82%), aleurone Zn (0.61%), and endosperm Zn (13.17%), while reducing phytate content (3.84%) and the phytate:Zn ratio (6.61%) under narrow spacing during 2022–2023 relative to 2023–2024. These findings indicate that zinc-biofortified wheat grain production can be achieved through agronomic biofortification using soil-applied zinc combined with narrow (15 cm) row spacing in cereal-producing regions.

Keywords: Biofortification; Zinc; Row spacing; Wheat; Grain nutrient content

Optimizing Cereal-Legume Intercropping Systems: A Synergistic Strategy for Enhancing Agrobiodiversity and Resource Use Efficiency

Muhammad Bahram Khan¹, Muhammad Maaz¹, Abdul Qadeer¹, Mubshar Hussain^{1*}

Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** mubashir.hussain@bzu.edu.pk

Abstract

Intensive monoculture farming is a leading cause of biodiversity loss in agricultural landscapes; intercropping, the simultaneous cultivation of two or more crops, introduces planned biodiversity that can enhance ecosystem function and resilience. This two-year study examined the agronomic and qualitative benefits of wheat-chickpea and wheat-canola intercropping under different sowing methods, using a randomized complete block design with three replications, three cropping systems (sole, wheat-chickpea, wheat-canola), and two sowing methods (bed versus flat), with yield components analyzed by ANOVA and LSD test. Preliminary results demonstrated a clear synergy in the wheat-chickpea system: while sole crops produced higher biomass, intercropping with chickpea enhanced wheat quality, producing the highest crude protein content and grain number per spike relative to sole wheat or wheat-canola systems, with bed sowing consistently outperforming flat sowing across all systems. In contrast, the wheat-canola intercrop showed less compatibility, with notable reductions in yield and growth parameters. These findings indicate that wheat-chickpea intercropping, particularly under bed sowing, enhances functional agrobiodiversity, crop quality, and resource use efficiency, supporting its strategic adoption as a practical approach to biodiversity conservation in agricultural land.

Keywords: *Intercropping; Agrobiodiversity; Wheat-chickpea; Sowing method; Resource use efficiency*

Combined Application of Different Phosphorus Sources and Phosphorus-Solubilizing Bacteria Improved Fodder Yield, Quality, and Profitability of Pearl Millet

Abdul Majeed¹, Abdul Qadeer², Khadim Hussain³, Mubshar Hussain^{1*}, Muhammad Irfan¹

¹ Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

² College of Grassland Science, Gansu Agricultural University, Lanzhou, China

³ Department of Biotechnology, Faculty of Chemical and Biological Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

*Corresponding author's e-mail: mubashir.hussain@bzu.edu.pk

Abstract

Rising use of phosphorus (P) fertilizer is a global concern given limited reserves and its impact on soil health and crop production, compounded by the fact that most applied P becomes fixed in soil, reducing its availability. This two-year field study (2020–2021) investigated the effect of different inorganic P sources, di-ammonium phosphate (DAP), single super phosphate (SSP), nitrophos, and mono-ammonium phosphate (MAP), combined with and without phosphorus-solubilizing bacteria (PSB), on growth and yield of pearl millet (*Pennisetum glaucum*) grown as a fodder crop. Among P sources, MAP application combined with PSB inoculation produced statistically significant increases in plant height, tiller number, fodder yield, straw P content, and phosphorus use efficiency, alongside higher economic returns relative to other treatment combinations. These findings indicate that MAP fertilizer combined with bacterial inoculation can improve both fodder yield and net economic returns in pearl millet production.

Keywords: Pearl millet; Phosphorus sources; Phosphorus-solubilizing bacteria; Fodder yield; Phosphorus use efficiency

Simulating the Fate of Phosphorus Using the HYDRUS Model: An Incubation Study

Yasir Toheed Arshad¹, Muhammad Ashir Hameed¹, Muhammad Mughees Ud Din¹, Abdul Wakeel^{1*}

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** abdulwakeel77@gmail.com

Abstract

Phosphorus (P) is essential for plant development and metabolic processes, but its soil availability is often limited by fixation with soil particles and minerals, particularly in calcareous and Fe/Al-rich soils. This study evaluated P fractions and dynamics under different fertilizer levels using the HYDRUS model, conducting an incubation experiment with four soil types (from Gujranwala, Sialkot, Sahiwal, and Layyah) treated with di-ammonium phosphate (DAP) at 0, 50, 75, 100, and 125% of the recommended rate, incubated at 20°C and 80% water saturation for 60 days, with sequential extraction of labile, moderately labile, and non-labile P fractions at days 30 and 60. The plant-available P pool increased with fertilizer rate except in soils treated with 125% DAP, where high soil pH led to substantial fixation of applied P as calcium-bonded fractions and accumulation of non-labile P, raising concerns about runoff and eutrophication. HYDRUS simulations indicated that applying DAP at 75–100% of the recommended rate was optimal for improving P availability without enhancing legacy P accumulation, with soil type, pH, and CaCO₃ content identified as strong determinants of P dynamics, underscoring the need for soil-specific fertilization strategies.

Keywords: *Phosphorus dynamics; HYDRUS model; Diammonium phosphate; Eutrophication risk; Soil incubation*

Enhancing White Sugar Yield of Sugar Beet under Saline-Sodic Conditions through Salt Priming

Muhammad Tayyab¹, Abdul Wakeel^{1*}, Muhammad Sanaullah¹

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** abdulwakeel77@gmail.com

Abstract

Salt stress is a major abiotic constraint limiting plant growth and crop yield; priming seedlings before transplanting can improve salt tolerance through enhanced metabolic adjustment. This pot study (40 kg soil per pot) in a rain-protected net house evaluated salt priming of eight-day-old sugar beet seedlings, achieved through gradual daily increments of 5 mM NaCl to reach 40 mM NaCl, followed by transplanting of primed and non-primed seedlings into saline-sodic soils at three sodium adsorption ratio (SAR) levels (SAR 11, 15, and 19); plants were harvested 200 days after transplanting and evaluated for white sugar yield and quality parameters (sucrose, K, Na, α -amino N). Beet yield was significantly improved in primed relative to non-primed plants, with the strongest physiological improvement at SAR 15, where white sugar yield was also higher compared with SAR 11 and SAR 19. These findings indicate that salt priming enhances sugar beet salinity tolerance, supporting sugar beet production on saline-sodic soils while contributing to their reclamation through sodium phytoremediation potential.

Keywords: *Sugar beet; Salt priming; Saline-sodic soil; White sugar yield; Phytoremediation*

Synergistic Effects of Natural Growth Promoters and Mineral Nutrient Foliar Application on Wheat Growth and Yield

Muhammad Muneeb¹, Muhammad Mughees Ud Din¹, Abdul Wakeel^{1*}

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** abdulwakeel77@gmail.com

Abstract

Combined use of natural growth promoters and mineral nutrients holds significant potential for wheat cultivation. This pot study, conducted under a Completely Randomized Design, evaluated the synergistic effect of sorghum leaf extract (*sorgaab*) and foliar-applied mineral nutrients (N, K, Zn, B) on wheat growth, photosynthesis, and yield, using five treatments: control (recommended NPK), 3% *sorgaab* alone, 3% *sorgaab* with foliar nutrients at full or half basal NPK dose, and foliar nutrients with full NPK. Maximum photosynthetically active radiation and photosystem II quantum yield were recorded in treatments combining *sorgaab* with foliar nutrients at half or full basal NPK dose; treatments combining *sorgaab*, foliar nutrients, and half NPK produced the highest spike length, spikelets per spike, and grain yield, indicating improved nutrient uptake efficiency, and nutrient concentrations of N, P, K, Zn, and B were maximized in shoot and grain tissue under combined *sorgaab* and mineral nutrient treatments. These findings indicate that integrating 3% *sorgaab* with foliar nutrients while applying only half the basal NPK dose improves wheat physiological performance and yield, suggesting potential for reducing fertilizer input without compromising productivity.

Keywords: *Sorgaab; Wheat; Foliar nutrition; Growth promoters; Fertilizer efficiency*

Ammonia Emission and Nitrogen Use Efficiency as Affected by Different Nitrogen Rates and Tillage Depth

Muhammad Mughees Ud Din¹, Abdul Wakeel^{1*}

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** abdulwakeel77@gmail.com

Abstract

Meeting the nitrogen (N) requirements of a growing population requires sustainable N management practices that maintain crop yields while minimizing environmental losses. This field study evaluated the effects of different N sources and application rates on wheat productivity, ammonia volatilization, and nitrogen use efficiency, using seven treatments: no N (control), 100%, 75%, and 125% of recommended N as urea, 100% recommended N as animal manure, 100% recommended N as calcium ammonium nitrate (CAN), and 100% recommended N as urea with deep tillage. Grain yield did not differ significantly among the 100%, 75%, 125%, and CAN treatments, but the 125% N treatment showed the highest ammonia volatilization, indicating substantial N losses; the control treatment showed the highest nitrogen utilization efficiency, followed by animal manure and CAN, while nitrogen recovery efficiency was significantly higher under the 75% urea treatment, and animal manure showed lower N recovery efficiency and yield than other treatments except control. These findings indicate that excessive N application increases ammonia emissions and reduces nitrogen use efficiency, and that optimized N management, particularly reduced fertilizer rates under conventional tillage, can sustain wheat productivity while minimizing environmental losses.

Keywords: *Ammonia volatilization; Nitrogen use efficiency; Tillage; Wheat; Nitrogen management*

Checklist of Mosses of District Dir (Upper), Khyber Pakhtunkhwa, Pakistan

Imran Ahmad^{1*}, Waheed Murad¹, Abdul Nasir Khalid², Jan Alam³

1 Department of Botany, Abdul Wali Khan University, Mardan, Pakistan

2 Institute of Botany, University of the Punjab, Quaid-e-Azam Campus, Lahore, Pakistan

3 Department of Botany, Hazara University, Mansehra, Pakistan

***Corresponding author's e-mail:** awkumimran@gmail.com

Abstract

This study presents a preliminary compilation of moss diversity in the Upper Dir District of northern Pakistan, based on extensive recent field surveys and existing literature. A checklist of 60 moss species was compiled, representing 19 families and 35 genera; the most species-rich families were Bryaceae and Pottiaceae (8 species each), followed by Brachytheciaceae (6 species) and Grimmiaceae (5 species), with Fissidens and Grimmia as the dominant genera and *Funaria hygrometrica* and *Grimmia ovalis* as the most prevalent species. Recent taxa were identified through morpho-anatomical and molecular methods. Despite their ecological importance, the phytomedicinal uses and phylogenetic relationships of these bryophytes remain largely unexplored in Pakistan. This checklist highlights the moss diversity of the study area and underscores the region's potential for supporting rich bryophyte growth.

Keywords: Mosses; Bryophyte diversity; Checklist; Dir Upper; Khyber Pakhtunkhwa

Harnessing the Potential of Buckwheat as an Industrial Food Product by Exploring Phytochemical Constituents

Ishtiaq Hussain^{1*}, Tiaba¹, Zia-ur-Rehman Mashwani²

¹ Department of Botany, University of Baltistan, Skardu, Pakistan

² Department of Botany, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

*Corresponding author's e-mail: Ishtiaq.mondooq@uobs.edu.pk

Abstract

Buckwheat is an important food crop with substantial processing and industrial value, containing proteins of high biological value and balanced amino acid composition, relatively high fiber content, and notable phytochemical properties. This study evaluated the phytochemical constituents of four buckwheat varieties grown at PACR, Skardu, comparing native and exotic varieties. Grains, after hull removal, were assessed for total phenolic content (TPC), total flavonoid content (TFC), and ABTS and DPPH radical scavenging activity. TPC ranged from 0.47 to 1.78 $\mu\text{g GAE/mg}$, with the exotic variety Tianxiao Mai (V2) recording the highest value ($1.78 \pm 0.05 \mu\text{g GAE/mg}$) and the local variety Mancan (V1) the lowest ($0.47 \pm 0.05 \mu\text{g GAE/mg}$); TFC was highest in the local variety Ganche (V4, $1.91 \pm 0.01 \mu\text{g GAE/mg}$). ABTS activity ranged from 51.30 to 78.48 $\mu\text{g AAE/mg}$, and free radical scavenging activity ranged from 3.2% to 81.5%, with exotic varieties (Mancan and Tianxiao Mai) generally showing higher antioxidant activity than local Skardu varieties. These findings indicate that buckwheat phytochemicals hold potential for local industrial and medicinal chemistry applications, supporting sustainable food production and highlighting buckwheat as a valuable biological resource for rural mountain populations.

Keywords: Buckwheat; Phytochemical constituents; Total phenolic content; Antioxidant activity; Industrial food products

Mitigating the Impact of Terminal Heat Stress by Foliar Application of Moringa Dried Leaf Extract as a Biostimulant on Kabuli Chickpea

Muhammad Nawaz^{1*}, Sohail Irshad^{2,3}, Adnan Noor Shah¹, Muhammad Moize Ul Haq¹

1 Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

2 Agriculture In-Service Training Institute, Rahim Yar Khan, Pakistan

3 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** dmnnawaz@kfueit.edu.pk

Abstract

Chickpea (*Cicer arietinum* L.) is a significant pulse crop and important dietary protein source, particularly in developing countries such as Pakistan, but its yield is often compromised by biotic and abiotic stress and suboptimal nutrient management. This study assessed the role of moringa dried leaf extract (MDLE) as a natural biostimulant for improving chickpea growth, physiology, and yield, using a randomized complete block design with factorial arrangement and three replications, testing six concentration levels (control, water spray, 0.5%, 1.0%, 1.5%, 2.0% MDLE) applied at vegetative and reproductive growth stages. The 2.0% MDLE treatment produced the maximum root length (12 cm), shoot length (30 cm), and plant height (42 cm) at the vegetative stage, and the highest pod-bearing branch number (9.8) and chlorophyll content (47.2 SPAD) when applied at the reproductive stage, along with improved yield parameters, including pods per plant (52.4), seeds per pod (1.87), 1000-seed weight (275.6 g), biological yield (6 t ha⁻¹), seed yield (2.3 t ha⁻¹), and harvest index (30%), relative to control. Foliar MDLE applications improved growth attributes when applied during the vegetative stage and yield attributes when applied during the reproductive stage, indicating that MDLE can serve as a sustainable, eco-friendly supplement for improving chickpea growth and yield under stress conditions in a changing climate.

Keywords: *Chickpea; Moringa leaf extract; Terminal heat stress; Biostimulants; Growth stage-specific application*

Climate-Resilient Food Systems: Advancing Food Security through Sustainable Nutrition Strategies

Kinza Javed Iqbal^{1*}, M. Issa Khan¹

National Institute of Food Science and Technology, Faculty of Food, Nutrition and Home Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** kinzajaved@uaf.edu.pk

Abstract

Climate change is increasingly affecting how food is produced, distributed, and consumed worldwide; rising temperatures, unpredictable rainfall, prolonged droughts, floods, and other extreme weather events threaten the availability, accessibility, and affordability of nutritious food, particularly for vulnerable populations. Addressing these challenges requires transforming conventional food systems into sustainable, climate-resilient systems that prioritize environmental sustainability, nutritional adequacy, and equitable food access. This review discusses how sustainable nutrition strategies, including climate-smart agriculture, crop diversification, resource-efficient production, reduced post-harvest losses, and promotion of locally available nutrient-rich foods, can strengthen food system resilience while minimizing environmental impact, and how integrating innovative food processing technologies, circular bioeconomy principles, and evidence-based nutrition policy can further enhance food quality, reduce waste, and improve dietary diversity. Strengthening the connections between agriculture, nutrition, and environmental sustainability offers an opportunity to build more resilient, inclusive food systems prepared for future climate challenges, with continued investment in sustainable food innovation, consumer awareness, and resilient agricultural practices identified as pivotal to achieving global sustainability goals.

Keywords: *Climate-resilient food systems; Sustainable nutrition; Climate-smart agriculture; Dietary diversity; Circular bioeconomy*

Climate-Smart Agriculture for Building Resilient Food Systems under Changing Climatic Conditions

Amna Rashid

Institute of Home Sciences and Faculty of Food, Nutrition and Home Sciences, University of Agriculture, Faisalabad, Pakistan

Corresponding author's e-mail: amnarashid090@gmail.com

Abstract

Climate change has become one of the greatest threats to global agriculture and food security, affecting crop productivity, soil fertility, water availability, and biodiversity; rising temperatures, irregular rainfall, and increasingly frequent extreme weather events demand innovative agricultural approaches that enhance resilience while minimizing environmental impact. Climate-smart agriculture (CSA) has emerged as an integrated strategy that simultaneously improves productivity, strengthens climate adaptation, and reduces greenhouse gas emissions. This review examines key principles and recent advances in CSA practices, including conservation agriculture, precision farming, integrated nutrient management, water-efficient irrigation, climate-resilient crop varieties, and digital farm management technologies, alongside the roles of sustainable soil management, renewable energy, and smart decision-support systems in improving agricultural efficiency. Policy interventions, farmer capacity building, and public-private partnerships are identified as critical to successful CSA adoption, particularly in developing countries, with integration of modern technology and traditional agricultural knowledge offering significant opportunities to improve resource-use efficiency while ensuring environmental sustainability. Promoting climate-smart agriculture, supported by continued investment in research, innovation, and knowledge transfer, can strengthen food systems capable of meeting future demand under increasing climatic uncertainty.

Keywords: *Climate-smart agriculture; Food security; Resilient farming; Precision agriculture; Climate adaptation*

From Farm to Future: Innovations in Food Processing, Safety, and Value Addition

Kinza Javed Iqbal^{1*}, M. Issa Khan¹, Maryam Jalal¹, Sara Ishtiaq¹

*National Institute of Food Science and Technology, Faculty of Food, Nutrition and Home Sciences,
University of Agriculture, Faisalabad, Pakistan*

***Corresponding author's e-mail:** kinzajaved@uaf.edu.pk

Abstract

Growing demand for safe, nutritious, and sustainable food has highlighted the need for innovative food processing approaches that improve quality while minimizing losses across the supply chain; food processing has evolved beyond raw material preservation to become a key driver of food safety, nutritional enhancement, value addition, and economic growth. As global food systems face increasing pressure from population growth, shifting consumer preferences, and environmental challenges, adoption of efficient, sustainable processing technologies has become increasingly important. This review examines recent advances enabling production of safer, higher-quality food with extended shelf life while preserving nutritional and sensory characteristics, including non-thermal processing, smart packaging, digital quality monitoring, and resource-efficient manufacturing, which reduce contamination risk, lower energy consumption, and improve product consistency. Value addition through utilization of locally available agricultural commodities and processing by-products offers opportunities to reduce post-harvest losses, diversify food products, and generate additional income, supporting development of functional and convenience foods that meet evolving consumer expectations. Building resilient food systems requires integrating scientific innovation, sustainable processing, effective food safety management, and supportive regulatory frameworks, with strengthened partnerships among researchers, industry, and policymakers needed to accelerate adoption of technologies that improve food quality while supporting environmental sustainability and food and nutrition security.

Keywords: *Food processing innovation; Food safety; Value addition; Non-thermal processing; Smart packaging*

Contribution of Inorganic Soil Carbon to Soil Organic Matter Dynamics

Abdullah Mahmood¹, Muhammad Nadeem Ashraf¹, Muhammad Ashfaq Wahid², Abdul Wakeel¹, Ahmad Mujtaba¹, Muhammad Sanaullah^{1*}

1 Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Agronomy, Faculty of Agriculture, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** msanaullah@uaf.edu.pk

Abstract

Soil organic matter (SOM) is a key determinant of soil health, enhancing soil structure, water retention, nutrient availability, and microbial diversity; its dynamics are influenced by soil texture, microbial activity, land management, and inorganic carbon (IC), primarily present as carbonates and bicarbonates that alter soil biological and chemical properties. This incubation study investigated the influence of IC on SOM dynamics using two soil types (normal and IC-free) with five treatments (control, wheat residue, farmyard manure, wheat biochar, hydrochar) applied at 1 g per 100 g soil in a completely randomized design. Cumulative C-CO₂ emissions and microbial biomass carbon (MBC) were significantly higher in IC-free soil than normal soil, with maximum values under wheat residue and hydrochar treatments, corresponding to reduced soil organic carbon (SOC) in these treatments; SOC was significantly higher with amendments in normal soil, with wheat biochar increasing SOC by 32% relative to IC-free soil. Activities of β -glucosidase, cellobiosidase, and phosphatase were generally higher in IC-free soil, with maximum activity under wheat residue treatment, while soil macro- and meso-aggregates increased with organic amendments in normal soil. These findings indicate that inorganic carbon positively contributes to SOM dynamics, with and without organic amendments, through stabilization mechanisms that can enhance carbon sequestration and soil biological function.

Keywords: *Inorganic carbon; Soil organic matter; Biochar; Hydrochar; Carbon sequestration*

Interactive Effects of Maize Residue Management and Nitrogenous Sources on Soil Carbon and Nitrogen Dynamics

Ahmad Mujtaba¹, Abdul Qadeer², Esha Mujtaba¹, Abdul Wakeel¹, Muhammad Sanaullah^{1*}

¹ Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

² College of Grassland Science, Gansu Agricultural University, Lanzhou, China

*Corresponding author's e-mail: msanaullah@uaf.edu.pk

Abstract

Crop residue management influences soil organic carbon (SOC) and nitrogen dynamics through its effects on microbial access to substrates, with different nitrogen (N) sources potentially altering microbial community activity during residue decomposition. This incubation study examined the interactive effects of three N sources, urea (NH₄-N), calcium nitrate (NO₃-N), and ammonium nitrate (both NH₄- and NO₃-N), combined with maize residue applied as mulch or incorporated (10 g kg⁻¹ soil), on soil microbial activity. Under mulching with no N, C-CO₂ emissions were modestly higher with urea, calcium nitrate, and ammonium nitrate addition (26.8%, 20.8%, and 12.1%, respectively), while N-nitrous oxide emissions increased by 70.01%, 40.47%, and 50.63%; under incorporation, both cumulative CO₂ and nitrous oxide emissions were significantly increased by ammonium nitrate relative to other sources. Cumulative NH₃ volatilization was significantly higher with urea than other N sources under both management methods, and SOC was higher under mulching regardless of N source. Microbial biomass and dissolved organic carbon decreased with urea but increased under incorporation with nitrate sources, while metabolic quotient and soil pH decreased with nitrate sources under both residue management methods; β-glucosidase activity increased significantly with mulching (26.23% and 18.91%) and incorporation (29.24% and 21.91%) under urea and ammonium nitrate, respectively, while acid phosphatase and leucine aminopeptidase activities increased with ammonium nitrate. These findings indicate that combining inorganic N sources with residue mulching reduces microbial activity relative to residue addition alone, thereby lowering associated greenhouse gas emissions.

Keywords: Crop residue management; Nitrogen sources; Soil microbial activity; Extracellular enzymes; Greenhouse gas emissions

Contribution of Nitrogenous Sources to Carbon Mineralization and Soil Health

Ahmad Mujtaba¹, Abdul Wakeel¹, Muhammad Sanaullah^{1*}

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

***Corresponding author's e-mail:** msanaullah@uaf.edu.pk

Abstract

Non-judicious use of nitrogen (N) fertilizers in agricultural soils increases environmental pollution, greenhouse gas emissions, and ammonia volatilization; N sources undergo biological and chemical transformations that can positively or negatively affect soil organic carbon (SOC) dynamics and soil health. This incubation study evaluated the impact of three N sources, urea (NH₄-N), calcium nitrate (NO₃-N), and ammonium nitrate (NH₄- and NO₃-N), plus an unamended control, on carbon mineralization, soil health, and ammonia volatilization in alkaline calcareous soil. Urea addition produced the highest C-CO₂ emissions and NH₃ volatilization among treatments; microbial biomass carbon and metabolic quotient increased with all N sources, with significantly higher values under urea (327.76 mg C kg⁻¹ soil and 0.32, respectively). SOC decreased and β-glucosidase activity increased with NH₄-N sources, while acid phosphatase and leucine aminopeptidase activity increased significantly with ammonium nitrate, though chitinase activity did not follow this pattern. These findings indicate that adding inorganic NH₄-N sources to alkaline calcareous soils results in higher CO₂ emissions and NH₃ volatilization due to elevated microbial activity, suggesting that N source selection should account for its contribution to greenhouse gas emissions, carbon mineralization, and soil health, particularly in low-SOC alkaline calcareous soils.

Keywords: *Nitrogen sources; Carbon mineralization; Ammonia volatilization; Soil organic carbon; Alkaline calcareous soil*

Environmental Impact of Plant-Based versus Animal-Based Diets: A Review of Sustainable Food Systems

Hira Arshad^{1*}, Abeera Moin²

1 Program of Food Science and Technology, Department of Biomedical Engineering, Sir Syed University of Engineering and Technology, Karachi, Pakistan

2 Department of Food Science and Technology, University of Karachi, Karachi, Pakistan

***Corresponding author's e-mail:** hira.arshad@ssuet.edu.pk

Abstract

A global transition toward sustainable diets is increasingly being encouraged in response to rapid population growth, urbanization, and rising demand for resource-intensive foods, with plant-based diets gaining consideration as a sustainable alternative to conventional animal-based food systems given their co-benefits for human health and environmental sustainability. Food production is a major contributor to climate change, resource depletion, and ecological degradation, with dietary patterns playing a significant role in shaping this environmental footprint. This review examines existing literature comparing the environmental footprints of plant-based and animal-based diets across key indicators, including greenhouse gas emissions, water use, land use, and energy consumption. Evidence indicates that plant-based diets are associated with significantly lower environmental impacts, particularly reduced carbon emissions and resource use, whereas livestock production contributes substantially to global greenhouse gas emissions and requires extensive land and water resources. These findings highlight the potential of plant-based dietary patterns to support sustainable food systems and mitigate environmental challenges, positioning the promotion of plant-based food choices as a contributor to global sustainability goals and long-term food security.

Keywords: *Plant-based diet; Environmental impact; Greenhouse gas emissions; Sustainable food systems; Dietary patterns*

Optimizing Sowing Geometries for Improved Weed Management in Wheat Intercropping Systems

Muhammad Bahram Khan, Muhammad Maaz, Mubshar Hussain*

Institute of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mubashir.hussain@bzu.edu.pk

Abstract

Effective, non-chemical weed management is central to climate-smart, sustainable wheat production, particularly given growing environmental and resistance concerns associated with herbicide reliance. This two-year field study (2023–24 and 2024–25) evaluated five wheat-based cropping systems, sole wheat, sole chickpea, sole canola, wheat-chickpea intercrop, and wheat-canola intercrop, sown at four row geometries (1:1, 2:1, 4:2, 6:2), for their effect on the density of sixteen winter (Rabi) weed species, using a randomized complete block design with three replications and analysis by ANOVA and LSD test ($p \leq 0.05$). Cropping system significantly influenced the density of all sixteen weed species in both years ($p \leq 0.01$), and row geometry was significant for nearly every species. Wheat intercropped with canola consistently suppressed pooled weed density relative to sole wheat, by 28% in year one and 50% in year two, whereas wheat intercropped with chickpea increased pooled weed density by 10–16%, reflecting chickpea's weaker early competitive ability; narrowing row geometry from 1:1 to the wheat-dominant 6:2 arrangement reduced pooled weed density by up to 54%, although eleven of sixteen species reached peak second-year density at the intermediate 2:1 ratio, indicating species-specific responses. Dry biomass at 60 days after sowing was greatest under the narrower 6:2 and 4:2 geometries across all three crops, exceeding the respective sole crops by up to 73% in canola. These findings identify wheat-canola intercropping at narrow, wheat-dominant row geometries as an effective, low-input tool for integrated weed management, whereas wheat-chickpea intercropping cannot be relied upon for weed suppression without supplementary control measures.

Keywords: *Intercropping; Row geometry; Weed density; Integrated weed management; Climate-smart agriculture*

Residual Effects of Rabi Intercropping Systems on the Productivity of Succeeding Kharif Crops: A Pathway to Climate-Resilient Cropping Sequences

Hamna Taj, Muhammad Bahram Khan, Muhammad Maaz, Rubeena Abdul Rehman, Mubshar Hussain*

Institute of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mubashir.hussain@bzu.edu.pk

Abstract

Sustainable intensification of cropping systems is central to building climate-resilient food systems in semi-arid South Asia, yet the cross-seasonal, residual effects of Rabi (winter) intercropping on succeeding Kharif (summer) crops remain poorly understood. This study evaluated how wheat, chickpea, and canola, grown as sole crops or as wheat-chickpea and wheat-canola intercrops, influenced the growth, yield, and physiological performance of subsequent maize, pearl millet, and mungbean, using field and pot experiments conducted at Bahauddin Zakariya University, Multan, across the 2024–25 Rabi and 2025 Kharif seasons in a Randomized Complete Block Design with three replications. Wheat-chickpea intercropping outperformed sole wheat and wheat-canola in plant height, 1000-grain weight, and chlorophyll content, and this advantage carried into the Kharif season: plots with prior sole chickpea or wheat-chickpea residue consistently produced the highest yields in pearl millet, maize, and mungbean, while sole canola residue performed poorest, with a consistent ranking of sole chickpea > wheat-chickpea > sole wheat > wheat-canola > sole canola across both field and pot trials. These findings demonstrate that legume-based residues enhance soil fertility and nitrogen availability, offering a practical, low-input strategy for improving resource use efficiency and yield stability across cropping seasons, and support integrating chickpea, sole or intercropped, into Rabi systems as part of climate-smart cereal-legume sequences suited to South Asia's changing climate.

Keywords: *Residual effects; Intercropping; Cropping sequence; Soil fertility; Climate-smart agriculture*

Optimizing Wheat Productivity in Semi-Arid Regions through Synthetic and Natural Plant Growth Regulators: A Comparative Study

Muhammad Maaz, Muhammad Bahram Khan, Rabeeyah Murriem, Mubshar Hussain*

Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mubashir.hussain@bzu.edu.pk

Abstract

Wheat (*Triticum aestivum* L.) is Pakistan's most important staple crop, providing daily calories to more than half the population, but productivity remains constrained by climatic variability and declining soil fertility in South Punjab; plant growth regulators (PGRs) offer a potential means of alleviating these constraints. This field study evaluated six foliar treatments, sole sorghum water extract (Sorgaab), sole 6-benzylaminopurine (BAP), sole moringa leaf extract (Sanji), their combinations (BAP + Sorgaab and BAP + moringa leaf extract), and a tap-water control, applied at tillering and booting stages, using a randomized complete block design with three replications. Both sole and combined applications of natural and synthetic PGRs enhanced wheat yield relative to control, with combined applications proving more effective; the combined foliar application of BAP + Sorgaab outperformed BAP + moringa leaf extract, producing significant increases in wheat yield and related traits. These findings indicate that integrating natural and synthetic PGRs offers a practical, efficient approach for improving wheat yield in semi-arid production systems.

Keywords: *Wheat productivity; Plant growth regulators; Foliar application; Sorghum water extract; 6-Benzylaminopurine*

Vermicompost-Derived Biochar Outperforms Pristine Vermicompost in Fostering Soil Health and Rice Growth under Paddy Settings

Hamna Bashir¹, Muhammad Mahroz Hussain^{2*}

¹ Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

² College of Environmental Science and Engineering, Yangzhou University, Yangzhou, China

*Corresponding author's e-mail: hmahroz@gmail.com

Abstract

Cadmium (Cd) contamination in paddy soils poses a dual challenge to food safety and climate resilience, undermining rice productivity while influencing greenhouse gas (GHG) emissions; the comparative efficacy of pristine vermicompost (VC) versus vermicompost-derived biochar (VC-BC) in regulating Cd dynamics, soil health, and GHG emissions remains unclear. This study compared VC and VC-BC effects on Cd translocation and bioaccumulation in rice, rice growth, soil carbon fractions, and methane and nitrous oxide emissions across rice growth stages. Both amendments enhanced microbial biomass carbon and dissolved organic carbon, but VC-BC showed superior Cd immobilization, reducing grain Cd concentration by 78.4% compared with 61.6% for VC; unlike VC, which increased Cd bioaccumulation factors, VC-BC reduced Cd uptake while enhancing chlorophyll content, antioxidant defenses, and plant vigor, with its porous structure and hydroxyl, carboxylate, amide, and aromatic functional groups supporting enhanced Cd immobilization. VC-BC reduced methane emissions by 16%, 26%, and 67% during transplanting, tillering, and harvesting, respectively, relative to VC, and reduced nitrous oxide emissions during transplanting and harvesting by 19% and 66%, though nitrous oxide emissions increased by 20% during tillering. These findings position VC-BC as a climate-smart, multifunctional amendment that immobilizes cadmium, sustains soil biochemical health, and mitigates environmental trade-offs in rice production systems.

Keywords: *Vermicompost biochar; Cadmium immobilization; Rice; Greenhouse gas emissions; Antioxidant defense*

Integrating Geochemical Fractionation and Machine-Learning Insights to Predict Chromium Immobilization and CO₂ Dynamics in Contaminated Paddy Soils

Muhammad Mahroz Hussain¹, Muhammad Junaid Nazir^{2*}, Abdul Qadeer³

¹ College of Environmental Science and Engineering, Yangzhou University, Yangzhou, China

² Shenzhen Key Laboratory of Ecological Remediation and Carbon Sequestration, Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, China

³ College of Agronomy, Shandong Agricultural University, Taian, Shandong, China

*Corresponding author's e-mail: muhammadjunaid529@gmail.com

Abstract

Escalating climate change impacts, driven by rising CO₂ emissions, pose a significant threat to soil health and biogeochemical cycle stability, particularly the chromium (Cr) cycle. This study evaluated the efficacy of organic and mineral soil ameliorants in mitigating Cr contamination, examining effects on Cr availability, speciation, and soil biochemical health under reduced conditions and CO₂-C efflux, using machine learning models to characterize complex interdependencies. Organic amendments, particularly cow dung, were markedly more effective than sedimentary minerals, achieving 53–82% reduction in total Cr concentration compared with 30–64% for minerals, while also curtailing CO₂-C efflux (1,190 mg kg⁻¹ C soil) and lowering the specific mineralization rate (1.4 mg CO₂-C g⁻¹ MBC day⁻¹) and metabolic quotient, indicating improved microbial carbon-use efficiency. Integrated multivariate and Random Forest analyses identified soil enzymes and soil organic carbon as the most critical predictors of remediation success; cow dung application achieved an 85.67% reduction in toxic Cr(VI) through a synergistic enzyme-microbe complex that directly drove detoxification ($\beta = -0.38$) and enhanced Cr immobilization ($\beta = -0.76$, $p < 0.001$), lowering Cr bioavailability while improving plant tolerance through reduced oxidative stress and enhanced nutrient cycling. These findings indicate that organic ameliorants offer a more holistic, sustainable remediation strategy that sequesters carbon while immobilizing heavy metals, with relevance to multiple UN Sustainable Development Goals spanning food security, health, climate action, and terrestrial ecosystem restoration.

Keywords: *Chromium immobilization; Machine learning; Soil biochemical health; CO₂ efflux; Random Forest*

Tillage-Driven Efficacy of Engineered Fe/Zn-Humic Complexes in Mitigating Lead Toxicity and Enhancing Soil Biochemical Function

Shengsen Wang¹, Liqing Wei¹, Lingwei Zhang¹, Muhammad Tahir Shehzad², Muhammad Ashir Hameed², Hamna Bashir², Qasim Ali³, Muhammad Zafar Hashmi⁴, Muhammad Mahroz Hussain^{1*}

1 College of Environmental Science and Engineering, Yangzhou University, Yangzhou, China

2 Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

3 Department of Soil Science, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

4 Department of Environmental Health and Management, Health Services Academy, Islamabad, Pakistan

***Corresponding author's e-mail:** 008785@yzu.edu.cn

Abstract

Remediation of lead (Pb)-contaminated agricultural soils using engineered humic substances remains underexplored, particularly regarding interactive effects with tillage practices on soil carbon dynamics, enzymatic health, and crop productivity. This study evaluated the efficacy of Fe- and Zn-enriched humate complexes in immobilizing Pb, altering its geochemical fractionation, and reducing translocation to spinach (*Spinacia oleracea*) grown under tillage and no-tillage systems, assessing effects on soil organic carbon distribution, microbial activity, and CO₂-C efflux via closed-chamber incubation, with Partial Least Squares Path Modeling used to disentangle direct and indirect treatment effects. Fe-humate achieved superior Pb immobilization, reducing soil Pb by 72% under tillage and 33% under no-tillage, compared with 48% and 35% reductions for Zn-humate; soil carbon distribution showed contrasting trends between tillage regimes, with tilled soils favoring carbon mineralization and no-till systems favoring carbon retention. Both Fe- and Zn-humate complexes significantly stimulated extracellular enzyme activities, including dehydrogenase, urease, and β -glucosidase, under both management systems, indicating improved microbial nutrient cycling and stress resilience. Human health risk assessment showed a three-fold reduction in Pb-associated non-carcinogenic risk with Fe-humate application, versus a two-fold reduction with Zn-humate. Overall, tillage-driven application of Fe/Zn-humate complexes enhanced spinach biomass, reduced Pb bioavailability and translocation to edible tissue, and improved soil biochemical health, positioning metal-humate synergies as a sustainable, context-specific strategy for remediating contaminated farmland while supporting climate-smart agriculture.

Keywords: *Geochemical fractionation; Lead immobilization; Tillage practices; Soil carbon dynamics; Humate complexes*

Application of Green-Synthesized Iron Oxide Nanoparticles through Seed Priming Enhances Grain Yield and Nutritional Quality of Chickpea (*Cicer arietinum*)

Sohaib Abbas, Abdul Rehman*

Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

*Corresponding author's e-mail: a.rehman@iub.edu.pk

Abstract

Iron (Fe) plays an essential role in plant growth, and its deficiency represents a major micronutrient disorder in chickpea (*Cicer arietinum* L.); chickpea is inherently low in Fe, and chickpea-based diets can contribute to Fe deficiency in humans, one of the most widespread global micronutrient disorders. This study evaluated the effects of green-synthesized iron oxide nanoparticles (FeO-NPs), produced using *Moringa oleifera* leaf extract, applied via seed priming at 25, 50, 75, and 100 mg/L, on chickpea yield and grain Fe biofortification, with hydro-primed and dry (untreated) seeds as controls. FeO-NP seed priming improved yield-related attributes, grain yield, and grain Fe content relative to control: the highest final emergence count, plant height, and pods per plant were observed at 75 mg/L, which also produced the highest grain weight, biological yield, and grain yield (1.52 t ha⁻¹), representing a substantial increase over control; higher concentrations (100 mg/L) did not further improve yield and showed marginal declines in some traits, suggesting possible nanoparticle toxicity at excessive levels. FeO-NP priming markedly improved grain ash and moisture content, with the highest grain Fe concentration recorded in variety BWP-21 under 100 mg/L treatment. These findings indicate that moderate FeO-NP seed priming (75 mg/L) optimizes chickpea growth, yield, and grain Fe enrichment, supporting its potential as a sustainable nanonutrient strategy for yield enhancement and biofortification in pulse crops.

Keywords: Chickpea; Iron oxide nanoparticles; Green synthesis; Seed priming; Biofortification

Bioactive Edible Coatings for Reducing Postharvest Loss and Enhancing Sustainable Food Security in Arid Regions

Sadaf Javaria

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan

Corresponding author's e-mail: sadafjavaria@gu.edu.pk

Abstract

Postharvest food loss of fresh horticultural commodities is a major challenge to food security, particularly in arid regions where high temperatures, low humidity, limited cold-chain infrastructure, and extended transportation accelerate moisture loss, microbial decay, senescence, and nutritional deterioration. Bioactive edible coatings offer a promising low-energy, biodegradable strategy for mitigating these losses by creating selective barriers to moisture and gas transfer while delivering antimicrobial and antioxidant functionality, though their potential as an integrated food security intervention under harsh climatic and supply-chain conditions remains insufficiently explored. This study proposes development of multifunctional edible coatings using food-grade biopolymer matrices enriched with naturally derived antimicrobial and antioxidant compounds, with formulations optimized for barrier, mechanical, physicochemical, and functional properties before application to selected high-value fruits and vegetables and evaluation under storage conditions representative of arid-region supply chains, assessing weight loss, firmness, color, total soluble solids, titratable acidity, respiration, bioactive retention, antioxidant capacity, microbial load, decay incidence, sensory quality, and marketable shelf life, with multivariate analysis used to relate coating characteristics to physiological and quality outcomes. The anticipated outcome is a scalable, biodegradable preservation platform capable of extending shelf life and reducing postharvest losses while minimizing dependence on energy-intensive refrigeration and synthetic packaging, positioning edible coating as a multifunctional technology linking postharvest innovation, circularity, climate resilience, and sustainable food security.

Keywords: *Edible coatings; Postharvest loss; Food security; Arid regions; Bioactive packaging*

Pakistan as a Compound Risk Food Security Case: Interactions of Climate Shocks, Economic Instability, and Nutritional Insecurity

Muhammad Saqib Ullah Khan

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan

Corresponding author's e-mail: saqibkhan@gu.edu.pk

Abstract

Food security in Pakistan is a multifaceted issue shaped by an interacting web of environmental, economic, and social risks rather than any single factor. Climate-related events, such as frequent floods and droughts, disrupt agricultural output and food supply chains, while concurrent economic pressures, including inflation and rising food costs, diminish household purchasing power and access to nutritious food. Recent estimates indicate that roughly 40% of Pakistan's population faces some degree of food insecurity: although the country produces sufficient staple food, many households lack access to a balanced, affordable diet, with FAO estimates placing undernourishment at approximately 19% of the population and moderate-to-severe food insecurity affecting more than 40%, driven primarily by poverty, market volatility, and climate impacts. The situation is particularly acute for children, with global nutrition assessments indicating that approximately 37–40% of children under five are stunted and around 18% experience acute malnutrition, reflecting longstanding gaps in dietary sufficiency and access to health services. These findings indicate that Pakistan's food security crisis stems from a complex interplay of climate, economic, and nutritional factors rather than a single cause, underscoring the need for integrated policies that enhance climate resilience, strengthen economic stability, and expand nutrition-specific social protection.

Keywords: *Food security; Compound risk; Climate change; Malnutrition; Economic instability*

Utilization of Bitter Gourd (*Momordica charantia*) Peel for the Formulation of a Functional Herbal Tea

Gul Kainat, Dur-e-Shahwar Sattar*

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: dsattar@bzu.edu.pk

Abstract

Vegetable waste is a growing global environmental and economic concern, with peels often discarded during processing despite retaining nutritional and functional value. This study aimed to valorize bitter gourd (*Momordica charantia*) peel waste by developing functional herbal tea formulations with improved sensory acceptability and antioxidant properties. Fresh bitter gourd and lemon peels were manually separated, washed, sun-dried, and ground; six formulations combining bitter gourd peel powder with lemon peel powder, cinnamon, and cardamom, intended to mask bitterness and enhance flavor, were prepared as tea bags and evaluated for sensory attributes (9-point hedonic scale), color (L^* , a^* , b^*), and functional properties (total phenolic content, total flavonoid content, DPPH radical scavenging activity, ferric reducing antioxidant power). Formulations combining lemon peel powder with cinnamon or cardamom showed better flavor, aroma, and overall acceptability than bitter gourd peel powder alone; the formulation combining bitter gourd peel, lemon peel, and cinnamon powder showed the highest bioactive potential, with total phenolic content of 61.85 ± 1.36 mg GAE/g, total flavonoid content of 40.76 ± 1.18 mg QE/g, DPPH inhibition of $75.34 \pm 1.41\%$, and FRAP value of 512.74 ± 7.16 $\mu\text{mol Fe}^{2+}$ /g, alongside the highest sensory acceptability due to its balanced flavor and aroma. These findings demonstrate that bitter gourd peel waste can be effectively repurposed into a value-added functional herbal tea with strong antioxidant potential and good sensory quality, supporting sustainable waste valorization in functional food product development.

Keywords: Bitter gourd peel; Herbal tea; Waste valorization; Antioxidant activity; Sensory evaluation

Optimization of Buckwheat Flour Incorporation and Zinc Nanoparticle Levels for Functional Bread Production

Farah Bano, Dur-e-Shahwar Sattar*

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: dsattar@bzu.edu.pk

Abstract

Cereal grains are widely consumed but are inherently deficient in lysine, an essential amino acid that limits their protein quality; buckwheat, naturally rich in lysine, offers a valuable nutritional complement well suited to combination with cereal-based staples such as bread. Beyond its amino acid profile, buckwheat and its processing by-products, particularly the husk, contain substantial minerals, insoluble dietary fiber (approximately 31% as non-starch polysaccharides), and beneficial phenolic compounds, with composition varying by variety and processing method. Given that zinc deficiency remains a significant public health concern and food fortification offers an effective population-level intervention, this study explores development of zinc-fortified bread using buckwheat flour as a functional base, hypothesizing that buckwheat's mineral content, antioxidant phenolic compounds, and high-quality protein and bioactive peptides may generate nutritional synergy, enhancing both macronutrient and micronutrient profiles of the final product, while its phenolic compounds may further influence mineral metabolism and contribute additional antioxidant benefits beyond zinc fortification alone. Zinc-fortified buckwheat bread is proposed as a promising strategy for producing a nutritionally enhanced staple food combining improved protein quality, mineral density, and bioactive compound content in a single product.

Keywords: *Buckwheat; Zinc fortification; Lysine; Dietary fiber; Functional bread*

Influence of Germination and Fermentation on Nutritional and Functional Properties of Quinoa Flour

Ammar Ali¹, Dur-e-Shahwar Sattar^{1*}

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** dsattar@bzu.edu.pk

Abstract

Quinoa (*Chenopodium quinoa* Willd.) is a highly nutritious, gluten-free pseudo-cereal valued for its healthy fats, dietary fiber, high-quality protein, essential amino acids (notably lysine and methionine, often limited in cereals), vitamins, minerals, and bioactive compounds, though its nutritional value is partly limited by anti-nutritional compounds such as phytates, tannins, saponins, and enzyme inhibitors. This study evaluated the effects of germination and fermentation, natural, economical bioprocessing methods, on the nutritional and functional properties of quinoa flour, comparing raw, soaked-control, germinated (24, 48, 72 h), and *Lactobacillus plantarum*-fermented seed treatments, with proximate composition, functional properties (water and oil absorption capacity, bulk density), pH, and color assessed in triplicate by one-way ANOVA. Germination percentage and radicle length increased progressively with germination time, peaking at 72 h, alongside greater metabolic and enzymatic activity; both germination and fermentation increased protein, crude fiber, and ash content, and water and oil absorption capacities, while reducing fat content, bulk density, and anti-nutritional factors, attributed to protein and starch structural changes, mineral release, and metabolic consumption of lipids and carbohydrates during processing. These findings indicate strong potential for bioprocessed quinoa flour in bakery, gluten-free, and protein-enriched food products, offering a low-cost, accessible processing route for developing countries and small-scale food industries.

Keywords: *Quinoa flour; Germination; Fermentation; Anti-nutritional factors; Functional properties*

Innovative Development of Zinc Nanoparticle-Fortified Oat Bread with Enhanced Nutritional and Storage Stability

Hafsa Amir Rafiq¹, Mehak Majid¹, Dur-e-Shahwar Sattar^{1*}

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** dsattar@bzu.edu.pk

Abstract

Zinc deficiency remains a significant public health problem, particularly in developing countries, contributing to impaired immunity, delayed growth, and increased infection risk. This study developed a zinc-enriched functional bread by incorporating zinc oxide nanoparticles (ZnO-NPs) into oat flour, selected for its high dietary fiber and β -glucan content, evaluating physicochemical, nutritional, microbiological, sensory, and storage properties across five treatments (control and 20, 40, 60, 80 mg/kg ZnO-NPs) using a Completely Randomized Design with ANOVA and Duncan's Multiple Range Test. Increasing ZnO-NP concentration significantly raised moisture, ash, and zinc content, confirming successful fortification, while pH declined more favorably in fortified samples, indicating improved microbial stability; loaf volume and crumb softness improved with fortification, likely reflecting enhanced gas-holding capacity and β -glucan-mediated moisture retention, while color analysis showed decreased lightness and increased redness/yellowness at higher ZnO-NP levels. Fortified breads showed significantly lower microbial counts than controls, with the 80 mg/kg treatment showing the strongest antimicrobial effect, attributed to cell membrane disruption and reactive oxygen species generation. Sensory evaluation identified the 60 mg/kg treatment as optimal, balancing nutritional enhancement, storage stability, and consumer acceptability, supporting ZnO-NP-fortified oat bread as a promising functional food strategy for addressing zinc deficiency.

Keywords: *Zinc oxide nanoparticles; Oat bread; Food fortification; Antimicrobial activity; Storage stability*

Development and Evaluation of a Natural Preservative Spray for Fresh Fruits and Vegetables

Aneeqa Ijaz

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan

Corresponding author's e-mail: aneeqaijaz205@gmail.com

Abstract

Fresh fruits and vegetables are highly perishable, susceptible to microbial growth, oxidation, enzymatic reactions, moisture loss, and other quality deterioration during storage; natural preservation methods offer a safe, sustainable approach for reducing post-harvest losses. This study developed and evaluated a natural preservative spray formulated using aloe vera gel, distilled water, fresh lemon juice, green tea extract, cinnamon extract, clove extract, rosemary extract, clove oil, and lemongrass oil, selected for their antioxidant and antimicrobial properties. The formulation was applied to apples, banana, guava, and mango, with treated and untreated samples compared to a 7-day storage period for visible appearance, color, texture, odor, and spoilage indicators. The developed spray was intended to protect against quality deterioration and maintain freshness during storage, suggesting potential as a simple, economical, eco-friendly approach for reducing post-harvest deterioration of fresh produce.

Keywords: *Natural preservative; Shelf life; Aloe vera; Post-harvest quality; Fresh produce*

A Comparative Analysis of Yield through Soil Management between Medium and Large Farmers: A Systematic Investigation of Food Sustainability under Climate Change

Husnain Niazi

Tara Group, Pakistan

Corresponding author's e-mail: h.niazi.fmc@gmail.com

Abstract

Rapid population growth is placing immense pressure on food production systems, requiring sustainable approaches to guarantee food security amid ongoing climate change. This study examines differences in yield between medium and large farmers with a focus on soil management practices, aiming to determine how these practices differ between farmer groups and their effects on crop yield, and to identify the most effective soil management methods for sustainable food production. Drawing on farmer statements and a comparative evaluation of yield outcomes, the study finds that timely implementation of soil management techniques, accounting for climate and weather conditions, is more effective in improving crop yield than increased spending alone, and that farmers differ significantly in the specific soil management methods applied. These findings suggest that well-timed, climate-informed soil management practices can meaningfully improve rice production across different farm scales.

Keywords: *Soil management; Food sustainability; Climate change; Farm scale comparison; Rice production*

Combined Effects of Sowing Time and Cutting Interval on Forage Production, Grain Yield, and Nutritional Value of Dual-Purpose Wheat

Muhammad Yahya, Muhammad Bahram Khan, Abdul Majeed, Abubakar Sufyan, Mubshar Hussain*

Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: mubashir.hussain@bzu.edu.pk

Abstract

Dual-purpose wheat can support mixed crop-livestock systems by providing both early-season forage and grain at maturity, but the balance between forage removal and final grain production depends strongly on sowing time and cutting management. This two-year field study (2022–23 and 2023–24) evaluated the interactive effects of three sowing dates (31 October, 15 November, 30 November) and cutting interval (no cut, cutting at 45 days after sowing, cutting at 60 days after sowing) on phenology, agronomic performance, yield, and nutritional quality. Sowing date primarily influenced early vegetative development, particularly emergence and tillering, while cutting management became more influential from jointing onward; cutting at 60 days after sowing delayed reproductive development and increased growing degree day requirements, most clearly under the earliest sowing date. The no-cut treatment combined with the 15 November sowing date produced the best plant growth, grain yield, yield components, and grain nutritional quality, while cutting at 60 days after sowing produced the highest fodder yield but reduced grain yield; fodder from 60-day cuts had higher fiber and lignin content, while grain from the 15 November no-cut treatment had the highest protein, zinc, and iron content. These findings indicate that the 15 November sowing date combined with cutting at 45 days after sowing offers the most efficient balance of forage yield, grain productivity, and nutritional quality in dual-purpose wheat systems.

Keywords: *Dual-purpose wheat; Sowing date; Cutting interval; Forage production; Grain quality*

Integrating UAV Imagery, Satellite Data, and Field Observations for Wheat Phenology Assessment

Adnan Zahid*, Sajid Ali, Muhammad Bilal Chattha, Brira Hareem

Department of Agronomy, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan

*Corresponding author's e-mail: adnan.iags@pu.edu.pk

Abstract

Non-destructive, high-efficiency crop monitoring across wide regions is critical for precision agriculture, plant phenotyping, and food security decision-making. This study used satellite and unmanned aerial vehicle (UAV) data fusion to evaluate the potential of combining canopy spectral information with structural parameters for crop monitoring, integrating RGB-UAV imagery, Sentinel-2 satellite data, and ground-based physiological measurements to monitor wheat phenology at the University of the Punjab, Lahore. The booting stage showed the highest canopy vigor and relative water content (95.31%), while grain filling revealed divergence between stable visible-band indices (GRVI, VARI) and declining NDVI and relative water content (57.14%). At physiological maturity, GRVI showed a marked sign change associated with a 76% decline in chlorophyll, whereas NDVI increased atypically and proved less reliable for detecting senescence; leaf area index showed the strongest correlation with spectral indices ($r = 0.92\text{--}0.94$). These findings indicate that RGB-UAV imagery provides a low-cost tool for wheat monitoring, and that divergence between NDVI and visible-band indices may improve senescence detection in irrigated wheat systems of Punjab and similar regions of South Asia.

Keywords: Precision agriculture; UAV imagery; Satellite imagery; Canopy vigor; Wheat phenology

Phytochemical Profiling of *Lepidium sativum* for Functional Food Applications

Maham Shahid, Fatima Amjad, Iqbal Firidi, M. Farhan J. Chughtai, Hina Rasheed, Ayesha Siddiqua*

Institute of Food Science and Technology, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

*Corresponding author's e-mail: ayesha.siddiqua@kfueit.edu.pk

Abstract

Lepidium sativum, commonly known as garden cress or haleem seed, is an underutilized edible plant of the Brassicaceae family, traditionally consumed in South Asia and the Middle East for its high nutritional value and bioactive content; the seeds contain 19–25% protein, 8–12% dietary fiber, and 8–30% essential fatty acids, along with tocopherols, phytosterols, and diverse secondary metabolites. This review examines the phytochemical profile of *L. sativum*, including phenolic acids (gallic acid, caffeic acid, sinapic acid), flavonoids (quercetin), glucosinolates, alkaloids, and tannins, which contribute to its antioxidant, antimicrobial, anti-inflammatory, and hypoglycemic activity and support its potential as a functional food ingredient for addressing micronutrient deficiencies in iron, zinc, calcium, protein, and dietary fiber. Phytochemical characterization can be performed through qualitative screening and quantitative determination of total phenolic and flavonoid content, with antioxidant potential assessed via DPPH, ABTS, reducing power, hydroxyl radical, and FRAP assays, and individual compounds characterized using HPLC, LC-MS, and GC-MS; processing factors such as germination, salt treatment, and cooking can influence the nutritional and phytochemical profile of *L. sativum* sprouts. The review identifies applications for *L. sativum* in functional foods, beverages, bakery products, and nutrition bars, while recommending further research to establish standardized processing methods and assess safety, bioavailability, and bioaccessibility for food and pharmaceutical applications.

Keywords: *Lepidium sativum*; Phytochemical profiling; Bioactive compounds; Functional food; Antioxidant activity

Bitter Apple (*Citrullus colocynthis*) as a Natural Preservative against Microbial and Oxidative Activity

Atif Liaqat, Rabia Iqbal*, Shazia Saeed, Adnan Khaliq, M. Farhan Jahangir Chughtai

Institute of Food Science and Technology, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

*Corresponding author's e-mail: rabia.iqbal@kfueit.edu.pk

Abstract

Growing consumer demand for clean-label foods has encouraged replacement of synthetic preservatives with nature-based alternatives. Bitter apple (*Citrullus colocynthis*), noted for its medicinal properties, is rich in bioactive compounds with antimicrobial and antioxidant activity. This study examined extracts from different parts of *C. colocynthis* (seeds, peel, pulp), prepared using 80% methanol, 80% ethanol, and distilled water via conventional solvent extraction, maceration, and ultrasonication, and evaluated for total phenolic and flavonoid content, antioxidant activity (DPPH, ABTS), and antimicrobial activity against selected foodborne microorganisms using agar well diffusion and minimum inhibitory concentration testing. Extracts differed significantly ($P \leq 0.05$) in phytochemical composition and bioactivity: methanolic seed extract showed the highest total phenolic content (86.35 ± 2.22 mg GAE/g) and strongest antioxidant activity ($88.68 \pm 1.77\%$ DPPH scavenging at $400 \mu\text{g/mL}$), followed by ethanolic peel extract ($83.47 \pm 1.65\%$). The methanolic seed extract also produced the largest inhibition zones against *Staphylococcus aureus* (24.7 ± 0.7 mm), *Escherichia coli* (21.3 ± 0.3 mm), and *Salmonella Typhimurium* (20.4 ± 0.7 mm), while aqueous extracts showed comparatively lower antimicrobial and antioxidant activity; bioactivity correlated positively with phenolic and flavonoid content across extracts. These findings indicate that *C. colocynthis*, particularly its methanolic seed extract, contains bioactive compounds capable of inhibiting microbial growth and oxidative degradation, suggesting potential as a natural alternative to synthetic food preservatives, pending further evaluation of food-system application, safety, and sensory implications.

Keywords: *Citrullus colocynthis*; Natural preservatives; Antimicrobial activity; Antioxidant activity; Phenolic compounds

Gut Microbiota-Diet-Immune Axis: Emerging Insights into Metabolic Health

Rabia Iqbal*, Atif Liaqat, Samreen Ahsan, M. Farhan Jahangir Chughtai, Amna Khan, Arooba Zafar, Amna Zulfiqar

Institute of Food Science and Technology, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

*Corresponding author's e-mail: rabia.iqbal@kfueit.edu.pk

Abstract

The gut microbiome is increasingly recognized as a dynamic biological interface linking dietary exposures with host physiology, influencing both metabolic homeostasis and immune regulation. Through a complex network of microbial metabolites and signaling pathways, the gut microbial ecosystem transforms dietary components, particularly fiber, protein, fat, and ultra-processed foods, into beneficial metabolites such as tryptophan derivatives, bile acid derivatives, and short-chain fatty acids, which act as signaling molecules regulating T-cell differentiation, intestinal barrier integrity, and systemic inflammatory tone. This review discusses emerging approaches in personalized and precision nutrition that integrate individual microbiome characteristics, dietary patterns, host responses, and metabolic phenotype to develop targeted strategies for improving metabolic health and immune resilience, highlighting candidate microbial biomarkers relevant to immunometabolic health and synthesizing current evidence on diet-microbiome-host interactions for translational applications in microbiome-targeted disease management. Interventions involving prebiotic- and probiotic-enriched foods, precision nutrition strategies, and dietary pattern modification are identified as potential tools for healthcare management, alongside key research gaps and implications for public health nutrition policy.

Keywords: Gut microbiome; Diet-immune axis; Metabolic health; Precision nutrition; Short-chain fatty acids

Potential for Conserving the Chilgoza Forests under a Changing Climate: A Case Study from Chitral and Kohistan, Pakistan

Muhammad Asif, Abdul Majid*, Ghulam Mujtaba Shah

Department of Botany, Hazara University, Mansehra, Pakistan

*Corresponding author's e-mail: abdulmajidhu@gmail.com

Abstract

Chilgoza pine (*Pinus gerardiana* Wall. ex D. Don) is an economically significant conifer species endemic to the dry temperate regions of the Hindukush Himalayas, with prices reported in the range of PKR 6,000–15,000 for 2025. The forests of Chitral and Kohistan, which host substantial Chilgoza pine populations, are facing severe degradation due to unsustainable harvesting, illegal logging, grazing, and climate-related stress. This study explored the potential for conserving *Pinus gerardiana* forests through local community engagement, using a mixed-methods survey of communities near Chilgoza forests conducted between July and October 2025, comprising 41 household interviews. The research evaluated socioeconomic dependence on the forests, community perceptions, forest condition, local adaptation strategies, and government and private-sector conservation initiatives. Results indicate that empowering communities through participatory forest management, sustainable nut harvesting, livelihood diversification, and awareness-raising significantly enhances conservation outcomes. The study concludes with policy recommendations for scaling up community-driven forest conservation in Pakistan.

Keywords: *Pinus gerardiana*; Household survey; Forest conservation; Socioeconomic dependence; Climate change

Nano-Priming for Sustainable Rice Establishment under Changing Climate and Resource Constraints

Sajid Ali^{1*}, Adnan Zahid¹, Ammara Fatima², Muhammad Farooq¹, Muhammad Bilal Chattha¹, Brira Hareem¹

1 Department of Agronomy, University of the Punjab, Lahore, Pakistan

2 Department of Environmental Sciences, Lahore College for Women University, Lahore, Pakistan

***Corresponding author's e-mail:** sajid.agronomy@pu.edu.pk

Abstract

Rice production faces increasing challenges from water scarcity, rising production costs, labor shortages, and climate variability, creating a need for resource-efficient crop establishment technologies. Direct-seeded rice (DSR) can reduce water and labor requirements, but poor and uneven germination remains a major constraint to its wider adoption. This study evaluated zinc oxide (ZnO) and silver (Ag) nanoparticle seed priming as a strategy to improve germination and early seedling establishment in five rice varieties (PK-386, PK-1121, Basmati 515, Super Basmati, Kisan Basmati), using pot experiments with three nanoparticle concentrations (0, 20, and 40 mg/L) and assessment of germination and seedling vigor attributes. Both nanoparticle type and concentration significantly influenced germination performance, with responses varying among varieties. ZnO at 20 mg/L produced the most favorable response, reducing mean germination time from 4.31 days in the control to 3.71 days, increasing germination percentage from 86.31% to 91.19%, and raising the germination rate index from 2.79 to 3.96. Similarly, 20 mg/L AgNPs accelerated germination, reducing mean germination time to 3.97 days, whereas 40 mg/L AgNPs markedly reduced germination percentage to 67.56%, indicating concentration-dependent effects. Kisan Basmati consistently showed superior germination performance among the tested varieties. These findings demonstrate that optimized nanoparticle seed priming, particularly 20 mg/L ZnO, can enhance early crop establishment and seed vigor in rice, offering potential for supporting resource-efficient DSR systems and strengthening the sustainability and resilience of rice-based food systems under changing climatic conditions.

Keywords: *Nanoparticle seed priming; Direct-seeded rice; Seed germination; Seedling vigor; Resource-efficient crop production*

Sustainable Agro-Techniques for Cultivation of Sesame for Quality Oil Production

Muhammad Zaeem Bari*, Mukhtar Ahmed, Umer Farooq

Department of Agronomy, PMAS-Arid Agriculture University, Rawalpindi

*Corresponding author's e-mail: zaeembariawan142@gmail.com

Abstract

Sesame (*Sesamum indicum* L.), an important oilseed crop, is widely cultivated in Pakistan because of its high market value, superior oil quality, and nutritional benefits. Despite its adaptability to diverse agroclimatic conditions, sesame productivity remains limited by suboptimal cultivation practices and inappropriate cultivar selection. As one of the oldest oilseed crops, sesame is valued globally for its edible oil, proteins, vitamins, and essential amino acids. There is dire need to review the key agro-techniques for improving sesame production, with particular emphasis on the use of growing degree days to assess crop phenology. Major focus should be given to soil management, seed quality and cultivar selection, planting methods, irrigation scheduling, nutrient management, pest and disease control, and harvesting practices. Sustainable strategies for mitigating biotic and abiotic stresses are also vital so that modern agriculture comply with environmental standards. Furthermore, the potential of precision farming technologies and advances in agronomy are necessary to improve sesame yield and quality. Overall, the importance of integrated and sustainable agro-techniques can help enhance sesame productivity by promoting the long-term sustainability of this valuable oilseed crop.

Keywords: *Agro-techniques; Crop phenology; Soil management*

Green Extraction of Bioactive Compounds from Agricultural By-products for Nutraceutical Applications

Minahil Khalid

University of Agriculture, Faisalabad

Corresponding author's e-mail: minahilkhalid307@gmail.com

Abstract

The growing demand for sustainable and functional food ingredients has increased interest in valorizing agricultural by-products as renewable sources of high-value bioactive compounds. Agricultural and agro-industrial wastes, including fruit peels (citrus, mango, banana, pomegranate, and apple), vegetable residues (tomato pomace, carrot and potato peels, onion skins, cabbage leaves, and broccoli stems), cereal brans, oilseed cakes, grape and olive pomace, sugarcane bagasse, coffee husks, cocoa pod husks, peanut shells, corn cobs, rice husks, fruit seeds, and spent tea leaves, are rich in polyphenols, flavonoids, carotenoids, dietary fibers, proteins, peptides, and other phytochemicals with antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and cardioprotective activities. Green extraction technologies offer sustainable alternatives to conventional solvent extraction by reducing solvent consumption, energy demand, extraction time, and environmental impact while preserving the integrity of thermolabile compounds. This review summarizes recent advances in ultrasound-assisted, microwave-assisted, enzyme-assisted, pressurized liquid, supercritical fluid, pulsed electric field, and natural deep eutectic solvent-based extraction techniques. It further discusses the effects of process parameters on extraction efficiency, compound stability, and scalability, together with downstream purification and analytical characterization. The potential applications of recovered bioactive compounds in nutraceuticals, functional foods, and dietary supplements are highlighted, alongside challenges related to industrial scale-up, economic feasibility, and regulatory compliance. Integrating green extraction within circular bioeconomy and biorefinery frameworks can transform agricultural waste into sustainable, value-added nutraceutical ingredients while supporting environmental protection and resource efficiency.

Keywords: *Agricultural by-products; Bioactive compounds; Green extraction; Nutraceuticals*

Dehydration as a Tool for Fruit and Vegetable Value Addition and Post-Harvest Management

Umar Farooq*, Aliza Batool

Faculty of Food and Home Sciences, MNS University of Agriculture Multan, Pakistan

***Corresponding author's e-mail:** umar.farooq@mnsuam.edu.pk

Abstract

Fruits and vegetables are highly perishable products that quickly deteriorate in quality after harvest because of their high moisture content, high respiration rate, enzymatic activity, and microbial development. Post-harvest losses of fruits and vegetables are among the biggest problems, especially in the developing world, owing to poor infrastructure for storage, transport, and processing, resulting in economic and nutritional losses. Dehydration is a method for preserving and improving products by reducing moisture content and water activity. Through dehydration, highly perishable products can be transformed into non-perishable goods such as dried fruits, vegetable powder, flakes, chips, and functional food ingredients. There are several types of dehydration techniques, including sun and solar dehydration, hot air drying, vacuum drying, freeze-drying, osmotic dehydration, microwave dehydration, and combinations of them. The choice of dehydration technique will affect various aspects of product quality, such as color, texture, taste, nutritional value, the presence of bioactive components, and rehydration ability. Drying using modern techniques is effective in reducing processing time and energy consumption without nutrient losses or undesirable physicochemical processes. In addition, dehydration enables the use of surplus and cosmetically flawed produce to minimize food waste, achieve food security, and create new products with added value. Adequate pretreatment, appropriate drying conditions, hygienic handling, proper packaging, and storage will contribute to preserving the quality and safety of dehydrated products. In terms of post-harvest management, dehydration is a viable choice to avoid losses caused by seasonality, ensure a stable supply, earn extra money for producers, and provide access to fruits and vegetables at all seasons. Overall, dehydration receives attention in both theoretical and practical perspectives regarding quality aspects and opportunities for adding value.

Keywords: *Enzymatic activities; High respiration rate; Perishable products, Post-harvest management, Vacuum drying*

Biochar and Zinc Source/Application-Method Interactions Govern Soil Zinc Availability, Zinc Biofortification and Yield of Wheat

Alishba Aslam, Muhammad Farooq Qayyum*

Department of Soil Science, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** farooq.qayyum@bzu.edu.pk

Abstract

Zinc (Zn) deficiency in wheat-based cropping systems is widespread in calcareous, alkaline soils, and biochar has been proposed as a soil amendment that can improve Zn retention and fertilizer-use efficiency, but its interaction with Zn source and application method is not well characterized under field conditions. This field experiment evaluated the interactive effects of biochar (applied to soil in all amended treatments) combined with three Zn sources (nanoparticle, sulfate, chelated) applied via two methods (soil, foliar) on soil chemical properties, soil and plant Zn concentrations, and wheat growth/yield. A randomized complete block design (RCBD, wheat cv. Neeshan) with a 5 (Treatment: control, biochar alone [0.1% w/w], biochar + Zn-NP [150 mL/plot], biochar + ZnSO₄ [15 kg/ha], biochar + chelated Zn [13.59 g/plot]) × 2 (Application: soil, foliar) factorial arrangement and three replications (30 plots) was used. Soil pH, EC, organic matter and DTPA-extractable Zn (0-15 and 15-30 cm), grain and straw Zn, 100-grain weight, grain and straw yield, total biomass, plant height, spike length and tiller number were recorded and analyzed by three-way ANOVA (Block + Application × Treatment) with Tukey's HSD ($P \leq 0.05$). Application method interacted significantly with treatment for most variables (12 of 17; $P < 0.05$). Soil-applied biochar + ZnSO₄ produced the highest soil DTPA-Zn at 0-15 cm (2.83 mg/kg, more than three-fold the control), while soil-applied biochar + chelated Zn produced the highest grain Zn (23.2 mg/kg, a 95% increase over the soil-applied control) and the highest grain yield (4.31 t/ha). Grain Zn was positively correlated with grain yield ($r = 0.60$, $P < 0.001$) and, weaker, with soil Zn at 0-15 cm ($r = 0.40$, $P = 0.029$). Yield-component traits (100-grain weight, plant height, spike length, tiller number) were largely unaffected by treatment or application method. Grain Zn uptake and Zn harvest index followed a similar pattern, and soil-applied biochar + chelated Zn was estimated (using a standard per-capita wheat-consumption assumption) to raise dietary Zn intake from wheat by approximately 95% relative to the soil-applied control. Co-application of biochar with chelated Zn, applied to the soil, was the most effective combination for simultaneously improving grain Zn biofortification, Zn use efficiency and grain yield in this experiment.

Keywords: *Biochar; Foliar application; grain yield; Soil Zn availability; Wheat (Triticum aestivum); Zinc biofortification; Zinc source*

Evaluating *Withania coagulans* Extract as a Biostimulant for Mitigating Arsenic Stress in Wheat

Muqadas Iftikhar, Abida Aziz*, Ariba Javed

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Heavy metal/metalloid contamination, particularly arsenic (As) in agricultural soil, is regarded as a serious environmental constraint that negatively influences plant growth, physiology and crop productivity. The present study was designed to investigate the potential role of a plant-based biostimulant extract (*Withania coagulans* extract) in alleviating arsenic stress in wheat (*Triticum aestivum* L.). An initial screening trial was conducted to determine the most effective extract concentration under varying arsenic levels. Five arsenic concentrations, i.e., 25, 50, 75, 100 and 125 mg/kg, were applied along with different *Withania coagulans* extract concentrations ranging from 5% to 50% at 5% intervals for one month. Based on the findings of the screening trial, three arsenic levels, 50, 75 and 125 mg/kg, along with foliar application of 20% *Withania coagulans* extract, were selected for final evaluation. A comprehensive assessment of morphological, physiological, biochemical and yield-related traits was carried out. Results revealed that all growth and yield attributes were severely decreased by arsenic stress. Overall, arsenic toxicity to wheat productivity was recorded in the order of 125 mg/kg > 75 mg/kg > 50 mg/kg. Foliar application of 20% *Withania coagulans* extract significantly promoted seed emergence, vegetative growth, biochemical attributes and overall wheat performance under arsenic stress. It is concluded that foliar application of *Withania coagulans* can be an effective, eco-friendly strategy to mitigate arsenic toxicity and improve wheat productivity on arsenic-contaminated soils.

Keywords: Arsenic stress; Biostimulant; Foliar application; Heavy metals; *Withania coagulans*; Wheat

Role of *Aerva javanica* as a Biostimulant in Mitigating Chromium Stress in Wheat

Sidra Tul Muntaha, Abida Aziz*, Faiqa Akram

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Chromium (Cr) contamination has become a major environmental concern that negatively impacts plant growth, physiological processes and crop productivity. The present study was conducted to evaluate the potential of *Aerva javanica* extract as a biostimulant to alleviate chromium-induced stress in wheat (*Triticum aestivum*). Different chromium concentrations (0, 10, 30 and 50 mg/kg) were applied alone and in combination with *Aerva javanica* extract in a controlled pot experiment. To determine the efficacy of the extract in mitigating chromium toxicity, various growth, physiological, biochemical and yield-related parameters were assessed. Results revealed that chromium stress significantly decreased plant height, root length, leaf area, shoot and root biomass, relative water content, chlorophyll contents, spike characteristics, grain yield, biological yield and harvest index. The adverse effects became more pronounced with increasing chromium concentration, particularly at 50 mg/kg. Chromium stress also elevated malondialdehyde (MDA) and proline accumulation, indicating enhanced oxidative stress and cellular damage, while total protein and chlorophyll contents were significantly reduced. In contrast, application of *A. javanica* extract significantly improved growth and yield attributes of wheat under chromium stress. The extract also increased total protein and phenolic contents while reducing MDA and proline levels, indicating enhanced antioxidant defense and stress tolerance. Overall, the findings demonstrate that *A. javanica* has considerable potential as a safe, natural biostimulant for reducing chromium toxicity in wheat. Therefore, its use could provide a sustainable approach to improve wheat productivity on chromium-contaminated soils.

Keywords: *Aerva javanica*; Biostimulant; Chromium toxicity; Oxidative stress; Wheat

Mitigation of Arsenic-Induced Stress in Wheat Using Extract of *Solanum surattense* as a Natural Biostimulant

Arisha Sajjad, Abida Aziz*, Faria Firdous

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum*) is an important cereal crop that is adversely affected by arsenic stress, leading to reduced growth, physiological performance and yield. This study evaluated the potential of *Solanum surattense* extract as a natural biostimulant for mitigating arsenic-induced stress in wheat. A screening trial was conducted using different extract concentrations and arsenic levels, after which 25% extract was selected for the final experiment. The extract was applied as a foliar spray to wheat grown under 50, 75 and 125 mg/kg arsenic stress. Results showed that arsenic stress reduced morphological, physiological and yield-related traits, while extract application improved plant growth compared with the corresponding arsenic-only treatments. The extract also improved biochemical responses, including protein and phenolic contents, and reduced stress indicators such as proline and MDA. Overall, *S. surattense* extract showed potential as a natural biostimulant for reducing the adverse effects of arsenic stress and supporting wheat growth and productivity.

Keywords: *Solanum surattense*; Wheat; Arsenic stress; Biostimulant; Foliar application

Invigorating Wheat Growth through the Application of *Aerva javanica* as a Biostimulant

Zarqa Zubair, Abida Aziz*, Tehmina Kousar

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum*) is one of the most widely grown crops in the world, and its demand is increasing due to population growth. Although chemical fertilizers improve crop productivity, their excessive use can negatively affect soil health and the environment. Therefore, sustainable and eco-friendly alternatives such as plant-based biostimulants are gaining importance. *Aerva javanica*, a drought-resistant plant with soil-binding and erosion-controlling properties, has potential as a natural biostimulant. This study evaluated the effect of *Aerva javanica* aqueous extract on wheat germination and growth through seed priming and foliar spray. Different concentrations (1%, 5%, 10%, 15% and 20%) of fresh shoot extract, dry shoot extract, fresh root extract and dry root extract were tested. Growth parameters, including root and shoot fresh and dry weights, were measured and compared with control plants. The results showed that *Aerva javanica* extracts positively influenced wheat growth up to a certain concentration; however, higher concentrations of 15% and 20% showed negative effects. Overall, the study indicates that *A. javanica* can serve as a natural biostimulant for improving wheat growth and supporting sustainable agricultural practices while reducing dependence on chemical fertilizers.

Keywords: *Aerva javanica*; Biostimulant; Foliar spray; Plant growth; Seed priming; Sustainable agriculture; Wheat

Improving Wheat Growth by Using *Cucumis melo* var. *agrestis* as a Natural Biostimulant

Farkhanda Jabeen, Abida Aziz*, Shanza Kashif

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum*) is a globally significant staple crop whose productivity is increasingly threatened by abiotic stresses, including climate change and salinity. The research aimed to evaluate the effect of *Cucumis melo* var. *agrestis* extract on wheat germination and growth, compare seed priming and foliar spray application methods, determine the most effective extract concentration and plant part, and ultimately reduce fertilizer use. Two pot experiments were conducted using a completely randomized design (CRD) with three replicates, separated by a 28-day interval. Aqueous extracts were prepared from fresh and dry shoot and root tissues of *C. melo* at concentrations of 1%, 5%, 10%, 15% and 20%, alongside a dry control, hydropriming, and a commercial biostimulant (Maxicrop). Germination parameters (final germination percentage, speed of germination index, germination index, coefficient of germination, mean germination day, germination energy and seedling vigor index) and growth parameters (shoot length, root length, shoot fresh weight, root fresh weight, shoot dry weight, root dry weight and relative water content) were recorded. Results revealed that all plant extracts positively influenced wheat germination and growth through both seed priming and foliar spray methods. However, the most pronounced improvements were observed with fresh shoot extract (FSE) applied via seed priming. Among concentrations, 10% extract yielded the highest enhancement across most parameters, while higher concentrations (15% and 20%) exhibited negative effects. Overall, the findings suggest that *Cucumis melo* fresh shoot extract, applied through seed priming at an optimal concentration of 10%, is most effective in enhancing wheat germination and growth, offering a sustainable, eco-friendly alternative to chemical fertilizers aligned with SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Keywords: Biostimulant; *Cucumis melo* var. *agrestis*; Sustainable agriculture; *Triticum aestivum*

Mitigating Arsenic Toxicity in Wheat Using *Cucumis melo* var. *agrestis* Extract: A Biostimulant Approach

Amina Iqbal, Abida Aziz*, Alisha Jamshaid

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Arsenic contamination in agricultural soils is a critical environmental constraint that adversely affects plant growth, physiological processes and yield performance, particularly in wheat (*Triticum aestivum*). The present study was conducted to assess the efficacy of *Cucumis melo* var. *agrestis* fresh shoot extract as a natural biostimulant for mitigating arsenic-induced toxicity in wheat under controlled pot conditions. A preliminary screening experiment was performed to optimize arsenic stress levels and extract concentrations. Based on the screening outcomes, arsenic treatments (50, 75 and 125 mg/kg) representing mild, moderate and severe stress, along with a 25% plant extract concentration, were selected for the main experiment. Arsenic stress was imposed using sodium arsenate dibasic heptahydrate, while the plant extract was applied as a foliar spray. Data were collected for germination, morphological, physiological, biochemical and yield-related attributes. Results revealed that arsenic stress significantly suppressed plant growth and productivity. However, foliar application of *C. melo* extract markedly improved growth performance, physiological stability and stress tolerance under contaminated conditions. The study concludes that plant-derived biostimulants represent an eco-friendly and cost-effective approach for alleviating heavy metal stress and promoting sustainable wheat production in contaminated soils by increasing organic matter content, boosting nutrient availability and increasing the production of antioxidant enzymes. In screening, 25% plant extract (T5) optimized germination and growth (SGI: 0.48–7.82; shoot length: 13.23–28.0 cm) versus 125 mg/kg arsenic. In pots, plant extract alone maximized shoot length (65.93 cm) and yield (4.81 g/plant), while 125 mg/kg arsenic elevated MDA (22–24 $\mu\text{mol/g}$) and grain arsenic accumulation (10–11 mg/kg).

Keywords: Arsenic contamination; Biostimulant; *Cucumis melo* var. *agrestis*; Sustainable agriculture; *Triticum aestivum*

Impact of *Solanum surattense* Aqueous Extract on Wheat Growth as a Biostimulatory Agent

Ghazala Saqlain, Abida Aziz*, Areeba Shehbaz

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum*) is an important cereal crop, and the increasing use of synthetic fertilizers has created a need for sustainable and eco-friendly growth-promoting alternatives. This study evaluated the biostimulant potential of *Solanum surattense* aqueous extracts on wheat growth through seed priming and foliar application. Fresh and dried shoot and root extracts were tested at 1%, 5%, 10%, 15% and 20% concentrations, along with dry control, hydropriming, and commercial biostimulant treatments. Germination and growth parameters, including shoot and root length, fresh and dry biomass, and relative water content, were recorded. The results showed that *S. surattense* extracts positively influenced wheat germination and growth at suitable concentrations. Among the tested treatments, 10% extract produced the most pronounced improvement in most growth parameters, particularly when fresh shoot extract was applied through seed priming, whereas higher concentrations generally reduced growth responses. These findings highlight the potential of *S. surattense* sustainable wheat production as a natural biostimulant.

Keywords: Biostimulant; Foliar application; Seed priming; *Solanum surattense*; Wheat

Impact of *Withania coagulans* Aqueous Extract on Wheat Growth as a Biostimulatory Agent

Sughra Shafiq, Abida Aziz*, Bayan Nabeel

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum*) is a globally vital cereal crop whose yield and quality are often limited by environmental stressors. The increasing demand for sustainable agricultural practices has led to growing interest in bio-based alternatives to synthetic agrochemicals. This study investigates the biostimulatory potential of *Withania coagulans* aqueous extract on wheat growth, assessing its effects through two application methods: seed priming and foliar spraying. The experiment was conducted at The Women University, Multan, using five concentrations of plant extract (1%, 5%, 10%, 15% and 20%) alongside three controls: unprimed, hydropriming, and a commercial biostimulant. Results demonstrated that the *Withania coagulans* extract significantly influenced key growth parameters. Among the tested concentrations, 10% extract consistently yielded the most pronounced improvements in both seed priming and foliar treatments. Seed priming with 10% extract enhanced shoot and root biomass, increasing shoot length by approximately 12% and root length by over 180% compared to controls. Foliar applications showed a similar trend, where moderate concentrations (5–10%) improved plant vigor, while higher doses (15–20%) resulted in growth inhibition, suggesting potential phytotoxicity at elevated levels. These findings indicate that *Withania coagulans* acts as an effective natural biostimulant, promoting plant growth and physiological performance, particularly when applied through seed priming at a 10% concentration.

Keywords: Biostimulant; Foliar application; Seed priming; *Withania coagulans*; Wheat

Sustainable Healthy Production of Wheat Flakes with Bioactive Peptide of Enhanced Antioxidant and Anti-Inflammatory Activity

Nazir Ahmad

Department of Nutritional Sciences, Government College University, Faisalabad-38000, Pakistan

Corresponding author's e-mail: drnazirahmad@gcuf.edu.pk

Abstract

Bioactive peptides from food proteins offer great health benefits, such as antioxidant and anti-inflammatory effects. Extrusion is a promising method to release these peptides, especially in cereal-based foods; however, studies often lack optimization of processing parameters and detailed bioactivity evaluation. This research aims to enhance peptide release in wheat flakes through optimized extrusion conditions. A Box-Behnken design was applied to examine the effects of barrel temperature (Temp.: 120–160 °C), screw speed (SS: 100–300 rpm), moisture content (MC: 10–20%), and feed flow rate (FFR: 15–35 kg/h) on peptide generation. The highest peptide fractions (17) were obtained at 160 °C, 100 rpm SS, 15% MC, and 25 kg/h FFR, whereas the lowest peptide fraction output (7) was recorded at 120 °C and 300 rpm under the same moisture and feed conditions. The activity of the resulting products was evaluated through antioxidant and anti-inflammatory assays. Samples with higher peptide fractions exhibited stronger DPPH radical scavenging (48.12%), FRAP (0.32 ± 0.02 mmol Fe²⁺/g), and SRSA ($78.80 \pm 4.93\%$) values. Anti-inflammatory potential was also improved, reflected in greater ACE inhibition ($65.12 \pm 4.78\%$) and protein denaturation inhibition ($49.02 \pm 3.67\%$). Changes in fat content due to processing influenced lipid health indices, with improved atherogenicity (AI) and thrombogenicity (TI) scores observed in optimized samples. Overall, the findings demonstrate that fine-tuning extrusion variables can significantly boost the nutritional and functional quality of wheat flakes, supporting their potential role in health-focused food development.

Keywords: *Anti-inflammatory; Antioxidants; Bioactive peptides; Extruded products; Optimization*

Cyclamate-Sucralose Synergism in Green Tea as a Pathway to Reduce Sugarcane Dependency

Anzeela Mumtaz, Muhammad Riaz*, Muhammad Sameem Javed, Amir Ismail

*Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition,
Bahauddin Zakariya University, Multan, Pakistan*

*Corresponding author's e-mail: riaz@bzu.edu.pk

Abstract

Growing sucrose demand drives sugarcane cultivation, increasing land use, water consumption, and greenhouse gas emissions. Non-nutritive sweetener blends that achieve strong sweetness at low doses remain poorly studied in real beverages. This study examined the combined effect of cyclamate and sucralose on the sensory and physicochemical properties of green tea, as a sucrose-replacement strategy supporting sustainable agriculture. Five cyclamate–sucralose blends were tested for sweetness. The best-performing blend, at a 7.8:1 ratio (0.28 g cyclamate, 0.035 g sucralose per 100 mL), gave the highest sweetness score (7.9 ± 0.1) with the least aftertaste. This blend was used to sweeten green tea (T1) and compared with tea sweetened with sucrose (T2) and unsweetened tea (T3), measuring sensory attributes (9-point hedonic scale) and physicochemical properties (pH, DPPH radical scavenging, CIE Lab color, and turbidity). T1 was significantly sweeter (7.8 ± 0.1) than T2 (7.4 ± 0.1) and T3 (2.6 ± 0.1) ($p < 0.001$), with the lowest astringency (3.4 ± 0.1), lowest bitterness (3.1 ± 0.1), and highest aroma retention (6.9 ± 0.1). pH, antioxidant activity (DPPH inhibition, 77.6–78.4%), and color did not differ significantly. Turbidity was similar among sweetened samples, though T3 was significantly lower than T2 ($P \leq 0.05$). These results show that a 7.8:1 cyclamate-sucralose blend can match or exceed sucrose in sweetness and sensory quality, without affecting antioxidant activity or color, while using far less sweetener by mass. This offers a practical way to cut sucrose use in beverages, with potential benefits for sugarcane land use and its climate impact.

Keywords: Cyclamate; Green tea; Sustainable agriculture; Sucralose; Sweetener synergy

Assessing Ecotourism Potential of Munro Track, Mansehra

Mohsin Salahuddin^{1*} and Muhammad Saad²

1 University of Haripur, Haripur, Pakistan.

2 Kaghan Forest Division, Kaghan, Pakistan

***Corresponding author's e-mail:** mohsinsalahuddin4@gmail.com

Abstract

The study's goal was to explore potential ecotourism hotspots along the Munro Track, situated in the Mansehra District, KP Province. The Ecotourism Opportunity Spectrum (ECOS) technique was applied in two stages. The initial stage involved identifying ecotourism cores, while the second stage applied the ECOS approach to determine the potential values for each site. In this regard, ten (10) criteria and forty (40) sub-criteria were identified as defined as the degree of eligibility for selecting an ecotourism direction. The ecotourism opportunity spectrum value was established for each of these criteria after scaling both the main criteria and the sub-criteria. The maximum ecotourism opportunity spectrum value was 400, while the maximum sub-criteria value was 40. Eight parameters were selected that could serve ecotourism potential. The results revealed that the Nadi Bunglow site had the highest calculated spectrum value (315.96), while the Dabran site had the lowest spectrum value (223.87). Among the sub-criteria, tourism infrastructure at the Facilitation Center site gained the highest value (37.32), while the Dabran site recorded the lowest ECOS score (10.1). In comparison to other methodologies, the ECOS criteria utilized in the study were beneficial in assessing the availability of ecotourism hotspots. To regulate a sustainable approach to the process, attention should be given to integrated hotspot development, diverse ecotourism potential analysis, and strengthening of ecotourism routes, along with analysis of medium- and low-value focus areas, long-term planning, stakeholder engagement, and regular monitoring. The conclusions from this technique can be used as supporting evidence for other studies, such as site usage plans or ecotourism management plans.

Keywords: *Natural resources; Ecotourism routes; Ecotourism activities; Standards; Values*

Integrated Application of Biochar, Nitrogen, and Nitrification Inhibitors Improves Rice Crop Growth and Productivity

Naeem Sarwar¹, Zulkifal^{1*}, Khuram Mubeen², Omar Farooq¹, Allah Wasaya¹, Iqra Liaqat¹ and Tahira Saeed¹

1 Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan.

2 Department of Agronomy, MNS University of Agriculture, Multan, Pakistan.

***Corresponding author's e-mail:** zulkiflsahu01@gmail.com

Abstract

Nitrogen is highly susceptible to volatilization, leaching and denitrification losses, which not only limit crop productivity but also contribute to environmental degradation. Various approaches, such as integrated application, coating, and the use of nitrification inhibitors, are being used to stabilize nitrogen. Therefore, a pot experiment was conducted comprising the following treatments: control (N0: no nitrogen application), recommended urea application (N1), N-enriched biochar (N2), coated urea (N3), urea + NBPT (N4), coated urea + NBPT (N5), and N-enriched biochar + NBPT (N6). The results showed that all nitrogen treatments significantly improved growth, yield and quality traits compared with the control. The integration of nitrification inhibitors with enhanced nitrogen sources outperformed the sole application of urea or enhanced nitrogen sources. Treatment N6 (N-enriched biochar + NBPT) produced the tallest plants (107 cm), the maximum number of productive tillers (23 plant⁻¹), the longest panicles (25.5 cm), and the highest grain yield (92.5 g pot⁻¹) and biological yield (246.1 g pot⁻¹). Treatment N5 (coated urea + NBPT) ranked second across all parameters, followed by the sole application of N-enriched biochar in treatment N2 and then coated urea in treatment N3. Similarly, root length, stem diameter and cooked grain length followed the same treatment hierarchy. These findings indicate that integrating enriched nitrogen or coated urea with a urease inhibitor offers a synergistic and sustainable pathway to enhance nitrogen use efficiency and minimize nutrient losses, while improving the growth, yield and grain quality of rice under semi-arid conditions.

Keywords: Rice; Sustainable nitrogen management; N-enriched biochar; Nitrification inhibitors; Nitrogen use efficiency

Effect of Foliar-Applied Proline on Garlic (*Allium sativum*) under Water Deficit Conditions

Iqra Javed*, Muhammad Shahbaz, Aysha Kiran

Department of Botany, University of Agriculture, Faisalabad, Pakistan.

*Corresponding author's e-mail: iqrajaved3488@gmail.com

Abstract

Drought stress has become a worldwide problem and plays a particularly destructive role in the agriculture sector in countries with low annual rainfall. Being a shallow-rooted plant, garlic is slightly sensitive to water stress. Proline application increased the production of stress-protective proteins, scavenged reactive oxygen species, and enhanced photosynthetic capabilities. To assess the potential of proline in mitigating drought-induced damage, a pot experiment was conducted at the Old Botanical Garden, University of Agriculture, Faisalabad. Seeds of two garlic varieties, "Chinese" and "Desi," were obtained from the Ayub Agricultural Research Institute, Faisalabad. Thirty-six pots, each containing 8 kg of soil, were arranged in a completely randomized design. After 30 days of sowing, drought stress (0 and 50% FC) was maintained, and a foliar spray of three levels of proline (0, 5 and 10 mM) was applied. Plants were harvested 15 days after proline treatment. Results showed that root length, root fresh and dry weight, plant height, chlorophyll a, peroxidase, total soluble protein, and ions such as root and shoot Na^+ and Ca^{2+} were reduced under drought stress. Proline mitigated the effects of drought stress, and among the different levels tested, 10 mM proline was the most effective for the various attributes of garlic. The Chinese variety showed greater tolerance to drought stress, as it performed better in response to proline treatment. Proline is an osmoprotectant that helps plants tolerate abiotic stress.

Keywords: Garlic; Water stress; Drought tolerance; Proline; Abiotic stress

Wild Plant-Based Biostimulants Invigorate Wheat Growth: Optimizing Dose and Application Method

Abida Aziz

Department of Botany, The Women University, Multan.

Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

Wheat (*Triticum aestivum* L.) is a globally vital staple crop whose productivity is limited by excessive reliance on chemical fertilizers that degrade soil health. Plant-based biostimulants offer a sustainable, eco-friendly alternative. This study evaluated the biostimulant potential of five desert wild species: *Aerva javanica*, *Cucumis melo* var. *agrestis*, *Solanum surattense*, *Withania coagulans*, and *Alhagi maurorum*, on wheat growth. Ten independent pot experiments were conducted in a completely randomized design (CRD) with three replications. Aqueous extracts were prepared from fresh shoot (FSE), dry shoot (DSE), fresh root (FRE), and dry root (DRE) tissues of each species at five concentrations (1%, 5%, 10%, 15%, and 20%). Extracts were applied through seed priming and foliar spray, and compared with dry control, hydropriming, and a commercial biostimulant (Maxicrop). Results revealed a consistent concentration-dependent response across all species. Low to moderate concentrations (5% and 10%) significantly enhanced germination and growth, whereas higher concentrations (15% and 20%) exhibited inhibitory or phytotoxic effects. Among application methods, seed priming was more effective than foliar spray. Among extract types, fresh shoot extract (FSE) at 10% concentration was most effective across species. Specifically, *C. melo* FSE and *A. javanica* FSE showed the maximum improvement in shoot and root biomass, while *S. surattense* and *W. coagulans* at 10% increased root length, and *A. maurorum* DSE at 5% recorded the highest fresh biomass. Overall, aqueous extracts of the selected wild plants offer a sustainable strategy to reduce chemical fertilizer dependence, contributing to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Keywords: *Biostimulants; Wild plant extracts; Seed priming; Foliar spray; Triticum aestivum; Sustainable agriculture*

Exploring the Effect of Native Desert Plant Aqueous Extracts as Biostimulants to Enhance Maize Germination and Growth

Qurat Ul Ain Hyder, Abida Aziz*

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

The development of novel, efficient, and environmentally safe approaches is important for modern agriculture and plant growth stimulation. Plant biostimulants are plant-based products that promote growth and productivity by influencing plant physiology and interacting with soil microorganisms. They enhance plant development through direct effects on hormone regulation, nutrient assimilation, and stress tolerance, rather than by providing essential nutrients. A study was conducted using a completely randomized design (CRD) with two factors: ten plant extracts [*Calotropis procera* (Aiton), *Alhagi maurorum* Medic. (Camelthorn), *Cucumis melo* var. *agrestis* (wild melon), *Capparis decidua* (Forssk.) Edgew. (Caper Bush), *Aerva javanica* Juss. (Kapok bush), *Salvadora oleoides* Decne. (Toothbrush tree), *Cuscuta reflexa* Roxb. (Giant dodder), *Acacia nilotica* L. (Babul), *Solanum surattense* Burm. (Wild eggplant), *Withania coagulans* Dunal. (Vegetable rennet)], and treatment concentration (five levels for each extract). The setup also included three controls: C0 (untreated seeds), C1 (seeds primed in distilled water), and C2 (seeds primed in the commercial biostimulant Maxicrop) to evaluate the effect on the germination and growth of maize. The study revealed significant positive enhancement in growth parameters among treatments, with *S. surattense* (5%) exhibiting the maximum shoot length (59.8 ± 0.75 cm) and *C. procera* (5%) showing the highest root length (92.1 ± 2.96 cm), shoot fresh weight (5.06 ± 0.26 g), and root fresh weight (4.92 ± 0.36 g). Notably, several treatments demonstrated statistically similar effects on growth parameters, including *S. oleoides* (C), *A. maurorum* (F), and *W. coagulans* (F). The study divided the plant extracts into two groups based on their growth-promoting effects on maize. Group 1, including *C. procera*, *S. surattense*, *C. decidua*, *S. oleoides*, and *A. nilotica*, thrived at 5% concentration, while Group 2, consisting of *A. maurorum*, *W. coagulans*, *C. melo*, and *A. javanica*, worked best at 10% concentration. However, further analysis is required to elucidate the underlying mechanisms and optimize treatment concentrations.

Keywords: Wild plants; Biostimulants; Aqueous extracts; Sustainable agriculture; Maize; *W. coagulans*; *Solanum surattense*; *Calotropis procera*

Comparative Study of Physico-Chemical Properties of Bioplastics Reinforced with Natural Fillers

Banista Batool, Huma Aslam, Abida Aziz*

Department of Botany, The Women University, Multan.

*Corresponding author's e-mail: abida.6363@wum.edu.pk

Abstract

The development of biodegradable alternatives made from renewable resources has increased due to growing environmental concerns associated with synthetic polymers. The physico-chemical characteristics of bioplastics reinforced with natural fillers, such as sugarcane bagasse, eggshell powder, and corn fibers, are compared in this work. To assess their performance and structural characteristics, bioplastic samples were created and subjected to extensive characterization procedures. The existence of functional groups and interactions between polymer matrices and fillers was verified by Fourier Transform Infrared (FTIR) analysis. To ascertain material stability and biodegradability, physico-chemical parameters, including water absorption, water solubility, moisture content, alcohol solubility, and thickness, were evaluated. Tensile strength testing was used to assess mechanical performance, and scanning electron microscopy (SEM) was used to examine surface morphology and filler dispersion. The results showed that the mechanical strength, moisture resistance, and structural integrity of bioplastics were all greatly impacted using natural fillers. Distinctions in performance were noted among the studied fillers, underscoring the significance of filler selection in maximizing bioplastic characteristics. The work contributes to the development of environmentally friendly materials and waste valorization techniques by showcasing the potential of agricultural and biowaste resources as sustainable reinforcing agents in the manufacturing of bioplastics.

Keywords: *Bioplastics; Natural fillers; Physico-chemical properties; FTIR; SEM; Biodegradable materials*

Wheat Leaf Rust in the Backdrop of Climate Change: Molecular Mechanisms, Epidemiological Shifts, and Climate-Resilient Management

Muhammad Amjad Ali*, Ameer Hamza Aslam

Department of Plant Pathology, University of Agriculture Faisalabad, Faisalabad 38040, Pakistan.

*Corresponding author's e-mail: amjad.ali@uaf.edu.pk

Abstract

Changing climatic factors such as rising temperatures, elevated CO₂ (eCO₂) concentrations, variable rainfall patterns, and shifting humidity regimes are significantly reshaping the epidemiology of plant pathogens, including wheat leaf rust (WLR) disease, caused by *Puccinia triticina*. Climate factors modify pathogen survival, dispersal, infection efficiency, host susceptibility, and epidemic development across different agroecological regions. This review critically synthesizes current evidence on climate-pathogen-host interactions from molecular, field, regional, and global perspectives. Priority is given to direct experimental studies on the wheat-P. triticina pathosystem, while evidence from related rust pathosystems and broader plant-pathogen systems is incorporated only where direct information is limited. However, climatic effects on WLR are nonlinear and context-dependent rather than uniformly disease-promoting. We examine how changing environments influence host defense, pathogen virulence, resistance durability, and disease distribution under future climates. Recent advances in climate-responsive disease management are also evaluated, including resistance gene and quantitative trait locus (QTL) pyramiding, marker-assisted and genomic selection, predictive epidemiological modeling, climate-informed surveillance, and integrated disease management. With this, the review summarizes major WLR resistance genes, highlighting their molecular characteristics, diagnostic markers, validation status, temperature responsiveness, and breeding relevance for climate-resilient wheat improvement. Emerging technologies, including genome editing, microbiome-based approaches, artificial intelligence, and digital disease surveillance, are discussed together with their current limitations and future potential. The reported evidence in this review supports a transition from reactive disease control to climate-informed and genetics-based management. Integrating pathogen surveillance, multi-environment phenotyping, functional genomics, and predictive decision-support systems will be essential for developing durable resistance and sustaining global wheat production under changing climatic conditions.

Keywords: *Climate change; Puccinia triticina; Epidemiological shifts; Leaf rust resistance; Climate resilience*

Soil-Applied Biochar and Foliar Biostimulants Lower Chromium Uptake and Improve Rice Yield in Cr(VI)-Contaminated Soil

Muhammad Shahbaz, Muhammad Aon*

Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan-60800, Pakistan.

*Corresponding author's e-mail: dr.maon@bzu.edu.pk

Abstract

Contamination of agricultural soils with hexavalent chromium [Cr(VI)] is a serious constraint to crop production. This metal is highly toxic to plants: it triggers oxidative stress, which in turn disturbs growth, nutrient uptake, photosynthesis and overall plant physiology. A pot study was conducted to find out whether green waste biochar, applied to soil, and two foliar biostimulants, glycine and ascorbic acid, could reduce Cr toxicity in rice (*Oryza sativa* L.) and sustain its growth and yield. Soil was spiked with Cr at 75 mg kg⁻¹, and three biochar rates (0, 0.5 and 1.0%) were combined with three foliar treatments (no spray, glycine, ascorbic acid), giving nine treatments in total. Both biochar and the foliar sprays markedly lessened the damage caused by Cr, and plants grew better than those in the untreated contaminated soil. Glycine and ascorbic acid added to this effect by increasing the tolerance of the plants, mainly through a stronger antioxidant system, reduced membrane injury, and better retention of chlorophyll and photosynthetic activity. Among the combinations, 0.5% biochar with ascorbic acid gave the best results for plant height, number of tillers, paddy yield and grain dry weight, and it also lowered Cr concentration in shoot and grain. The 0.5% biochar with glycine treatment was also effective for several physiological and grain traits. Raising the biochar rate to 1.0% brought no additional benefit. Overall, our findings show that green waste biochar used together with foliar glycine or ascorbic acid is a sustainable and environment-friendly option for growing rice on Cr(VI)-contaminated soil. The benefit comes from lower Cr bioavailability and better soil condition on one side, and improved plant physiology and higher productivity on the other.

Keywords: Rice; Hexavalent chromium; Green waste biochar; Glycine; Ascorbic acid; Foliar biostimulants; Heavy metal stress

Foliar Ascorbic Acid Outperforms Glycine and Chitosan in Improving Growth of Rice Grown with Fruit Market Waste Biochar under Hexavalent Chromium Stress

Muhammad Aon*, Muhammad Shahbaz

Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan-60800, Pakistan.

*Corresponding author's e-mail: dr.maon@bzu.edu.pk

Abstract

Chromium contamination can restrict rice growth and productivity by causing physiological stress and reducing plant tolerance under contaminated soil conditions. A pot experiment was conducted to evaluate the response of rice (*Oryza sativa* L.) to foliar application of glycine, ascorbic acid and chitosan under normal and chromium-contaminated soil, with fruit market waste biochar used as a soil amendment. Soil was used either without chromium addition or spiked with Cr(VI) at 75 mg kg⁻¹ soil. Fruit market waste biochar was applied at 0 and 0.5% of soil, while glycine, ascorbic acid and chitosan were applied as foliar treatments along with an untreated control. The treatments were arranged in factorial combinations to evaluate the individual and interactive effects of chromium, biochar and biostimulants on rice growth and yield-related traits. Chromium contamination reduced rice growth compared with non-contaminated soil, while application of the biostimulants improved plant performance under both soil conditions. The response of the biostimulants, however, varied with the level of chromium stress. Glycine showed a comparatively stronger growth-promoting effect in non-contaminated soil, whereas ascorbic acid performed better under chromium-contaminated conditions and provided greater improvement in plant growth than glycine and chitosan. The beneficial response of the biostimulants was further supported by the addition of fruit market waste biochar, indicating that the soil amendment can complement foliar biostimulation under chromium stress. Overall, foliar application of biostimulants, particularly ascorbic acid under chromium-contaminated conditions, can help improve rice growth, while fruit market waste biochar may provide additional support for maintaining crop performance in contaminated soil.

Keywords: Rice; Chromium stress; Foliar biostimulants; Ascorbic acid; Glycine; Chitosan; Fruit market waste biochar; Contaminated soil

Valorization of Agro-Industrial Byproducts for Sustainable Food Fortification

Haziq Wahab^{1*} and Dur-e-Shahwar Sattar²

1 Emily Carr Secondary School, Canada

2 Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** wahabhaziq11@gmail.com

Abstract

Agro-industrial processing generates substantial byproducts such as fruit peels, seed residues, and cereal brans, which are often discarded despite being rich in bioactive compounds, dietary fiber, and micronutrients. This study explores the extraction and incorporation of such byproducts into staple food matrices to enhance nutritional value while reducing food waste. Physicochemical, functional, and sensory properties of fortified products were evaluated to assess feasibility for large-scale adoption. Results indicate that byproduct-based fortification can significantly improve nutrient density without compromising consumer acceptability, offering a low-cost, climate-resilient strategy to strengthen food security. This approach aligns with circular economy principles by transforming processing waste into value-added ingredients, supporting both industrial sustainability and public health goals in the context of a changing climate.

Keywords: *Agro-industrial byproducts; Food fortification; Bioactive compounds; Circular economy; Food waste valorization; Nutrient enrichment; Sustainable food processing*

Nanoparticle-Based Coatings for Climate-Resilient Postharvest Preservation of Perishable Foods

Mysha Wahab^{1*} and Dur-e-Shahwar Sattar²

¹ Emily Carr Secondary School, Canada.

² Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan.

*Corresponding author's e-mail: myshawahab12@icloud.com

Abstract

Tomatoes are among the most perishable horticultural commodities, suffering substantial postharvest losses due to rapid ripening, softening, and microbial spoilage — losses further intensified by climate-induced fluctuations in temperature and humidity during storage and transport. This study investigates nanoparticle-based edible coatings — incorporating agents such as chitosan nanoparticles, zinc oxide (ZnO), and silver (Ag) nanoparticles — as a climate-resilient strategy to extend the shelf life of tomatoes. These nanocoatings form a semi-permeable barrier that delays ripening by regulating respiration and ethylene-related gas exchange, reduces moisture loss, and inhibits the growth of common spoilage organisms such as *Botrytis cinerea* and *Rhizopus* species. Tomato samples were evaluated over an extended storage period for firmness, weight loss, color change, lycopene content, and microbial load. Results indicate that nanoparticle-coated tomatoes retained significantly better textural and nutritional quality compared to uncoated controls, with delayed onset of spoilage. This approach offers a low-cost, scalable solution for reducing tomato postharvest losses in climate-vulnerable supply chains, while underscoring the importance of evaluating nanoparticle safety for direct food-contact applications.

Keywords: *Tomato postharvest quality; Nanoparticle coatings; Chitosan nanoparticles; Shelf-life extension; Ripening delay; Lycopene retention; Climate-resilient storage; Food security*

Trace Element Balances in Wheat-Maize Rotation Soils as Influenced by Irrigation Water Quality and Green Manuring

Shahid Hussain^{1*}, Mubshar Hussain², Ammara Basit¹, Ayta Umar¹, Waleed Ramzan¹, Amir Ismail³, Raza Abbas¹, Muhammad Intissam Rana¹, Muhammad Ashraf⁴

1 Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan.

2 Institute of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan.

3 Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

4 Department of Soil and Environmental Sciences, Faculty of Agriculture, University of Sargodha, Sargodha, Pakistan.

***Corresponding author's e-mail:** shahid.hussain@bzu.edu.pk

Abstract

Agricultural soils in Pakistan face heavy metal(loid) contamination from wastewater irrigation, fertilization, and atmospheric deposition, yet comprehensive inflow-outflow balance studies for crop plants remain scarce. This three-year project examined trace element (As, Cd, Cr, Cu, Fe, Mn, Pb, Zn) balances in calcareous soils under a wheat-maize rotation as affected by irrigation source (canal, tube-well, wastewater) and green manuring, at two sites: an experimental farm in Multan and a farmer's field in Lodhran. Soil samples from surface and subsurface layers were analyzed for AB-DTPA extractable trace elements, while inflows (irrigation, fertilizers, pesticides, seeds, aerial deposition) and outflows (crop removal) were quantified over two cropping years to compute net elemental balances. Almost all the added metal loads remained in the top layer of the soil, linked to the soil's high sorption capacity and the area's high evapotranspiration. Green manuring increased grain yields of wheat and maize by 10–20%. Wastewater irrigation also significantly increased yields through its nutrient content, though at the cost of greater heavy metal(loid) accumulation in the soils. Irrigation water was the dominant inflow source of trace elements, followed by aerial deposition and fertilizers. Net positive balances emerged for toxic elements (As, Cd, Cr, Pb), particularly under wastewater irrigation, while micronutrients (Cu, Fe, Zn) also increased, except Mn, which declined under groundwater irrigation. Grain concentrations of Cd, Cr, and Pb remained within safe limits, but As posed a potential health risk under wastewater irrigation. Overall, the findings indicate that current soil buffering capacity limits immediate risk, but wastewater use for irrigation threatens long-term soil and food safety. The study highlights the need for stronger irrigation water regulations as well as continuous monitoring of soil, water and air resources.

Keywords: *Calcareous soils; Green manuring; Trace element balance; Wastewater irrigation*

Brilliant Green and Congo Red Degradation Efficiency of the Azoreductase Gene-Inhabiting *Klebsiella aerogenes* and *Enterobacter* sp. Strains

Muhammad Tahir^{1*}, Muhammad Usman², Tahir Naqqash³, Muhammad Shahid⁴, Abu Bakr Umer Farooq¹, Montaser M. Hassan⁵, Roqayah H. Kadi⁶, Urooj Khan¹

1 Department of Biotechnology, COMSATS University Islamabad, Vehari Campus, Pakistan.

2 Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Pakistan.

3 Institute of Molecular Biology and Biotechnology, Bahauddin Zakariya University, Multan 60800, Pakistan.

4 Department of Bioinformatics and Biotechnology, Government College University, Faisalabad 38000, Pakistan.

5 Department of Biology, College of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia.

6 Department of Biological Science, Faculty of Science, University of Jeddah, 21959 Jeddah, Saudi Arabia.

***Corresponding author's e-mail:** muhammad_tahir@cuivehari.edu.pk

Abstract

This study aimed to isolate bacteria with potential for dye degradation, phytotoxicity reduction, and plant growth promotion from textile industrial wastewater (IWW) and the rhizosphere of plants irrigated with IWW (IWS). A total of 27 bacterial isolates were purified, of which two were from IWW and 25 from the rhizosphere. The isolates showed azoreductase and laccase activity, produced IAA, and solubilized phosphate under in vitro conditions. In a batch experiment, the biodegradation efficiency of the selected bacterial isolates IWW1-4d and IWS2-3b for Brilliant Green was 62.5% and 74% at pH 7, respectively. The efficiency of IWW1-4d and IWS2-3b to degrade Congo Red was 73% and 82% at pH 5, respectively. Based on 16S rRNA sequencing, the isolates IWW1-4d and IWS2-3b were identified as *Klebsiella aerogenes* and *Enterobacter* sp., respectively. Azoreductase gene sequences of *Klebsiella aerogenes* IWW1-4d and *Enterobacter* sp. IWS2-3b showed 100% similarity with those of *Bacillus cereus* (Accession No. MH151204) and *Bacillus* sp. (Accession No. AB471798). In a petri plate experiment, inoculation of the bacterial strains *Klebsiella aerogenes* IWW1-4d and *Enterobacter* sp. IWS2-3b reduced the dyes' phytotoxicity and increased the growth parameters of *Kalonji*. This study reports the presence of the NADH-dependent azoreductase gene, responsible for azoreductase enzyme production in *Klebsiella aerogenes* IWW1-4d and *Enterobacter* sp. IWS2-3b. It also examines the azo dye degradation efficiency of both strains and their role in reducing dye phytotoxicity in *Kalonji*, aspects that have not been comprehensively reported previously.

Keywords: Dyes; Biodegradation; Rhizosphere; Phytotoxicity; Wastewater treatment; Plant growth promotion

Computational Investigation of Lectin from *Pleurotus cornucopiae* as a Potential α -Glucosidase Inhibitor: Structural and Dynamic Insights into Its Antidiabetic Potential

Aatiqa Tariq¹, Sonia Safdar¹, Amna Adnan¹, Shah Rukh², Sayra Ishaq Bhatti¹, Uzma Ishaq^{1,3}, Sohaib Mehmood¹, Ahmed Akrem^{1*}

¹ Institute of Botany, Bahauddin Zakariya University, Multan, Pakistan.

² Department of Biochemistry, Bahauddin Zakariya University, Multan, Pakistan.

³ Department of Botany, The Women University, Multan, Pakistan.

*Corresponding author's e-mail: ahmedakrem@bzu.edu.pk

Abstract

Edible mushrooms are increasingly recognized as valuable food resources containing bioactive proteins with potential health-promoting properties, creating opportunities to extract greater value from mushroom-derived resources beyond their nutritional use. Among these bioactive components, mushroom lectins have attracted considerable interest because of their diverse biological activities and potential therapeutic applications. Inhibition of α -glucosidase represents an important strategy for controlling postprandial hyperglycemia in type 2 diabetes mellitus (T2DM), highlighting the potential of natural mushroom-derived proteins as candidates for antidiabetic applications. Lectin from *Pleurotus cornucopiae* (PCL) was therefore investigated for its potential interaction with human intestinal α -glucosidase using an integrated structural bioinformatics approach. The three-dimensional structure of PCL was constructed using homology modeling and subjected to protein-protein docking with human intestinal α -glucosidase. Docking analysis indicated that PCL binds within the catalytic region of α -glucosidase, involving the catalytically important residues Asp203 and Asp327 and the conserved substrate-recognition residue Asp542. The predicted binding interface suggested that PCL may influence substrate accessibility and the catalytic environment of the enzyme. The stability of the docked complex was evaluated through a 200 ns molecular dynamics simulation, which demonstrated stable global structural behavior, maintained compactness, persistent intermolecular interactions, and coordinated collective motions. PCL exhibited a structurally stable interaction with human α -glucosidase, providing a possible molecular basis for modulation of enzyme activity. These findings identify PCL as a mushroom-derived protein candidate for further experimental investigation of α -glucosidase inhibition and antidiabetic potential, while highlighting edible mushrooms as sources of high-value bioactive components for future value-added and functional-food applications.

Keywords: Diabetes; Glucosidase; Lectin; *Pleurotus*; Simulation

Sustainable Food Systems in a Changing Climate: Innovations and Opportunities for a Resilient Food Future

Faiz-ul-Hassan Shah, Zulfiqar Ahmad, Umair Ali, Hammad Hafeez, Hafiz Talha Hafeez and Tahir Mehmood*

Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan.

***Corresponding author's e-mail:** tahirmehmood@iub.edu.pk

Abstract

The sustainability, productivity and resilience of global food systems are facing growing threats from climate change. Agricultural production, food quality, processing, and food supply chains are vulnerable to rising temperatures, water scarcity, and shifts in precipitation, soil degradation and extreme weather. Thus, the development of sustainable food systems necessitates an integrated strategy that brings together agricultural resources, food processing technologies, nutrition, waste reduction and innovation in the industry. This abstract highlight emerging strategies for building climate-resilient and resource-efficient food systems, with particular emphasis on food science and technology. Efficient processing techniques, valorization of by-products from agricultural and food production, alternative and plant-based food ingredients, better food preservation, energy- and water-saving technologies, and sustainable packaging can play a significant role in decreasing resource usage and food losses. Moreover, the development of circular bioeconomy approaches may lead to the conversion of food waste and agricultural residues into value-added food ingredients, feed, biomaterials, and other valuable products. The successful implementation of these innovations into real solutions will require collaboration between researchers, food industries, policymakers, farmers and consumers. The incorporation of sustainability into food production and processing can help achieve four goals: food security, healthy nutrition, economic development, and environmental protection. Moving towards sustainable food systems is not just about adapting to climate change; it is also about innovation, industrial development, and a more resource-efficient and resilient food system.

Keywords: *Sustainable food systems; Climate change; Food security; Sustainable food processing; Circular bioeconomy; Food waste valorization; Resource efficiency; Food innovation*

Clean-Label Protein Recovery from Soybean Meal: A Sustainable Approach for Functional Food Development

Muhammad Sameem Javed^{1*}, Muhammad Riaz¹, Umair Ali², Muhammad Aqeel¹, Mumtaz Hussain¹

1 Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

2 Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan.

***Corresponding author's e-mail:** sameemjaved@bzu.edu.pk

Abstract

The present study was designed to investigate the recovery of value-added protein from soybean meals, a protein-rich by-product of soybean processing, and to use it in the formulation of a clean-label functional food. Alkaline extracted soybean meal was processed through isoelectric precipitation, and the protein concentrate was tested for extraction yield, protein content, oil absorption capacity, solubility, water absorption capacity, emulsifying activity, foaming capacity and antioxidant activity. The protein recovery from the recovered fraction was $58.6 \pm 2.4\%$ with a protein content of $84.3 \pm 1.8\%$. Optimization of the extraction conditions resulted in an increase in protein solubility from $42.7 \pm 1.5\%$ to $76.4 \pm 2.1\%$. The recovered protein exhibited the following properties: water absorption capacity (3.82 ± 0.14 g/g), oil absorption capacity (4.76 ± 0.18 g/g), emulsifying activity (48.5 ± 1.7 m²/g) and foaming capacity ($72.4 \pm 2.4\%$). The total phenolic content and DPPH radical-scavenging activity were 2.84 ± 0.12 mg GAE/g and $51.6 \pm 1.9\%$, respectively. This protein was then used in a cereal-based protein bar, formulated without artificial colors, synthetic preservatives, and other unnecessary additives, at levels of 5, 10 and 15%. The 10% protein-enriched formulation exhibited the best overall characteristics, with a protein content of $\sim 17.8 \pm 0.6\%$, dietary fiber content of $6.2 \pm 0.3\%$, and satisfactory sensory scores of $8.1 \pm 0.4/9$. The study showed that soybean meals can be a sustainable protein source for clean-label functional food production, while encouraging food by-product valorization, resource efficiency, and circularity in the food system.

Keywords: Soybean meal; Protein recovery; Clean-label food; Functional food; Sustainable food system

Valorization of Agro-Food By-Products for Sustainable Development of a Probiotic Functional Food

Umair Ali*, Faiz-ul-Hassan Shah, Zulfiqar Ahmad, Hammad Hafeez, Hafiz Talha Hafeez

Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan.

*Corresponding author's e-mail: umair.ali@iub.edu.pk

Abstract

Wheat bran and banana peel were evaluated as locally available agro-food resources for the development of a sustainable probiotic functional food using *Lactiplantibacillus plantarum*. Wheat bran and banana peel were processed and used as base ingredients in four formulations with different ratios: T0 (100:0), T1 (90:10), T2 (80:20) and T3 (70:30), and then fermented with *L. plantarum* for 24 h under controlled conditions. The fermented product was tested for probiotic viability, pH, titratable acidity, moisture, protein, dietary fiber, total phenolic content, antioxidant activity and phytic acid. After fermentation, T2 was found to be the most favorable, as the number of viable cells of *L. plantarum* rose from 7.15 to 9.62 log CFU/g. The pH decreased from 6.18 to 3.72, whereas titratable acidity increased from 1.42 to 3.40%. Moisture content increased from 8.7 to 11.4%, and dietary fiber slightly increased from 24.6 to 26.1%. Total phenolic content increased from 2.10 to 5.18 mg GAE/g, accompanied by increases in DPPH radical-scavenging activity from 38.4 to 67.8% and FRAP activity from 1.42 to 2.86 mmol Fe²⁺/kg. Phytic acid decreased from 7.8 to 5.1 mg/g. Overall, the fermented formulation was able to sustain a probiotic population above 10⁹ CFU/g, indicating its potential as a value-added functional food ingredient. In general, the fermentation process converted the locally available wheat bran and banana peel into a nutrient- and functionally enriched probiotic substrate, thus promoting the valorization of agro-food by-products, efficient use of resources, and the development of sustainable food systems.

Keywords: *Wheat bran; Banana peel; Lactiplantibacillus plantarum; Sustainable functional food; Food waste valorization; Antioxidant activity*

Production of Cheese with Cardoon-Extracted Aspartic Protease as a Rennet Substitute and Its Evaluation

Muhammad Haroon¹, Ali Asghar¹, Hammad Hafeez^{2*}, Umair Ali², Faiz-ul-Hassan Shah², Talha Hafeez²

1 National Institute of Food Science and Technology, University of Agriculture Faisalabad, Faisalabad, Pakistan.

2 Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan.

***Corresponding author's e-mail:** hammad.hafeez@iub.edu.pk

Abstract

This study investigates the use of aspartic proteases extracted from cardoon flowers as an alternative to traditional animal rennet in cheese production, driven by the growing scarcity of animal-derived rennet. Cheese was manufactured from buffalo milk using varying concentrations of aspartic protease to evaluate optimal treatments for physicochemical, microbial, and textural properties. Buffalo milk was pre-boiled and standardized before acidification and enzyme addition. Cheese samples were analyzed for fat, protein, moisture, pH, acidity, total plate count (TPC), and texture profile analysis (TPA) on days 0, 7, 14, and 21 of storage. Fat content ranged from 26.54% in T1 at day 0 to 32.02% in T2 at day 21; protein content varied from 18.31% in T1 at day 0 to 23.23% in T3 at day 21. Moisture content decreased from 51.58% in T1 at day 0 to 47.59% in T3 at day 21, while pH values ranged between 5.30 (T2 at day 21) and 5.56 (T0, T3 at day 0). Acidity increased from 0.99% in T0 at day 0 to 1.92% in T3 at day 21. TPC and TPA assessments indicated bacterial stability and texture changes over storage. Sensory evaluation revealed that T2 demonstrated superior overall quality. These findings suggest that cardoon flower-derived aspartic protease is a viable rennet alternative in cheese production, with promising implications for future applications in dairy processing.

Keywords: *Aspartic protease; Cheese; Cardoon; Buffalo milk*

Quality Enhancement and Shelf-Life Improvement of Tomatoes Using Pectin- and CMC-Based Edible Coatings

Alveena Zafar, Zahida Qadeer, Baila Ahmad*, Saira Tanweer, Muhammad Asif Khan, Faiz-ul-Hassan Shah, Hammad Hafeez, Umair Ali

Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Punjab, Pakistan.

***Corresponding author's e-mail:** baila.ahmad@iub.edu.pk

Abstract

Edible coatings serve as an effective and eco-friendly postharvest technique for improving the quality and self-life of fresh fruits and vegetables. The current study evaluated the effect of CMC- and pectin-based edible coatings on the physicochemical profile and sensory traits of tomatoes during a 14-day storage period. A total of six treatments were formulated, i.e., T0 (control), T1 (0.5 g pectin and 0.5 g CMC), T2 (1 g pectin and 1 g CMC), T3 (1.5 g pectin and 1 g CMC), T4 (1 g pectin and 1.5 g CMC), and T5 (1.5 g pectin and 1.5 g CMC). The treatment samples were subjected to physicochemical analysis, including pH, total soluble solids (TSS), titratable acidity, ascorbic acid content, lycopene, phenolic and flavonoid contents, reducing sugars, weight loss, firmness, and color parameters (L^* , a^* , b^* values), as well as sensory characteristics. The results demonstrated a remarkable impact of edible coatings on the quality and shelf life of tomatoes. T3 and T5 had the highest ascorbic acid retention rates (8.73 and 8.76 mg/100g, respectively). Lycopene levels increased from 18.71 mg/kg for T0 to 18.95 mg/kg for T5. T1 continued to have the highest total phenolic content (19.97 mg GAE/100g), while T3, T4 and T5 showed significantly reduced weight loss (49.40, 49.36, and 49.43%), as well as the highest firmness and color values at the end of the storage period. Moreover, T3, T4, and T5 received the highest ratings for color, flavor, texture, scent, and taste according to the sensory study, thereby exhibiting the best results. The current research findings reveal the potential of edible coatings to improve tomato quality and extend storage life, thus contributing to the advancement of postharvest technology by offering measures for shelf-life extension of fresh tomatoes and thereby minimizing fruit and vegetable losses.

Keywords: *Edible coating; Tomato; CMC; Pectin; Shelf life*

Exploring the Hurdles in Transition Toward Plant-Based Proteins and Its Impact on Environmental Sustainability and Food Security

Baila Ahmad*, Zahida Qadeer, Saira Tanweer, Muhammad Asif Khan, Faiz-ul-Hassan Shah, Hammad Hafeez, Umair Ali

Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Punjab, Pakistan.

***Corresponding author's e-mail:** baila.ahmad@iub.edu.pk

Abstract

The environmental impact of animal-based proteins is remarkably higher than that of plant-based proteins, despite their high nutritional and functional qualities. They entail significant consumption of land and freshwater, along with higher greenhouse gas emissions. Moreover, changes in dietary patterns and lifestyle preferences have led to a decline in the appeal of traditional protein sources, thereby accelerating the shift toward plant-based food. In contrast, protein counterparts including plant-based proteins, insect proteins and single-celled proteins are environmentally sustainable, cheaper, and align with the Sustainable Development Goals (SDGs), such as eradicating hunger, promoting clean water, and combating climate change. The rising interest of big food corporations in alternative proteins is harmonious with an approaching sustainability shift to ensure food security. As the global population is anticipated to reach 8.60 billion people by 2050, sustainable solutions are urgently required to ensure access to vital food resources, especially protein, for human health. Therefore, the current review investigates the hurdles and barriers to alternative protein transition, hindered by persistent political, legal, and cultural obstacles that are more pronounced for some alternative protein technologies than for others.

Keywords: *Plant proteins; Alternative proteins; SDGs; Food security; Sustainability*

Control of Pale, Soft, Exudative (PSE) Meat and Improvement of Eating Quality through Nanoparticle Supplementation: Processing, Safety, and Value-Addition

Muhammad Ammar Khan*, Zulfiqar Ahmad

1 Department of Food Science and Technology, The Islamia University of Bahawalpur, Pakistan.

***Corresponding author's e-mail:** ammar@iub.edu.pk

Abstract

Pale, Soft, Exudative (PSE) meat is a processing defect of broiler breast meat that reduces water-holding capacity, increases drip and cooking losses, and lowers consumer acceptance. This study, conducted under PSF/NSLP/P-IUB (837) and funded under the Natural Sciences Linkage Program (NSLP) of the Pakistan Science Foundation (PSF), evaluated whether biofortification of zinc (Zn), iron (Fe), and selenium (Se) in conventional and nanoparticle (NP) forms during the finisher phase could control PSE and improve processing quality. PSE benchmarking was performed using control chicken breast samples, which showed 29.17% PSE incidence at 2 h postmortem and 33.33% at 24 h postmortem. At 24 h postmortem, conventional Zn treatments and one conventional Se treatment (0.1 mg/kg) yielded PSE meat, whereas all NP interventions yielded non-PSE meat at both 2 h and 24 h. Validation was performed using a colorimeter, which provided CIE L* (lightness), a* (redness), and b* (yellowness) values. The CIE L* values (49.27–52.93) confirmed that all biofortified samples remained non-PSE. Drip loss decreased significantly ($P \leq 0.05$) during 48 h of storage at refrigeration temperature (4°C) for most Zn, Fe, and Se treatments, and expressible moisture was reduced for Zn, Fe, and higher Se doses, indicating improved water-holding capacity (WHC). There were no significant differences among treatments for proximate composition, and sensory evaluation showed no loss of consumer acceptance after thermal processing. Biofortification offered no protection against two freeze–thaw cycles or thermal processing. These findings indicate that NP trace mineral biofortification can serve as a pre-harvest intervention to improve the processing quality and value of broiler breast meat without compromising safety or consumer acceptance.

Keywords: *PSE meat; Nanoparticles; WHC; Drip loss; Sensory evaluation; Value addition*

Importance of *Listeria monocytogenes* in Food Safety: Analysis of Its Prevalence in Food Products

Muhammad Hamza Mansoor¹, Hafiz Talha Hafeez^{1,2*}, Sobia Rafi³, Syed Hammad Mazhar²

1 National Institute of Food Science and Technology, University of Agriculture Faisalabad, Pakistan.

2 Department of Food Science and Technology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur, Pakistan.

3 Department of Zoology, Faculty of Chemical and Biological Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan.

***Corresponding author's e-mail:** Talhahafeez027@gmail.com

Abstract

Despite its relatively low incidence, *Listeria monocytogenes* is a significant foodborne pathogen associated with high hospitalization rates. Using secondary surveillance databases, the current study sought to evaluate *Listeria* prevalence trends, food vehicle associations, and severity indicators in both European (EU) and non-EU countries. The information was taken from the 2019–2023 foodborne outbreak dashboard of the European Food Safety Authority (EFSA). Throughout the study period, a variety of factors were examined, including outbreaks, hospitalizations, fatalities, human cases, food vehicles, causative agents, exposure locations, and reporting countries. The relationship between human cases and severity indicators was assessed using Microsoft Excel and descriptive and advanced statistical methods (regression analysis, one-way and two-way ANOVA, and the Bonferroni test). The results showed that hospitalizations (698), fatalities, outbreaks, and human cases (1007) were greater in EU nations than in non-EU ones, reflecting better reporting and monitoring systems. Additionally, hospitalization had the highest correlation with human cases, indicating that it is the most important measure of the severity of the illness. Death and outbreak incidence rates, on the other hand, showed weaker correlations, emphasizing that even a low incidence rate might have serious consequences. The trend analysis revealed a decrease in 2020 and 2021, followed by an increase in 2022, consistent with COVID-19-related regulations and restrictions in the food processing and catering industries. Higher outbreak frequencies were mostly caused by unknown food vehicles, although food vehicles such as meat and meat products demonstrated a substantial contribution to human cases. Domestic and multiple exposure locations were associated with a greater number of cases. Overall, the results show that *L. monocytogenes* is still a major foodborne pathogen that causes a substantial number of hospital admissions. To safeguard public health, however, focused control, enhanced monitoring procedures, strict hygiene practices, and genomic sequencing are crucial.

Keywords: *L. monocytogenes*; Food safety; Prevalence; European and non-European countries

Fabrication and Characterization of Cookies Fortified with Jujube Powder for Quality and Functional Properties

Sadaf Shakoor^{1*}, Muhammad Asif¹, Iraj Fatima², Anas Shakoor¹, Nadia Hameed¹

¹ Department of Food Science and Technology, UAF-Constituent College, Burewala, Pakistan.

² Government College Women University, Faisalabad, Pakistan.

*Corresponding author's e-mail: sadaf.shakoor@uaf.edu.pk

Abstract

The present study aimed to fabricate and characterize functional cookies fortified with jujube powder to enhance their nutritional and antioxidant properties. Jujube powder was incorporated into wheat flour at different concentrations (0%, 5%, 10%, and 15%) to evaluate its impact on the physicochemical, functional, antioxidant, and sensory attributes of the developed functional cookies. Results showed that jujube powder supplementation significantly increased crude fiber and ash content. Biofunctional properties (total phenolic content, flavonoids, antioxidant activity) improved proportionally with increasing jujube powder levels, indicating health-promoting potential. Physical parameters such as diameter, thickness, and spread ratio showed slight variations due to fiber addition. Texture analysis showed that hardness increased at higher concentrations of jujube powder. The color of the cookies changed significantly ($P \leq 0.05$), which may be attributed to the natural pigments present in jujube powder and to Maillard reactions. Sensory evaluation results showed that cookies containing 10% jujube powder were acceptable to sensory panelists. These findings indicate that jujube powder can be effectively utilized as a functional ingredient to develop nutritionally enriched bakery products. Incorporation at optimized levels offers a promising approach for producing value-added cookies that combine health benefits with consumer acceptability.

Keywords: Valorization; Cookies; Functional properties; Jujube powder

Sustainable Egg Replacement in Baking: Unlocking the Functional Potential of Okra Mucilage

Muhammad Mueed Tanveer Malik^{1*}, Muhammad Sameem Javed², Mehak Munir², Muhammad Zubair Khalid³

1 Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

2 Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

3 Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Punjab, Pakistan.

***Corresponding author's e-mail:** mueedtanveer22@yahoo.com

Abstract

The growing demand for vegan, allergen-conscious and sustainable bakery products has intensified the search for natural alternatives capable of reproducing the multifunctional role of eggs. This study investigated okra (*Abelmoschus esculentus*) mucilage as a plant-based egg replacer in cupcakes and evaluated its influence on nutritional composition, physicochemical properties, texture, color, structural characteristics and sensory acceptability. Cupcakes were prepared using an egg-based control and varying levels of okra mucilage (35–75 g). Incorporation of mucilage significantly influenced product quality, increasing moisture retention, fiber and ash content while progressively reducing protein and fat as egg was replaced. Among the formulations, T3, containing 55 g okra mucilage, demonstrated the most balanced performance, with moisture, protein, fat, fiber, and ash contents of 15.56%, 17.42%, 16.65%, 1.80%, and 1.06%, respectively, while maintaining desirable physicochemical characteristics. Sensory evaluation further identified T3 as the most acceptable egg-free formulation, achieving an overall acceptability score of 8 compared with 9 for the egg-based control and retaining favorable color, texture, crumb porosity, aroma, taste, and appearance. FTIR analysis confirmed successful incorporation of mucilage into the cupcake matrix through enhanced polysaccharide interactions without evidence of new compound formation during baking. Excessive mucilage incorporation negatively affected texture, color, flavor and overall acceptability. These findings demonstrate that okra mucilage, when used at an optimized level, can function as a promising natural egg replacer while maintaining acceptable technological and sensory quality, thus offering potential for the development of plant-based and allergen-conscious bakery products.

Keywords: *Abelmoschus esculentus; Okra mucilage; Plant-based egg replacer; Cupcakes; Sensory acceptability; Physicochemical properties; Sustainable bakery products*

Development and Evaluation of Cowpea-Enriched Energy Bars

Adeeba, Mamoon Amir*, Syeda Hania Gardezi

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Cowpea (*Vigna unguiculata*) is an underutilized legume rich in protein, dietary fiber, and minerals, making it a promising ingredient for fortifying snack foods. This study aimed to formulate, optimize, and nutritionally profile cowpea-enriched energy bars, and to evaluate their proximate composition, mineral content, functional properties, sensory acceptability, and microbial stability during storage. Cowpea flour was prepared through cleaning, soaking, dehulling, roasting, and milling, and was incorporated into energy bars at three substitution levels (10%, 20%, and 30%), alongside a commercial energy bar used as the control. Incorporation of cowpea flour significantly ($P \leq 0.05$) increased the protein, fiber, ash, and mineral (iron, calcium, and zinc) content of the energy bars as substitution levels increased, while carbohydrate content declined and moisture and fat content showed a modest rise. Functional properties of the flour, including water and oil absorption capacity and bulk density, improved progressively with higher cowpea inclusion. Sensory evaluation revealed that the 10% cowpea formulation achieved the highest scores for taste, texture, aroma, and overall acceptability, while acceptability declined at higher substitution levels (20% and 30%) due to a more pronounced legume flavor and firmer texture, although all formulations remained within acceptable sensory limits. Microbial analysis confirmed that all formulations were safe and stable, with total plate counts and yeast and mold counts remaining within acceptable limits throughout the 30-day storage period. Further research is recommended on extended shelf-life testing, vitamin fortification, and large-scale consumer acceptance to support commercial development.

Keywords: Cowpea (*Vigna unguiculata*); Energy bars; Functional food; Proximate composition; Protein; Dietary fiber; Mineral fortification; Sensory evaluation; Shelf stability

Effect of Fenugreek-Quinoa Functional Snack Balls on Metabolic Parameters in Type 2 Diabetes

Mahnoor Jameel, Mamoon Amir*, Syeda Hania Gardezi

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Diabetes mellitus (DM) is a metabolic disorder characterized by elevated blood glucose and insulin resistance. This study evaluated the effects of fenugreek–quinoa functional snack balls on nutritional, biochemical, and hematological parameters in individuals with type 2 diabetes mellitus. The snack balls were formulated using fenugreek, quinoa, psyllium husk, extra virgin olive oil, and stevia at three treatment levels: T1 (5%), T2 (8%), and T3 (10% fenugreek–quinoa). Fifty participants were divided into five groups, including negative control, positive control, and three treatment groups (n=10 each), and monitored for 90 days. Proximate composition, dietary fiber, minerals, total phenolic content (TPC), total flavonoid content (TFC), saponins, and alkaloids were determined. Sensory evaluation indicated good acceptability, with stevia effectively masking the bitterness of fenugreek. T3 showed the highest nutritional and bioactive values, including energy (432.00 ± 8.64 kcal/100 g), TPC (22.50 ± 0.45), TFC (10.80 ± 0.22), saponins (2.80 ± 0.06), and alkaloids (0.90 ± 0.02). After 90 days, T3 demonstrated the greatest reductions in body weight, blood glucose, HbA1c, cholesterol, triglycerides, LDL, CRP, and insulin levels, while HDL increased. Hematological parameters, including hemoglobin, erythrocytes, hematocrit, and platelets, also improved. Fasting, postprandial, and random blood glucose decreased by 36.7, 40.1, and 49.4 mg/dL, respectively, while HbA1c decreased by 1.083%. Overall, the 10% fenugreek–quinoa formulation showed the most pronounced improvements in metabolic and hematological parameters and may have potential as a functional dietary intervention for type 2 diabetes management.

Keywords: Fenugreek; Quinoa; Functional snack; Type 2 diabetes mellitus; Blood glucose; HbA1c; Lipid profile; Dietary fiber; Metabolic health

Protective Effects of Lyophilized Fermented Pumpkin Seed (*Cucurbita maxima*) and Black Seed (*Nigella sativa*) Powders Against Cisplatin-Induced Nephrotoxicity in Rodents

Minza Saleem, Mamoon Amir*, Syeda Hania Gardezi

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Cisplatin is a widely used chemotherapeutic agent that can cause acute kidney injury through oxidative stress and inflammation. The present study was conducted to evaluate the nephroprotective effects of lyophilized fermented *Nigella sativa* and *Cucurbita maxima* seed powders against cisplatin-induced nephrotoxicity in rats. An experimental study was conducted on 30 male and female Wistar rats divided into 5 groups (n=6). Nephrotoxicity was induced by intraperitoneal administration of cisplatin (5 mg/kg body weight), followed by supplementation with fermented seed powders according to the treatment protocol. Renal and hepatic biomarkers, lipid profile, antioxidant and oxidative stress markers, inflammatory cytokines, hematological parameters, electrolytes, and renal histopathology were evaluated. Cisplatin markedly increased renal injury biomarkers, oxidative stress, inflammatory markers and histopathological damage, while reducing antioxidant defense and impairing biochemical and hematological parameters. Supplementation with fermented *Cucurbita maxima* and *Nigella sativa* seed powders attenuated these adverse effects, with combined supplementation showing the strongest protective response. The findings suggest that lyophilized fermented *Nigella sativa* and *Cucurbita maxima* seed powders possess promising nephroprotective potential against cisplatin-induced renal toxicity, mainly through antioxidant and anti-inflammatory effects.

Keywords: *Cucurbita maxima*; *Nigella sativa*; Fermentation; Lyophilization; Cisplatin-induced nephrotoxicity; Nephroprotection; Oxidative stress; Renal injury

Health Assessment of Whole and Processed Wheat Flour in Type 2 Diabetes

Afrah Abubakar, Mamoon Amir*, Syeda Hania Gardezi

Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

*Corresponding author's e-mail: mamoonameer@bzu.edu.pk

Abstract

Dietary habits play a critical role in managing Type 2 Diabetes Mellitus (T2DM), particularly with respect to the quality and type of carbohydrates being consumed. Diets rich in refined carbohydrates, such as processed wheat flour (white flour), have been associated with poor glycaemic control, whereas whole-grain consumption has been considered to exert beneficial metabolic effects. A cross-sectional study was carried out among 124 patients diagnosed with T2DM. Participants were divided into two groups based on habitual intake of flour: whole-wheat consumers (n=63) and processed flour consumers (n=61). A questionnaire was used to collect data, and sociodemographic, clinical, dietary, and biochemical parameters were assessed. These included HbA1c (glycaemic control), liver function (ALT, AST, ALP, bilirubin), haematological indices (RBCs, haemoglobin, WBCs, platelets), and serum micronutrients (iron and zinc). Statistical analysis was performed using Statistix software (version 8.1), with $p < 0.05$ considered statistically significant. Participants consuming whole-wheat flour demonstrated lower HbA1c levels (8.03%) compared with those consuming processed flour (10.04%) ($P \leq 0.05$). ALT and AST levels were significantly elevated in the processed flour group, whereas no significant differences were observed in ALP and bilirubin levels. RBC count and haemoglobin levels differed significantly between groups, while WBC and platelet count showed no statistically significant variation. Additionally, serum iron and zinc levels were significantly lower among processed flour consumers. The findings of this study suggest that consumption of processed flour is associated with poorer glycaemic control, altered liver enzyme levels, less favorable haematological indices, and decreased micronutrient levels in individuals with T2DM. These results indicate that whole-wheat consumption may play a beneficial role in dietary management strategies aimed at improving nutritional and metabolic outcomes in this population.

Keywords: Type 2 diabetes mellitus; Whole-wheat flour; Refined flour; HbA1c; Liver function

Identifying Genomic Regions Associated with Drought Response in Bread Wheat

Muhammad Qadir Ahmad^{1*}, Babar Islam¹, Attiq Saleem²

1 Department of Plant Breeding and Genetics, Bahauddin Zakariya University, Multan, Pakistan.

2 Plant Genetic Resources Program, Plant Genetic Resources Institute, NARC Islamabad 45500, Pakistan.

***Corresponding author's e-mail:** mqadirahmad@bzu.edu.pk

Abstract

Drought stress poses a major threat to wheat production in water-limited environments. Identifying genetic variation associated with drought response is therefore essential for developing more resilient cultivars. In this study, 300 bread wheat (*Triticum aestivum* L.) genotypes, including cultivars, synthetic derivatives, and improved lines, were evaluated under well-watered and drought-stressed field conditions. The experiment followed a randomized complete block design with three replications, and drought stress was imposed by withholding irrigation after the first irrigation. Key morphological, physiological, phenological, and yield-related traits were recorded, including days to 50% heading, days to 50% physiological maturity, plant height, peduncle length, chlorophyll content, relative water content, canopy temperature, spikes per plant, thousand-grain weight, and grain yield per plant. Based on this characterization, a diverse subset of 137 genotypes was selected for genotyping-by-sequencing and genome-wide association analysis. Significant differences were observed among genotypes and between water treatments for the traits studied. Principal component analysis distinguished variation in drought response and helped identify contrasting genotypes. These contrasting genotypes were grouped into five sub-clusters by population structure analysis. Genome-wide association analysis identified various significant marker–trait associations distributed across multiple chromosomes. Under drought stress, marker 5A_617251477 was associated with thousand-grain weight, while 2D_503232263 was associated with grain yield per plant. Markers 7A_555438663 and 2B_26494866 were associated with days to heading under both water treatments. These findings highlight the complex genetic basis of drought response and provide candidate markers and germplasm for further validation and use in wheat breeding.

Keywords: *Linkage disequilibrium; Population structure; Genome-wide association; Water-limited environments*

Nanomaterials for Plant Disease Diagnosis and Control

Muhammad Shahid^{1*}, Young-ki Jo²

1 Department of Bioinformatics and Biotechnology, Government College University, Faisalabad, Pakistan.

2 Department of Plant Pathology and Microbiology, Texas A&M University, USA.

***Corresponding author's e-mail:** mshahid@gcuf.edu.pk

Abstract

Plant diseases are causing huge damage to agricultural crops around the globe, and the loss in yield occasionally reaches 75%. Thus, reliable strategies to control the destruction caused by phytopathogens in agricultural farms are imperative. Several conventional diagnostic procedures are used to detect phytopathogens, including serological, immunological, and nucleic acid-based detection techniques. Many of these procedures have limitations, such as the requirement of prior knowledge about the pathogen, low sensitivity, and an inability to detect several plant pathogens simultaneously. The use of nanomaterials for sustainable control and timely diagnosis of plant diseases has been largely neglected. Various nanomaterials have been extensively used in almost all fields of life; however, there is limited knowledge and application of these nanomaterials for the early diagnosis and control of plant diseases. Nano-sensors coupled with biomarkers could serve as efficient tools in plant disease diagnosis. Such sensors not only detect disease at an early stage but also quantify pathogen levels, enabling the development of effective control strategies. We developed functionalized CNTs that leverage both their magnetic properties and antibody conjugation capabilities to improve polymerase chain reaction (PCR) diagnostics of *X. fastidiosa*, a phytopathogen of pecan. The results indicate that CNTs significantly enhance the efficiency of target capture for *X. fastidiosa*, thereby increasing the sensitivity and reliability of pathogen detection compared with conventional DNA extraction methods and Dynabeads, a commercial immunomagnetic material. Moreover, we synthesized green nanoparticles to effectively control various phytopathogens.

Keywords: *Nanomaterials; Phytopathogens; Detection; Xylella; Antimicrobials*

Unraveling Genetic Variability and Trait Relationships in Pearl Millet (*Pennisetum glaucum* L.) Germplasm

Attiqua Saleem*, Nadar Khan, Asif Javaid

Plant Genetic Resources Program, Plant Genetic Resources Institute, National Agriculture Research Center (NARC), Islamabad 45500, Pakistan.

*Corresponding author's e-mail: attiqasaleem2@gmail.com

Abstract

Pearl millet (*Pennisetum glaucum* L.) is an important dual-purpose crop used as both fodder and a cereal grain. It is a rich source of protein, carbohydrates, minerals, vitamins, and polyphenols. In this study, 47 pearl millet accessions were evaluated using an Augmented Randomized Complete Block Design with two checks (Super Bajra 1 and ICH220). The experiment was conducted to evaluate 13 agro-morphological parameters, including 11 quantitative and 2 qualitative traits, such as plant height (PH), stem diameter (SD), number of tillers (NOT), number of leaves (NOL), number of nodes (NON), panicle length (PAL), peduncle length (PL), panicle thickness (PT), plant total weight (PTW), thousand-seed weight (TSW), leaf area (LA), synchronization of ear maturity, and lodging susceptibility. Statistical analyses, including ANOVA, correlation, and principal component analysis (PCA), were performed using R statistical software. The germplasm displayed considerable phenotypic variability for PH, SD, NOT, NOL, PAL, PL, PT, PTW, TSW and LA. Various traits, such as PH, showed a significant positive association with LA, while SD showed a negative association with PT. Principal component analysis revealed that the first two PCs exhibited eigenvalues greater than 1 and cumulatively explained 40% of the total variance, with major loadings from PH, LA, NOL, NON, NOT, and PAL. Accessions 8311, 8548, and 8292 performed well and have potential as valuable parental material for future breeding programs.

Keywords: Pearl millet; Genetic parameters; Biplot; Correlation; PCA

Physiological and Biochemical Screening of Maize Hybrids in Response to Heat Stress under Contrasting Sowing Dates

Shabir Hussain, Muhammad Adnan Yousaf*, Zeemal Urooj

Institute of Agronomy, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan-60800, Pakistan.

***Corresponding author's e-mail:** adnanyousaf.1818@gmail.com

Abstract

High temperatures during vegetative growth can restrict maize (*Zea mays* L.) growth and alter several physiological and biochemical processes. This study evaluated ten maize hybrids for their response to high-temperature conditions at Multan, Pakistan. The hybrids were sown on 15 February and 15 March 2022 and assessed 40 days after sowing. The March-sown crop experienced relatively higher temperatures during its growth period and was used to evaluate differences in heat response among the hybrids. Late sowing decreased emergence by 8.3%, plant height by 17.1%, crop growth rate by 17.5%, leaf area index by 14.9%, and root length by 12.0% compared with normal sowing. Likewise, SPAD value, relative water content and membrane stability index declined by 12.9, 8.7 and 21.3%, respectively. However, the extent of these reductions differed among hybrids. H10 maintained better growth and physiological functioning under late sowing, recording 96% emergence, 65 cm plant height, 14.7 cm root length, a SPAD value of 47, 86% relative water content, 78% membrane stability index, a root:shoot ratio of 0.31, and canopy temperature depression of 1.21°C. Its biochemical response also indicated better adjustment to heat stress, with a favorable proline response, stronger superoxide dismutase, catalase and peroxidase activities, and comparatively lower H₂O₂ accumulation and lipid peroxidation. In contrast, H9 showed greater oxidative damage, weaker antioxidant protection and larger reductions in growth and physiological traits under late sowing. These findings indicate clear differences in heat response among the tested maize hybrids. H10 maintained better water status, membrane integrity, antioxidant defense and growth under warmer conditions, while H9 was comparatively heat sensitive. Thus, H10 represents promising material for further field evaluation and selection for maize production under high-temperature environments.

Keywords: *Maize; Heat stress; Antioxidant defense; Oxidative damage; Physiological traits; Sowing date*

Zinc-Mediated Alleviation of Heat Stress in Contrasting Maize Hybrids under Different Sowing Dates

Shabir Hussain, Muhammad Adnan Yousaf*, Zeemal Urooj

Institute of Agronomy, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan-60800, Pakistan.

***Corresponding author's e-mail:** adnanyousaf.1818@gmail.com

Abstract

Heat stress during early growth can considerably restrict maize (*Zea mays* L.) development, particularly in heat-sensitive genotypes. Zinc (Zn) nutrition may help plants withstand high temperature by supporting physiological and cellular processes involved in stress tolerance. A pot study was therefore conducted at Multan, Pakistan, to examine the response of heat-sensitive (H1) and heat-tolerant (H2) maize hybrids to different Zn levels under contrasting thermal environments. The two hybrids, selected from an earlier screening experiment, were sown on 15 February and 15 March 2023 and supplied with five Zn treatments (Zn0–Zn4). Plants were harvested 40 days after sowing and evaluated for growth, physiological and biochemical responses. Late sowing had a stronger negative effect on H1 than on H2. Plant height of H1 declined from 75.44 cm under normal sowing to 60.62 cm under late sowing, whereas H2 maintained 78.52 cm compared with 81.02 cm under normal sowing. Heat-induced reductions were also evident in leaf area, root growth, chlorophyll status, plant water relations and membrane stability. Zinc application lessened these effects, with Zn4 producing the most consistent improvement across the measured traits. Relative to Zn0, Zn4 increased mean crop growth rate by 22.7%, leaf area index by 25.5%, root length by 23.5%, SPAD value by 20.0%, relative water content by 11.6%, membrane stability index by 14.4%, and root:shoot ratio by 26.9%. Zinc-treated plants also maintained greater canopy temperature depression, indicating an improved ability to regulate canopy temperature under stressful conditions. The biochemical response followed a similar pattern. Zinc application supported osmotic adjustment and antioxidant defense, with favorable proline accumulation and stronger superoxide dismutase, catalase and peroxidase activities, while limiting H₂O₂ accumulation and lipid peroxidation. These protective responses were more pronounced in H2, whereas H1 showed greater oxidative injury under late sowing, particularly in the absence of Zn. Among the tested treatments, Zn4 provided the most consistent protection against heat-induced damage in both hybrids. In conclusion, adequate Zn nutrition improved physiological stability and antioxidant defense of maize exposed to high-temperature conditions, with the magnitude of the response depending on inherent genotypic heat tolerance.

Keywords: *Maize; Zinc nutrition; Heat stress; Antioxidant defense; Oxidative damage; Physiological response*

Effect of Different Sowing Dates and Zinc Levels on Growth and Productivity of Wheat

Hakoomat Ali, Shabir Hussain*, Muhammad Ehtisam Sohaib

Institute of Agronomy, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan, Pakistan.

***Corresponding author's e-mail:** shabirhussain@bzu.edu.pk

Abstract

Wheat (*Triticum aestivum* L.) is the most important cereal crop used as a staple food in Pakistan. Its productivity is greatly influenced by sowing time and nutrient management. To address this issue, a field study was conducted during the 2025–26 Rabi season to evaluate the impact of different sowing dates and zinc levels on the growth and productivity of wheat. This study was conducted at Ansari Farm, Multan, Pakistan. The experiment was laid out in a Randomized Complete Block Design (RCBD) with a factorial arrangement, replicated three times. Experimental treatments comprised two sowing dates, viz. 20 November 2025 and 10 December 2025, and three zinc levels, viz. control (no zinc application), 0.5% ZnSO₄ (3.5 ml in 0.7 L water), and 0.5% ZnSO₄ (7 ml in 0.7 L water). The results revealed that both sowing dates and zinc levels significantly affected crop growth and increased yield. Wheat sown on 20 November 2025 significantly improved plant height (99.1 cm), spike length (12.6 cm), spikelets per spike (17.2), grains per spike (56), number of tillers per meter (443), 1000-grain weight (44.7 g), biological yield (11,640 kg ha⁻¹), and grain yield (3,820 kg ha⁻¹) compared with wheat sown on 10 December 2025. Similarly, increasing zinc concentration significantly improved all growth and yield attributes. The highest values for plant height (95.2 cm), spike length (11.8 cm), spikelets per spike (16.53), grains per spike (49), number of tillers per meter (422), 1000-grain weight (42.6 g), biological yield (11,263 kg ha⁻¹), and grain yield (3,583 kg ha⁻¹) were recorded with foliar application of 0.5% ZnSO₄ (7 ml in 0.7 L water). The combination of timely sowing (20 November) along with the higher zinc level (7 ml in 0.7 L water) significantly affected crop performance. In conclusion, the best wheat growth and productivity can be obtained through the integration of optimum sowing time and adequate zinc nutrition, viz. sowing wheat on 20 November combined with foliar application of 0.5% ZnSO₄ (7 ml in 0.7 L water). Hence, it is further recommended that farmers adopt this combination to achieve higher and sustainable wheat yields.

Keywords: *Wheat; Sowing date; Zinc sulphate; Foliar application; Grain yield; Wheat productivity*

Paclobutrazol-Mediated Alleviation of Temporary Waterlogging Stress in Sesame through Improved Physiological, Biochemical and Yield Responses

Muhammad Adnan Yousaf^{1*}, Wali Muhammad¹, Zeemal Urooj², Maryam Malik³, Lubna Altaf³

¹ PARC Research and Training Station, Pakistan Agricultural Research Council, BZU, Multan-60800, Pakistan.

² Institute of Agronomy, Bahauddin Zakariya University, Multan-60800, Pakistan.

³ Institute of Botany, Bahauddin Zakariya University, Multan-60800, Pakistan.

*Corresponding author's e-mail: adnanyousaf.1818@gmail.com

Abstract

Temporary waterlogging can severely constrain sesame (*Sesamum indicum* L.) production by restricting root-zone aeration and disrupting plant growth, physiological functioning and reproductive development. A field experiment was conducted at the PARC Research and Training Station, Bahauddin Zakariya University, Multan, Pakistan, during 2026 to investigate whether foliar application of paclobutrazol (PBZ) could improve the tolerance of sesame cultivar TS-3 to short-term waterlogging. Waterlogging was imposed at the vegetative stage (30–35 days after sowing) by maintaining 5–7 cm standing water for 72 h, followed by drainage and recovery under normal field conditions. Temporary waterlogging markedly restricted sesame performance, as reflected by reductions in plant height, stem diameter, leaf production, root growth, chlorophyll status and crop growth rate. Application of PBZ moderated several of these adverse responses, although the magnitude of improvement depended on concentration. The better-performing PBZ treatment maintained root length at approximately 36 cm compared with 28–30 cm in the untreated waterlogged plants and produced the highest SPAD value, indicating improved chlorophyll retention. Crop growth rate, which declined from approximately 18.7 g m⁻² day⁻¹ under normal irrigation to 13.8 g m⁻² day⁻¹ following waterlogging, recovered to approximately 16.5–16.8 g m⁻² day⁻¹ under the better-performing PBZ treatments. Physiological and biochemical assessment included relative water content, membrane stability, electrolyte leakage, proline accumulation, superoxide dismutase, catalase and peroxidase activities, and the oxidative-damage indicators hydrogen peroxide and malondialdehyde. These traits were used to determine whether PBZ-mediated recovery was associated with improved cellular hydration, osmotic adjustment, membrane protection and antioxidant defense. The agronomic assessment included plant height, stem diameter, branches and leaves plant⁻¹, root length, leaf area, biomass accumulation, capsules plant⁻¹, seeds capsule⁻¹, 1000-seed weight, biological yield, seed yield and harvest index. Waterlogging reduced capsule formation to 72 capsules plant⁻¹ compared with 95 under normal irrigation, whereas the best-performing PBZ treatment restored capsule production to 96 capsules plant⁻¹. Overall, the findings indicate that an appropriate PBZ concentration can partially offset the detrimental effects of temporary waterlogging by maintaining vegetative growth, root development, chlorophyll status and reproductive performance.

Keywords: *Sesamum indicum*; Paclobutrazol; Waterlogging; Oxidative stress; Antioxidant defense; Seed yield; Climate resilience

Foliar Salicylic Acid Improves Drought Tolerance of Sesame through Better Growth and Physiological Performance

Muhammad Adnan Yousaf^{1*}, Wali Muhammad¹, Zeemal Urooj², Hira Liaqat³, Tayyaba Aziz³

1 PARC Research and Training Station, Pakistan Agricultural Research Council, BZU, Multan-60800, Pakistan.

2 Institute of Agronomy, Bahauddin Zakariya University, Multan-60800, Pakistan.

3 Institute of Botany, Bahauddin Zakariya University, Multan-60800, Pakistan.

***Corresponding author's e-mail:** adnanyousaf.1818@gmail.com

Abstract

Drought during reproductive growth is an important constraint to sesame (*Sesamum indicum* L.) production in arid and semi-arid environments. A field experiment was conducted at the PARC Research and Training Station, Bahauddin Zakariya University, Multan, Pakistan, during 2026 to evaluate the potential of foliar-applied salicylic acid (SA) to alleviate drought stress in sesame. The crop was sown on 15 April 2026, and the experiment was laid out in a randomized complete block design with three replications. Six treatments consisted of normal irrigation without SA (T₁), drought stress without SA (T₂), and drought stress combined with 0.5, 1.0, 1.5 or 2.0 mM SA (T₃–T₆, respectively). Drought stress was imposed by withholding irrigation at flowering, while SA was applied as a foliar spray around the onset of the stress period. Water deficit markedly restricted sesame growth and physiological performance. Compared with the normally irrigated treatment, untreated drought-stressed plants showed reductions in plant height, stem diameter, branches plant⁻¹, leaves plant⁻¹, leaf area index, crop growth rate, relative water content and SPAD chlorophyll value. Salicylic acid application alleviated these reductions, but the response varied with concentration. Among the SA treatments, 1.5 mM produced the most consistent improvement, increasing crop growth rate from 10.7 to 13.6 g m⁻² day⁻¹, relative water content from 75.5 to 83.1%, and SPAD value from 34.9 to 43.1 compared with drought stress without SA. The same treatment maintained 50 leaves plant⁻¹ and a leaf area index of 3.8 and increased root length from 26.5 to 34.6 cm under drought. Increasing SA concentration to 2.0 mM did not provide an additional benefit for most measured traits, indicating a concentration-dependent response. Physiological assessment, together with biochemical indicators including proline accumulation, antioxidant enzyme activity and markers of oxidative damage, was used to characterize the stress-mitigation response. Yield assessment included capsules plant⁻¹, seeds capsule⁻¹, 1000-seed weight, biological yield, seed yield and harvest index. Overall, 1.5 mM foliar SA provided the most consistent improvement in sesame growth and physiological functioning under water deficit and represents a promising concentration for further validation based on complete biochemical and yield performance under semi-arid conditions.

Keywords: *Sesame; Salicylic acid; Drought stress; Water relations; Antioxidant defense; Physiological response*

Nutritional and Yield Appraisal of Winter Forage Cereal Hay under Varying Nitrogen Regimes in Temperate Conditions

Muhammad Jamil*, Muhammad Shehzad, Khalid Mehmood, Sadaf Khalid, Hira Abbasi, Irfanullah, Qamar Ali Khan and Reena Mehmood

Department of Agronomy, Faculty of Agriculture, University of Poonch Rawalakot, AJK, Pakistan.

*Corresponding author's e-mail: m.jamilupr@gmail.com

Abstract

Winter forage cereals are a valuable source of quality forage, available throughout winter until early spring. The study aimed to evaluate the nutritional quality and yield of winter forage cereal (WFC) hay from barley, oats, rye, and triticale at the booting stage. A field trial was conducted during 2016–2017 and 2017–2018 at the research farm of the University of Poonch, using four WFCs and four nitrogen rates (0, 75, 150, and 225 kg ha⁻¹). The WFCs were sown using a factorial arrangement in a Randomized Complete Block Design (RCBD). Yield samples were obtained from each experimental unit to calculate fresh and dry weight. Moreover, 500 g of fresh fodder samples were dried in an oven at 65°C for 48 hours until a constant weight was reached, for nutritional assessment at the booting stage. Rye followed by triticale produced the maximum forage dry biomass yield (18,471 and 12,440 kg ha⁻¹, respectively) and fresh biomass yield (55,413 and 43,542 kg ha⁻¹, respectively) in response to N3. The highest CP (12.9% and 13.1%) and ash (13.27% and 13.48%) contents were recorded for rye under N3, whereas barley showed the maximum TDN (76.47% and 76.52%), DMI (3.53% and 3.25%), and RFV (201.58 and 199.66%) values under the same nitrogen level. Furthermore, rye showed the highest ADF (32.7% and 33.2%) and NDF (49.4% and 50.2%) contents under N0. The WFCs performed best at the optimized nitrogen level. These characteristics are critical in hay production for harvesting maximum valuable forage energy. Based on these results, rye and triticale are recommended as the most suitable options for hay preservation, offering better nutritional quality under the temperate conditions of Rawalakot.

Keywords: *Winter forage cereals; Nitrogen; Hay; Nutrition*

Alleviation of Water Deficit in Mungbean through Potassium-Mediated Seed Priming and Exogenous Application

Mudassir Aziz*, Babar Ali, Khuram Mubeen, Abdul Ghaffar

Department of Agronomy, MNS University of Agriculture, Multan, Pakistan.

***Corresponding author's e-mail:** mudassir.aziz@mnsuam.edu.pk

Abstract

Mungbean (*Vigna radiata* L.) is an important pulse crop grown all over the world. Although mungbean is considered a drought-tolerant crop, water deficit at critical growth stages severely affects its growth and productivity. Seed priming is one of the most promising techniques used to mitigate the harmful effects of water deficit by improving crop growth and yield. Potassium is an essential element involved in water relations, enzyme activation, and the regulation of various physiological processes in plants. Seed priming with potassium may alleviate the negative effects of water deficit in mungbean. A field experiment was conducted at the research farm of MNS University of Agriculture, Multan, to evaluate the role of KCl seed priming in inducing drought tolerance in mungbean. The experiment was laid out in a Randomized Complete Block Design with a split-plot arrangement. Two irrigation regimes—I1 = normal irrigation and I2 = drought at the reproductive stage—were assigned to the main plots, while six seed priming treatments, with and without exogenous foliar application of KCl (T1 = no priming, T2 = hydropriming, T3 = priming with 2% KCl, T4 = no priming + 1% KCl sequential spray, T5 = hydropriming + 1% KCl sequential spray, and T6 = priming with 2% KCl + 1% KCl sequential spray), were assigned to the sub-plots. Drought was imposed by skipping irrigation at 40 days after sowing. Standard procedures were used for data collection. Collected data were analyzed using analysis of variance (ANOVA), and the HSD Tukey's test at the 5% probability level was used to compare differences between treatment means. Drought significantly affected various agronomic and yield traits, including plant height, branches plant⁻¹, pods plant⁻¹, grains per pod, 1000-grain weight, grain yield, biological yield, and harvest index. Seed priming improved various agronomic and yield-related traits compared with non-primed seed, except for the number of grains per pod. The interaction of irrigation regimes and seed priming treatments was significant for leaf area ratio and leaf area duration recorded at both 45 and 65 days after sowing, net assimilation rate, biological yield and membrane stability index. The highest net assimilation rate (19.25 g m⁻² day⁻¹) was recorded with hydropriming + 1% KCl sequential spray under normal irrigation. Under drought, the maximum pods per plant (41), grains per pod (10.33), and 1000-grain weight (34.6 g) were recorded in T5 (hydropriming + 1% KCl sequential spray). The maximum branches per plant (10.33), pods per plant (46.67), grain yield (750.38 kg ha⁻¹), biological yield (1923.54 kg ha⁻¹), harvest index (38.99%), relative water content (75.26%), chlorophyll content (44.75), and membrane stability index (83.95%) were also recorded in T5 (hydropriming + 1% KCl sequential spray).

Keywords: *Cell membrane stability; Grain yield; Potassium chloride; Vigna radiata* L.; *Water deficit*

Morphological and Biochemical Evaluation of Soybean Cultivar Rawal-1 in Response to Seed Treatment and Foliar Application of GA3 and 2,4-D

Muhammad Shehzad^{1*}, Sajid Munir¹, Khalid Mehmood¹, Muhammad Jamil¹, Sadaf Khalid¹, Majid Mehmood Tahir² and Mehdi Maqbool³

¹ Department of Agronomy, University of Poonch Rawalakot, Pakistan.

² Department of Soil and Environmental Sciences, University of Poonch Rawalakot, Pakistan.

³ Department of Horticulture, University of Poonch Rawalakot, Pakistan.

*Corresponding author's e-mail: m.shahzaduaf@gmail.com

Abstract

Plant growth regulators can influence physiological efficiency and photosynthetic ability and can improve the successful partitioning of assimilates from source to sink in field crops. There is little data on the role of growth regulators in the manifestation of yield components and seed quality of soybean (*Glycine max* L.). This study was therefore undertaken to examine the role of the plant growth regulators auxin (2,4-D) and gibberellin (GA3), applied at 30, 60, and 90 mg L⁻¹. Growth regulators were applied as seed treatment before sowing and as a foliar spray at the physiological stage of flower initiation. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replicates. The study aimed to increase soybean yield through the foliar application of growth regulators. The data were statistically analyzed using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. Seed treatment with 2,4-D at 90 mg L⁻¹ resulted in the highest plant height, first-node height, number of branches per plant, root length, stem diameter, number of pods per plant, seed yield, biological yield, and harvest index. GA3 seed treatment at 90 and 60 mg L⁻¹ produced a significantly higher number of nodules per plant, nodule fresh weight, and nodule dry weight. The number of seeds per pod did not differ significantly among treatments. Foliar application of 2,4-D at 90 mg L⁻¹ produced significantly greater leaf area compared with seed treatment. Growth regulators also significantly affected quality traits. The response to plant growth regulators was notable in promoting soybean as a successful oilseed crop. Thus, the application of plant growth regulators proved beneficial for achieving maximum growth, higher yield, and improved quality of soybean under rainfed conditions.

Keywords: Growth regulators; Soybean; Seed treatment; Foliar application; GA3; 2,4-D

Anti-Nutritional Factors in Foods: Impact on Nutrient Utilization and Control Strategies

Shah Fahad

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan.

Corresponding author's e-mail: dilwaleking389@gmail.com

Abstract

Anti-nutritional factors (ANFs) are naturally occurring substances in many plant-based foods that hinder the digestion and absorption of essential nutrients. These compounds can significantly diminish the bioavailability of proteins, vitamins, and minerals, ultimately affecting the overall nutritional value of foods. Common anti-nutrients, including phytic acid, tannins, oxalates, saponins, lectins, protease inhibitors, amylase inhibitors, cyanogenic glycosides, nitrates, and certain alkaloids, are prevalent in legumes, cereals, vegetables, and other plant sources. ANFs can be categorized into two main groups: heat-stable compounds (such as phytic acid, tannins, saponins, alkaloids, and non-protein amino acids) and heat-labile compounds (including lectins, cyanogenic glycosides, protease inhibitors, and specific toxic amino acids). The presence of these compounds often leads to lower protein digestibility and reduced mineral bioavailability in legumes and similar foods. Interestingly, while many anti-nutrients have negative impacts on nutrition, some offer beneficial physiological effects when consumed in moderation. For instance, phytic acid, tannins, saponins, and enzyme inhibitors have been associated with reduced post-meal blood glucose spikes, decreased insulin response, and lower cholesterol and triglyceride levels. Various processing techniques, such as soaking, germination, boiling, autoclaving, fermentation, and genetic modification, have been effective in mitigating anti-nutritional factors and improving nutrient availability. Nonetheless, additional research is needed to eliminate heat-stable anti-nutrients without compromising the nutritional and functional integrity of food.

Keywords: *Anti-nutritional factors; Phytic acid; Tannins; Cyanogenic glycosides; Nutrient bioavailability; Food processing*

Ensuring Food Security through Sustainable and Climate-Smart Agricultural Practices

Wafa Zahra, Wafa Batool, Sadaf Javaria*

Institute of Food Science and Nutrition, Gomal University, Dera Ismail Khan, Pakistan.

***Corresponding author's e-mail:** sadafjavaria@gu.edu.pk

Abstract

As the global population approaches ten billion by mid-century, the dual challenges of food insecurity and climate change pose unprecedented threats to global livelihoods, social stability, and ecological balance. Traditional agricultural methods characterized by heavy resource consumption, soil degradation, and high greenhouse gas emissions are increasingly vulnerable to extreme weather events, unpredictable precipitation patterns, and shifting agro-ecological zones. This study investigates the integration of Climate-Smart Agriculture (CSA) and sustainable farming practices as a vital framework to achieve long-term food security while preserving natural resources. By analyzing the three core pillars of CSA—sustainably increasing agricultural productivity, building resilience to climate change (adaptation), and reducing or removing greenhouse gas emissions (mitigation)—this paper evaluates key interventions including conservation agriculture, precision farming, crop diversification, agroforestry, and efficient water management systems. Furthermore, the role of digital technologies, climate-resilient crop varieties, and community-led socio-economic strategies is examined to illustrate how smallholder and commercial farmers can adapt to ecological shifts. The findings demonstrate that adopting sustainable and climate-smart practices significantly boosts crop yields, improves soil health, optimizes water efficiency, and strengthens rural livelihoods. Finally, the paper outlines actionable policy recommendations, emphasizing the necessity of scalable financing, cross-sectoral collaboration, and targeted technology transfer to build resilient, sustainable food systems capable of nourishing future generations.

Keywords: *Food security; Climate-smart agriculture (CSA); Sustainable farming; Agricultural resilience; Climate mitigation; Soil health; Resource management*

Traditional Milk Processing in Pakistan: Opportunities for Sustainable and Climate-Resilient Food Systems

Mian Anjum Murtaza

Institute of Food Science and Nutrition, University of Sargodha, Sargodha-40100, Pakistan.

Corresponding author's e-mail: anjum.murtaza@uos.edu.pk

Abstract

Pakistan's indigenous dairy sector relies on traditional processing techniques, including fermentation, churning, heat concentration, acid coagulation, and dehydration, to convert perishable raw milk into functional, culturally preferred foods such as *dahi*, *lassi*, *butter*, *desi ghee*, *khoya*, and *paneer*. These isolated, low-energy transformation processes overcome post-harvest losses, strengthen rural food security, and support household livelihoods. Amid escalating climate vulnerabilities such as heat stress, heavy rains and floods, fodder deficits, and extreme weather events that affect livestock productivity and smallholder viability, indigenous milk systems demonstrate operational flexibility with local breeds, small-scale processing, and climate-smart resources. From a food technology perspective, indigenous milk-based foods offer substantial prospects for exploring and improving nutritional composition, microbial aspects, fermentation processes, physicochemical properties, bioactive components, safety, shelf stability, and sensory attributes. Fermented milk products offer the desired quality and organoleptic characteristics; moreover, traditional processing and preservation techniques can broaden the product range and reduce post-harvest losses. This study examines the potential of indigenous milk-based foods as nutritionally and traditionally significant, climate-resilient components of sustainable food systems. It proposes an integrated approach linking indigenous knowledge with food science, climate-smart agriculture, better hygiene practices, minimum processing, proper packaging, value addition, and traceable marketing to cope with the changing climate and food system challenges. The scientific documentation and ecological valorization of indigenous dairy foods can contribute to food and nutrition security, cultural and biodiversity conservation, the rural economy, and climate resilience.

Keywords: *Indigenous dairy; Milk process optimization; Food safety; Climate resilience; Sustainable food systems; Rural economy*

Mango Ripening Under the Lens of Sustainability: Physicochemical Indicators, Export Barriers, and Quality Management

Tanvir Ahmed^{1,2*}, Amir Ismail¹, Muhammad Sameem Javed¹, Muhammad Aqeel¹, Aliza Batool³, Hamza Rehman¹, Amna Iqbal¹, Usama Nasir⁴, Umer Mushtaq¹, Maria Fiaz¹, Mumtaz Hussain¹

1 Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

2 Department of Environmental Sciences, Faculty of Agriculture, Gomal University, Dera Ismail Khan, Pakistan.

3 Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan.

4 Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan.

***Corresponding author's e-mail:** tani1569@gmail.com

Abstract

Mango (*Mangifera indica* L.) is one of the economically important fruit crops in Pakistan and plays a significant role in the agricultural economy of South Punjab. Nevertheless, poor maturity assessment, rapid postharvest softening, mechanical damage, and deteriorative changes during handling, transport, and storage still hinder its export potential. The aim of this experiment was to examine pulp firmness as the major physicochemical parameter indicating the maturation process of mango, in addition to total soluble solids (TSS), in three commercially important varieties: Mosami Chaunsa, White Chaunsa, and Sindhri. Mature and fully mature fruits were analyzed to determine the changes in firmness and TSS to assess their importance for sustainable postharvest quality management. It was observed that firmness decreased greatly during the maturation process for all varieties. For example, Mosami Chaunsa decreased from 95–110 N at maturity to 1.5–3.5 N at full maturity, while White Chaunsa decreased from 85–100 N to 2.0–4.0 N. Sindhri showed comparatively greater firmness retention, declining from 110–130 N to 4.5–7.0 N. Based on the midpoints of the ranges, firmness declined by 97.6%, 96.8%, and 95.2% for Mosami Chaunsa, White Chaunsa, and Sindhri, respectively. In addition, TSS gradually increased from 16–18 to 23–25 °Brix in Mosami Chaunsa, 16–18 to 22–24 °Brix in White Chaunsa, and 15–17 to 21–23 °Brix in Sindhri, as the fruits progressed from the unripe to the ripe stage. This demonstrates the typical characteristics of mango fruit maturation and ripening. Firmness is a useful criterion for determining mango maturity in conjunction with TSS. With respect to sustainability, precise maturity evaluation can aid optimized harvest, minimize mechanical and postharvest losses, increase transit tolerance, and ensure uniformity in the export-oriented supply chain. Setting variety-specific maturity standards may prove useful in improving the exportability of mangoes, minimizing food losses, and optimizing resource use in the mango-growing areas of Pakistan.

Keywords: *Mangifera indica* L.; Mango; Firmness; Total soluble solids; Ripening; Maturity assessment; Postharvest quality; Export quality; Sustainability; South Punjab

Postbiotics as Next-Generation Biotherapeutics Targeting the Gut-Immune-Metabolic Axis: Mechanisms, Safety, and Clinical Applications

Muhammad Khurram Afzal¹, Asad Abbas¹, Fahid Nazir², Naveed Ahmad^{3*}, Adan Ijaz³, Rimsha Naeem³

¹*Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan*

²*University of Management and Technology, Sialkot Campus, Sialkot, Pakistan*

³*Department of Nutritional Sciences, Multan College of Allied Health Sciences, Multan Medical and Dental College, Multan, Pakistan*

***Corresponding author's e-mail:** navidahmad.ft@gmail.com

Abstract

The gut-immune-metabolic axis is disrupted in metabolic disorders, inflammatory bowel disease (IBD) and immune dysfunction, largely through dysbiosis. Probiotics show inconsistent efficacy owing to variable colonization potential and the possible risk of antimicrobial resistance, whereas postbiotics have emerged as a promising alternative in microbiota-based therapeutics. This review summarizes the mechanisms of action, safety advantages and clinical applications of postbiotics. Postbiotics comprise diverse bioactive compounds, including short-chain fatty acids (butyrate, propionate, acetate), exopolysaccharides, lipopolysaccharides, peptidoglycans and bacterial membrane vesicles. Short-chain fatty acids signal through G-protein coupled receptors and inhibit histone deacetylases (HDAC), epigenetically remodeling intestinal immune tolerance. Postbiotics strengthen the intestinal barrier by upregulating tight junction proteins (claudins, occludin, zonula occludens-1), suppress inflammatory signaling through NF- κ B, and promote the differentiation of regulatory T cells and IL-10-producing B cells. Compared with live probiotics, postbiotics offer distinct safety and functional advantages: no risk of antimicrobial resistance gene transfer or pathogen translocation, consistent efficacy and bioavailability, ease of manufacture and storage, extended shelf life, and suitability for immunocompromised patients. Clinical evidence indicates that postbiotics reduce inflammatory markers (CRP, TNF- α , IL-6), help restore dysbiotic microbiota composition and attenuate metabolic endotoxemia in patients with metabolic syndrome, IBD and obesity. These findings support the rational design of functional foods and pharmaceutical formulations for dysbiosis-related diseases. Robust randomized controlled trials are needed to establish standardized protocols for metabolic syndrome, maintenance of IBD remission and prevention of infectious diseases.

Keywords: *Postbiotics; Gut-immune-metabolic axis; Microbiota-derived metabolites; G-protein coupled receptors; Regulatory T cells; Dysbiosis*

Sea Buckthorn (*Hippophae rhamnoides*): Nutritional Significance, Phytochemistry, Molecular Mechanisms, and Therapeutic Potential in Chronic Disease Prevention

Muhammad Khurram Afzal¹, Asad Abbas^{1*}, Muhammad Bilal², Naeem Sarwar¹, Talha Bin Iqbal³

¹Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Pharmacy, University of Naples Federico II, Naples, Italy

³Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: asadabbaskhichi@gmail.com

Abstract

Sea buckthorn, an ancient deciduous shrub native to the Hengduan Mountains and East Himalayas, has attracted considerable scientific interest in its exceptional nutritional density and diverse pharmacological properties. This review summarizes its phytochemical constituents, molecular mechanisms and therapeutic potential in preventing and treating chronic metabolic and inflammatory diseases. The berries are rich in vitamins (ascorbic acid 200–1000 mg/100 g, α -tocopherol, retinol equivalents and B-complex vitamins), minerals and the bioactive omega-7 fatty acid (25–40% of berry lipids). Their polyphenols include quercetin, kaempferol and caffeic acid derivatives, and their carotenoids include β -carotene, lycopene and zeaxanthin, a combination that confers strong antioxidant and immunomodulatory activity. Sea buckthorn bioactives counter oxidative stress by scavenging free radicals and upregulating endogenous antioxidant enzymes, namely superoxide dismutase, catalase and glutathione peroxidase. Its polyphenols inhibit NLRP3 inflammasome activation and NF- κ B-mediated signaling, thereby downregulating pro-inflammatory cytokines (TNF- α , IL-6 and IL-1 β), while omega-7 acts through G-protein coupled receptor agonism and enhances mucosal barrier integrity. Clinical studies report benefits in lipid lowering, hepatoprotection, antifibrotic activity, collagen synthesis and immune enhancement in immunocompromised individuals. Potential applications include cardiovascular disease prevention, skin health, gastrointestinal disorders and neuroprotection in age-related cognitive decline. Its multi-target pharmacology and favorable safety profile make sea buckthorn a promising dietary strategy for chronic disease prevention. Randomized controlled trials of standardized extracts in metabolic syndrome, liver disease and cardiovascular outcomes are needed to build the evidence base for therapeutic protocols.

Keywords: Sea buckthorn; Phytochemistry; Polyphenols; Carotenoids; Antioxidant activity; Functional foods; Chronic disease prevention

Soybean Production as a Cornerstone for Global Protein Security and Sustainable Agriculture

Muhammad Khurram Afzal¹, Asad Abbas^{1*}, Fahid Nazir², Walisha Aamir¹, Sannia Munawar³, Naeem Sarwar¹, Talha Bin Iqbal⁴

¹*Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan*

²*University of Management and Technology, Sialkot Campus, Sialkot, Pakistan*

³*Department of Nutritional Sciences, Multan College of Allied Health Sciences, Multan Medical and Dental College, Multan, Pakistan*

⁴*Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan*

***Corresponding author's e-mail:** asadabbaskhichi@gmail.com

Abstract

Soybean (*Glycine max*) is one of the world's most versatile and nutrient-dense protein crops, serving as both a primary human food and the foundation of animal feed. With global production reaching about 370 million metric tons annually, it is critical to the sustainable development goals, particularly food security and poverty alleviation. However, climate change threatens productivity in major growing regions, including South America, Asia and North America, through altered precipitation patterns, temperature extremes and increased pest pressure. This paper examines climate adaptation strategies to sustain soybean productivity and nutritional output under changing environmental conditions. Key areas include: (1) climate-resilient varieties with enhanced drought tolerance, heat resistance and nitrogen-fixation efficiency; (2) regenerative soil management, including cover cropping, reduced tillage and optimized biological nitrogen fixation, to maintain carbon sequestration while reducing reliance on synthetic fertilizers; (3) integrated pest management adapted to climate-driven shifts in pest distribution; and (4) precision agriculture technologies (remote sensing, soil moisture monitoring and predictive analytics) to improve resource-use efficiency and reduce environmental footprint. Soybean's symbiosis with nitrogen-fixing bacteria further lowers dependence on energy-intensive fertilizers, reducing both agricultural emissions and production costs. We propose an integrated framework that balances productivity, environmental sustainability and economic viability for smallholder and commercial farmers alike, positioning soybean as a keystone crop for climate-smart agriculture and global food security in the 21st century.

Keywords: *Climate adaptation; Soybean production; Protein security; Regenerative agriculture; Nitrogen fixation; Sustainable intensification*

Quinoa as a Climate-Resilient Superfood Crop: Nutritional Security and Agronomic Performance Under Stressed Environments

Asad Abbas¹, Muhammad Khurram Afzal^{1*}, Naveed Ahmad², Walisha Aamir¹, Sidra Imtiaz¹, Naeem Sarwar¹, Talha Bin Iqbal³

¹Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Nutritional Sciences, Multan College of Allied Health Sciences, Multan Medical and Dental College, Multan, Pakistan

³Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: khurram.afzal@bzu.edu.pk

Abstract

Quinoa (*Chenopodium quinoa* Willd.) offers a paradigm-shifting opportunity for sustainable therapeutic nutrition in climate-vulnerable, food-insecure and resource-limited settings. This study assessed nutrient-dense, quinoa-based ready-to-use therapeutic food (RUTF) formulations as a locally produced alternative to imported protein sources for treating malnutrition. Quinoa showed an excellent amino acid profile, with a crude protein content of 14.8% and essential amino acids including leucine (7.2 g/100 g), lysine (6.1 g/100 g), isoleucine (5.8 g/100 g), methionine (4.3 g/100 g) and phenylalanine (5.2 g/100 g). The Protein Digestibility-Corrected Amino Acid Score (PDCAAS) was 0.92, and the Digestible Indispensable Amino Acid Score (DIAAS) was 0.88, indicating protein quality comparable to that of animal-based sources. Micronutrient analysis revealed high iron (8.4 mg/100 g), zinc (3.1 mg/100 g) and magnesium (197 mg/100 g), which can help address key micronutrient deficiencies in malnourished groups. The formulated RUTF products were microbiologically safe (*E. coli* and *Salmonella* negative), organoleptically acceptable (scores >7.5/10) and oxidatively stable over 12 months of storage. These results highlight quinoa's nutritional profile and high amino acid bioavailability, making it an excellent candidate for RUTF production, particularly within climate-resilient food systems. Locally grown, quinoa-based therapeutic foods could advance sustainable food security, help combat child malnutrition and promote climate-smart agriculture in vulnerable regions.

Keywords: Quinoa; Climate resilience; Complete protein; Nutritional security; Marginal lands; Food sovereignty

Plant-Based Protein Systems: Bridging the Global Protein Gap While Mitigating Climate and Environmental Impacts of Animal Agriculture

Asad Abbas¹, Muhammad Khurram Afzal^{1*}, Naveed Ahmad², Muhammad Bilal³, Walisha Aamir¹, Naeem Sarwar¹, Talha Bin Iqbal⁴

¹*Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan*

²*Department of Nutritional Sciences, Multan College of Allied Health Sciences, Multan Medical and Dental College, Multan, Pakistan*

³*Department of Pharmacy, University of Naples Federico II, Naples, Italy*

⁴*Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan*

***Corresponding author's e-mail:** khurram.afzal@bzu.edu.pk

Abstract

Global protein demand is projected to rise by 60–100% by 2050 owing to population growth, urbanization and increasing per capita consumption. Current protein production is dominated by animal agriculture, which occupies about 77% of agricultural land yet supplies only about 18% of global calories and 37% of protein. It also contributes 14–18% of global greenhouse gas emissions and drives deforestation, freshwater use and biodiversity loss, making a shift toward plant-based protein essential for climate mitigation and environmental sustainability. This paper examines plant protein systems in terms of agronomic resilience, nutritional adequacy, environmental footprint reduction and scalability for global food security. Legumes (soybean, peas, beans, lentils), grains (wheat, quinoa, amaranth) and novel sources (algae, fungal proteins) have complementary nutrient profiles that, when combined or co-processed, provide complete amino acid coverage. Lifecycle emissions of plant proteins are 75–95% lower than those of beef, with about 80% less land and 90% less water required. Legume–cereal mixtures are especially effective, delivering balanced protein while improving soil fertility through biological nitrogen fixation, thereby reducing fertilizer use and agricultural carbon emissions. The paper reviews evidence on (1) the bioavailability and digestibility of plant proteins as affected by processing; (2) innovations in protein extraction, fortification and product development; (3) integration of protein-rich crops into agroecological rotations; (4) economic viability and market development for smallholder producers; and (5) consumer acceptance and behavior change. Replacing 50% of animal protein with plant protein could reduce global agricultural land use by 35% without compromising nutrition. Policy measures such as subsidy reform, carbon pricing, public procurement standards and nutrition labeling are crucial to accelerate this transition. We present a vision of plant protein systems as central to sustainable food security, climate mitigation and circular economy transitions, adaptable across regions and farm scales.

Keywords: *Plant proteins; Sustainable agriculture; Climate mitigation; Nutrition security; Legumes; Circular food systems*

Indigenous-Based Ready-to-Use Therapeutic Foods: Enhancing Nutritional Sustainability and Food Security in Malnutrition Management

Asad Abbas¹, Muhammad Khurram Afzal^{1*}, Naveed Ahmad², Adan Ijaz², Fatima Khalid², Mubarraah Chahel², Elsa Malik², Anza Saleem²

¹Department of Human Nutrition, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Nutritional Sciences, Multan College of Allied Health Sciences, Multan Medical and Dental College, Multan, Pakistan

*Corresponding author's e-mail: khurram.afzal@bzu.edu.pk

Abstract

Ready-to-use therapeutic foods (RUTFs) are a pivotal intervention for community-based management of acute and chronic malnutrition, offering high nutrient density, long shelf life and minimal preparation. However, their heavy reliance on imported ingredients such as peanut butter and fortified oils raises sustainability, cost and availability concerns for vulnerable groups in low-resource settings. This study formulated and tested RUTFs based on locally available indigenous protein sources, soybean and quinoa. Three soybean–quinoa RUTF formulations were evaluated for nutritional composition, oxidative stability, microbiological safety and organoleptic acceptability over 90 days of storage. Peroxide value (PV), acid value (AV), thiobarbituric acid (TBA) value, water activity (aw), total color change (ΔE), total plate count (TPC), total mold count (TMC) and sensory attributes (trained panel) were assessed, and data were analyzed by two-way ANOVA for treatment and storage effects. The formulations had a protein content of 12–15%, fat content of 25–30% and a therapeutic energy density of 520–550 kcal/100 g. Oxidative stability was excellent, with only minimal PV increases during storage (1.03–1.69 meq O₂/kg) and well-controlled TBA values (0.02–0.08 mg MDA/kg). Water activity decreased significantly ($P \leq 0.05$), indicating good preservation. TPC and TMC remained within WHO safety limits throughout storage, and ΔE values of 2.5–3.1 reflected minimal color change and sustained sensory acceptability. Shelf stability was comparable or superior to that of conventional RUTFs made with imported ingredients. Overall, RUTFs prepared from indigenous soybean and quinoa provided a comparable nutritional profile, better oxidative stability, assured microbiological safety and lasting sensory acceptability. Such locally produced alternatives can reduce import dependence, strengthen regional, cost-effective food systems and support the sustainable development goals. Clinical trials in malnourished populations are recommended to establish efficacy, acceptability and adherence, with the aim of improving access to malnutrition therapy in resource-poor settings.

Keywords: Ready-to-use therapeutic foods; Malnutrition treatment; Soybean; Quinoa; Sustainable food systems; Food security

Growth and Yield Response of Summer-Planted Maize under Different Levels of Horse Purslane (*Trianthema portulacastrum*) Interference

Khuram Mubeen*, Mudassir Aziz, Abdul Ghaffar, Nabeel Ahmad Ikram

Department of Agronomy, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: khuram.mubeen@mnsuam.edu.pk

Abstract

The study was conducted during the Kharif (summer) season at the Research Farm of MNS University of Agriculture, Multan, on a field with a history of high horse purslane infestation. The objective of this study was to quantify the effect of horse purslane on the growth and yield components of maize. The study was carried out in a Randomized Complete Block Design with three replications. The experiment consisted of ten treatments, viz., weed-free (whole season), horse purslane-free until 20 days after emergence (DAE), horse purslane-free until 40 DAE, horse purslane-free until 60 DAE, all weeds-free until 20 DAE, all weeds-free until 40 DAE, all weeds-free until 60 DAE, weedy check (all weeds), weedy check except horse purslane, and weedy check containing only horse purslane. Hand weeding was carried out to control weeds according to the treatment schedule. Parameters related to weeds and the growth and yield of maize were recorded during the study. Data were analyzed using appropriate statistical techniques, and variation among treatments was tested using standard methods. The results showed that the weed-free (whole season) treatment produced the maximum yield and yield-related parameters, including plant height (178 cm), cob weight (159 g), cob diameter (4.4 cm), cob length (18.7 cm), stover yield (10.2 t ha⁻¹), and grain yield (6.4 t ha⁻¹). In the horse purslane-free until 40 DAE treatment, grain yield was higher compared with the horse purslane-free until 20 DAE treatment. CGR, LAI, LAD, and NAR were also maximum in the weed-free (whole season) treatment. Based on the data obtained, it may be concluded that farmers should monitor horse purslane infestation and control it within the first 40 days in maize fields to avoid interference from this weed.

Keywords: Horse purslane; Weeds; Weed dynamics; Yield; Growth; Zea mays

Effect of Drying Method and Storage Conditions on the Microbial Safety and Bioactive Quality of Kinnow Peel Powder from Juice-Processing By-Products

Mavra Ameen *

Institute of Food Science and Technology, Faculty of Agriculture, Gomal University, Dera Ismail Khan, Pakistan

Corresponding author's e-mail: mavrazuby@gmail.com

Abstract

Kinnow (*Citrus reticulata*) is a major citrus crop in Pakistan, and juice processing generates large quantities of peel that is commonly discarded or sold as low-value feed. Kinnow peel contains phenolic compounds, flavonoids, dietary fiber and essential oils, making it a potential functional food ingredient. However, its use in foods depends on safety and stability: peel is exposed to surface contamination during harvest and processing, and inadequate drying or storage may allow microbial growth and loss of bioactive compounds. Information linking drying and storage conditions to both the safety and quality of peel powders from local processing units is limited. This proposed study aims to evaluate how drying methods and storage conditions affect microbial safety, physicochemical quality and bioactive retention of kinnow peel powder. Peels will be collected from juice-processing units, washed, and dried by sun drying and hot-air drying at selected temperatures. The dried peel will be milled to a controlled particle size, packed in two packaging types, and stored under ambient and controlled conditions, with sampling at fixed intervals. Moisture content, water activity, total plate count, yeast and mold count, and coliforms will be determined, along with total phenolic content, antioxidant activity (DPPH) and color. Where analytical facilities allow fresh peels to be screened for pesticide residues to judge its suitability for food use. Data will be analyzed by analysis of variance to compare drying methods, packaging and storage time. This work is at the proposal stage, and no experimental results are presented. The expected outcome is a set of drying and storage conditions that keep kinnow peel powder microbiologically safe while retaining its bioactive quality, supporting its safe use in functional food formulations and better utilization of citrus-processing by-products.

Keywords: *Kinnow peel; Food safety; Drying; Storage stability; By-product valorization*

Climate Change and the Plate: Nutritional Status, Food Security, and Household Dietary Diversity in Farming Communities

Fatima Khan^{1*}, Saliha¹, Nida Yousaf¹, Ali Hamza², Ambreen Naz³

¹*Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan*

²*Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan*

³*Department of Home Sciences, MNS University of Agriculture, Multan, Pakistan*

***Corresponding author's e-mail:** fatimakhann686@gmail.com

Abstract

Climate change is increasingly recognized not only as an agricultural and environmental problem but also as a determinant of household diet quality and food security, particularly in farming communities whose livelihoods depend on rain-fed and irrigation-sensitive crops. Against a backdrop of shifting rainfall patterns, rising temperatures and frequent crop losses, this study examined household dietary diversity, food security status and nutritional outcomes among agricultural households. A cross-sectional survey of farming households used a structured questionnaire to collect the Food Consumption Score, Household Dietary Diversity Score and a food insecurity experience scale, together with basic anthropometric measurements of women and children in the same households. To relate dietary habits to climate-related livelihood stress, respondents were also asked about perceived changes in crop output, income stability and food access over recent cropping seasons. Greater vulnerability to climate-related crop loss was associated with lower dietary diversity scores, heavier reliance on cereal-based staples and correspondingly lower consumption of dairy, pulses, fruits and vegetables. Smallholder and tenant-farming households experienced higher levels of food insecurity than households with larger or irrigated landholdings, and children from food-insecure households were more likely to be underweight and stunted than those from food-secure households. These findings indicate a direct link between climate-related agricultural stress and compromised diet quality and nutritional status at the household level. Food security and nutrition programs in climate-vulnerable farming regions should therefore go beyond calorie adequacy to actively protect dietary diversity.

Keywords: *Livelihoods; Rain-fed crops; Dietary diversity; Climate change; Food insecurity; Agricultural stress*

Shell to Shelf: Development of Low-Cost Pasta through Valorizing Eggshell Waste

Fatima Khan^{1*}, Saliha¹, Nida Yousaf¹, Ali Hamza², Ambreen Naz³

¹Department of Human Nutrition and Dietetics, MNS University of Agriculture, Multan, Pakistan

²Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan

³Department of Home Sciences, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: fatimakhann686@gmail.com

Abstract

Eggshells are among the most common by-products of the baking and poultry industries, yet over 90% are dumped in landfills. Containing about 94% calcium carbonate, eggshell is a cheap and accessible calcium source that has received little attention as a food-grade ingredient. This study investigated the viability of adding eggshell powder to durum wheat semolina pasta for both calcium fortification and food waste valorization. Eggshells were collected, cleaned, boiled to remove the inner membrane, oven-dried and ground into a fine powder, which was sieved through a 100-mesh screen and substituted for semolina in the pasta dough at four levels, alongside an unfortified control. Cooking quality (optimum cooking time, water absorption index and cooking loss), texture profile, color and sensory acceptability (nine-point hedonic scale, trained panel) were assessed, and calcium content was determined by flame photometry. Up to a moderate substitution level, firmness and overall sensory acceptability were like the control; beyond that, panelists reported a chalky aftertaste and reduced elasticity. Increasing eggshell powder produced a clear, dose-dependent rise in calcium content, accompanied by a gradual increase in cooking loss and slight darkening of color. These results show that, within an optimal inclusion range, eggshell powder can be used to produce calcium-enriched pasta without sacrificing consumer acceptance, offering an affordable approach to calcium deficiency while reducing agro-industrial waste.

Keywords: Food fortification; Eggshell powder; Food waste valorization; Durum wheat pasta; Functional food

Application of Decision Support System for Agrotechnology Transfer: A Case of Punjab, Pakistan

Shakeel Ahmad^{1*}, Ghulam Abbas^{1,2}, Mukhtar Ahmed³, Zartash Fatima¹, Sajjad Hussain^{4,5}, Aftab Wajid⁶, Abid Hussain⁶, Ashfaq Ahmad^{6,7}, Gerrit Hoogenboom^{8,9}

¹*Institute of Agronomy, Bahauddin Zakariya University, Multan 60800, Pakistan*

²*Extension Wing, Department of Agriculture, Government of Punjab, Pakistan*

³*Department of Agronomy, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi 46300, Pakistan*

⁴*Department of Horticulture, Bahauddin Zakariya University, Multan 60800, Pakistan*

⁵*Citrus Center, Texas A&M University, Texas, USA*

⁶*Department of Agronomy, Faculty of Agriculture, University of Agriculture, Faisalabad, Pakistan*

⁷*Ghazi University, Dera Ghazi Khan, Punjab, Pakistan*

⁸*Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, USA*

⁹*Global Food Systems Institute, University of Florida, Gainesville, FL 32611, USA*

***Corresponding author's e-mail:** shakeelahmad@bzu.edu.pk

Abstract

The Decision Support System for Agrotechnology Transfer (DSSAT) is a Windows-based software package (v4.8.5) comprising more than 45 dynamic crop growth simulation models and tools for their effective use, including database management programs for soil, weather, crop management and experimental data, along with utilities and application programs. The models simulate crop growth, development and yield as a function of soil–plant–atmosphere dynamics and have been applied widely across the world. We calibrated and evaluated DSSAT using field data and then applied it to individual crops (rice, wheat, maize, cotton) and diverse cropping systems (rice-wheat, cotton-wheat, maize-maize, sunflower-sunflower) in Punjab, Pakistan. Applications included modeling phenology (sugarcane, canola, cotton, safflower, tomato, rice–wheat, maize–maize, sunflower-sunflower, potato-potato, soybean-soybean); plant density and nitrogen management (rice); plant density and irrigation management (rice); yield gap analysis (canola); nitrogen management (cotton); determination of sowing windows (spring and autumn maize); and climate change impact assessment and adaptation strategies (cotton, sugarcane, rice–wheat, cotton–wheat, maize–maize, potato–potato). The results show that DSSAT is a useful decision support tool for agrotechnology transfer, improving standards of teaching and research and helping to address real-world problems faced by the farming community in Punjab, Pakistan.

Keywords: *Crop phenology; Climate change; DSSAT; Sowing window; Yield gap*

Coccolithophore Supplementation: A Climate-Smart Strategy to Enhance Productivity and Reduce Methane Emissions in Dairy Cows

Ahsan Siddique Bhatti¹, Riaz Mustafa², Umar Farooq², Waseem Abbas¹, Muhammad Farooq Khalid², Asfa Fatima¹, Muhammad Aziz ur Rahman^{1*}

¹Institute of Animal and Dairy Sciences, University of Agriculture Faisalabad, Pakistan

²University of Agriculture Faisalabad, Constituent College Toba Tek Singh, Pakistan

*Corresponding author's e-mail: drazizurrahman@uaf.edu.pk

Abstract

Livestock methane emissions are a major contributor to global warming, underscoring the need for sustainable feeding interventions. This study evaluated coccolithophore as an alternative to sodium bicarbonate as a dietary buffer in crossbred dairy cows. Thirty first-lactation cows (600 ± 20 kg body weight; 20 ± 2 L/day milk yield) were assigned to five diets: control (no buffer), sodium bicarbonate (200 g/day), or coccolithophore at 100, 150 or 200 g/day. Cows fed 150 and 200 g/day of coccolithophore showed higher dry matter intake, nutrient digestibility and milk yield than controls ($P \leq 0.05$). Rumen pH was improved by both coccolithophore and sodium bicarbonate ($P \leq 0.05$), while milk composition was enhanced only with coccolithophore ($P \leq 0.05$). Plasma metabolites were unaffected by dietary treatments. Notably, fecal methane and CO₂ emissions were significantly reduced by coccolithophore supplementation ($P \leq 0.05$). These findings highlight coccolithophore as an eco-efficient buffer that enhances dairy productivity while mitigating greenhouse gas emissions, contributing to climate-smart and sustainable livestock production.

Keywords: *Coccolithophore; Buffer; Digestion; Production; Methane*

HPLC Quantification of Fluoroquinolone Residues in Retail Meat from Multan: Food Safety and Consumer Health Concerns

Mumtaz Hussain¹, Muhammad Zubair Khalid², Muhammad Aqeel¹, Aliza Batool³, Maria Fiaz¹, Muhammad Riaz^{1*}

¹Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Food Science, Faculty of Allied Sciences, Government College University Faisalabad, Pakistan

³Department of Food Science and Technology, Faculty of Food and Home Science, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: riaz@bzu.edu.pk

Abstract

Antibiotics are given to birds and animals to prevent or treat disease, but excessive use of fluoroquinolones, particularly ciprofloxacin and enrofloxacin, is a significant public health concern because pharmacologically active residues persist in edible tissues and may select for antimicrobial-resistant zoonotic pathogens, including *E. coli*, *Salmonella* spp. and *Campylobacter* spp. This study quantified ciprofloxacin and enrofloxacin residues in beef, mutton and chicken sold at butcher shops in Multan, Pakistan. A total of 54 meat samples were collected from six geographically distinct towns of Multan following standard procedures and transported to the laboratory for analysis. Residues were quantified by high-performance liquid chromatography (HPLC), and data were analyzed using Microsoft Excel and SPSS. Ciprofloxacin residues in beef, mutton and chicken were 13.85 ± 0.92 , 14.04 ± 2.47 and 70.50 ± 45.96 $\mu\text{g/kg}$, respectively, while enrofloxacin residues were 13.50 ± 0.71 , 15.25 ± 1.06 and 69.60 ± 46.53 $\mu\text{g/kg}$. All beef and mutton samples were below the maximum residue limits (MRLs), indicating regulatory compliance. In contrast, two chicken samples exceeded the MRL for ciprofloxacin and one exceeded the MRL for enrofloxacin. These results suggest that beef and mutton in local retail markets are safe with respect to these residues, whereas chicken meat poses a significant food safety risk. Excessive and uncontrolled use of ciprofloxacin and enrofloxacin in the poultry sector threatens the effectiveness of human medicine. Effective monitoring, adherence to withdrawal periods and strict enforcement of veterinary prescription are therefore needed to ensure food safety and limit antibiotic resistance in Pakistan.

Keywords: Meat; Fluoroquinolone residues; Antibiotic resistance; MRLs

Synergistic Effects of Zn and Ca Nanoparticles along with Biochar under Salinity Stress in Canola

Muhammad Shahid Rizwan^{1*}, Khaleeq uz Zaman¹, Qaiser Shakeel¹, Sajjad Ali²

¹*Cholistan Institute of Desert Studies, The Islamia University of Bahawalpur, Pakistan*

²*Department of Entomology, The Islamia University of Bahawalpur, Pakistan*

*Corresponding author's e-mail: shahid.rizwan@iub.edu.pk

Abstract

Salinity stress is a major constraint to crop productivity, particularly in arid and semi-arid regions, where excessive soluble salts disrupt water relations, nutrient uptake, photosynthesis and cellular redox balance. This study evaluated the potential of biochar combined with zinc (Zn) and calcium (Ca) nanoparticles to improve salinity tolerance and growth of canola (*Brassica napus* L.). A pot experiment was conducted at the Cholistan Institute of Desert Studies, The Islamia University of Bahawalpur, using soil amended with biochar. After establishment, plants were exposed to salinity stress and then treated with Zn and Ca nanoparticles. Plant growth, nutrient uptake, physiological responses, antioxidant activities, oxidative damage and selected soil health indicators were evaluated. Salinity stress adversely affected plant growth and physiological performance, whereas biochar amendment and nanoparticle supplementation alleviated these effects. The combined application of biochar with Zn and Ca nanoparticles produced a stronger positive response than the individual treatments, as reflected by improved growth and nutrient acquisition, enhanced antioxidant defense and reduced oxidative damage, indicating better cellular protection under saline conditions. Biochar likely improved soil conditions and nutrient availability, while Zn and Ca nanoparticles supported the nutritional and physiological functions involved in stress tolerance. Overall, integrated application of biochar with Zn and Ca nanoparticles is a promising approach for improving canola performance under saline conditions and supports integrated carbon and nanoparticle management in saline agriculture.

Keywords: *Canola; Salinity stress; Biochar; Zinc nanoparticles; Calcium nanoparticles; Salt tolerance*

Cucumber Production under Salt Stress: A Review of Biostimulants for Sustainable Stress Management

Muhammad Sadam, Hasan Sardar*

Department of Horticulture, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: hasan.sardar@bzu.edu.pk

Abstract

Cucumber (*Cucumis sativus* L.) is an important vegetable crop valued for its fresh consumption, nutritional contribution and economic significance, and sustainable management of salt stress is essential for maintaining production in salt-affected environments. This narrative review examines the potential of biostimulants to support cucumber performance under saline conditions. Its scope includes seaweed extracts, humic substances, protein hydrolysates and beneficial microorganisms, with attention to application methods, treatment rates and crop developmental stages. The review considers salinity responses related to growth, water relations, photosynthetic pigments, nutrient uptake, ion balance and antioxidant defense, and how these relate to fruit yield and quality. Emphasis is placed on the consistency of biostimulant effects across formulations, salinity levels and experimental conditions, and on distinguishing evidence from controlled pot experiments from findings in greenhouse and field production systems. It further considers research gaps concerning combined environmental stresses, treatment compatibility, economic feasibility and practical application. By connecting physiological and biochemical responses with production outcomes, this review aims to clarify the opportunities and limitations of biostimulants as components of integrated salinity management and to identify priorities for sustainable cucumber production.

Keywords: *Cucumber; Salt stress; Biostimulants; Salinity management; Sustainable horticulture*

Broccoli Responses to Spent Mushroom Biochar under Salt Stress: Morphological and Biochemical Attributes

Kishwar Jam, Hasan Sardar*, Safina Naz

Department of Horticulture, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** hasan.sardar@bzu.edu.pk

Abstract

Broccoli (*Brassica oleracea* var. *italica*) is a nutritionally valuable vegetable that contributes vitamins, minerals and bioactive compounds to the human diet, so sustainable approaches to managing salt stress are relevant to maintaining its production. This study evaluated the effects of biochar application on the morphological, physiological and biochemical attributes of broccoli under saline conditions. A pot experiment was conducted in a completely randomized design (CRD) with four replications at two salinity levels, 0 and 120 mM. Morphological assessments included head size, fresh weight, leaf area and leaf number. Physiological and biochemical assessments included leaf relative water content, chlorophyll and carotenoid contents, antioxidant enzyme activities, total soluble solids and vitamin C content. Among the treatments evaluated, spent mushroom biochar applied at 2% showed the best overall performance, identifying it as a promising amendment for further investigation in broccoli production under salt stress. Using spent mushroom residues for biochar production links agricultural waste reuse with crop stress management and sustainable vegetable production. Further field evaluation is needed to establish the effectiveness of this treatment across different soils and growing conditions.

Keywords: *Broccoli; Spent mushroom biochar; Salt stress; Morphological attributes; Biochemical attributes; Sustainable agriculture*

Phytochemical Inhibitors of Peanut Allergens Ara h1 and Ara h2: Molecular Docking and ADMET-Based Lead Identification

Mumtaz Hussain¹, Maria Fiaz¹, Muhammad Aqeel¹, Aliza Batool², Muhammad Sameem Javed^{1*}

¹Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Food Science and Technology, Faculty of Food and Home Science, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: sameemjaved@bzu.edu.pk

Abstract

Peanut allergy caused by Ara h1 and Ara h2 is one of the most clinically severe and persistent food hypersensitivity disorders worldwide. Thermal processing such as boiling and frying attenuates IgE-binding capacity through structural denaturation of allergenic epitopes, whereas roasting promotes Maillard reaction-mediated crosslinking that generates novel conformational and linear epitopes, thereby augmenting allergenicity. Phytochemical-derived bioactive compounds are a promising but underexplored avenue for developing anti-allergenic therapeutics. This study evaluated the effects of thermal processing on the structural integrity of Ara h1 and Ara h2 and identified lead phytochemical inhibitors of these allergens through molecular docking. A library of 2,576 bioactive phytochemicals was retrieved from PubChem and prepared for docking using Open Babel. Active binding sites on the allergen structures were identified using prediction algorithms, and docking was performed against each target. The ten highest-ranking compounds for each allergen were subjected to ADMET profiling to assess pharmacokinetic suitability and drug-likeness. Cepharanthine emerged as the leading inhibitor of Ara h1, and zapoterin as the leading inhibitor of Ara h2, both with favorable binding affinity. Docking of both compounds against the histamine H1 and H2 receptors also showed substantial binding affinity, suggesting potential for allergen inhibition and downstream anti-histaminic activity. These findings establish cepharanthine and zapoterin as structurally and pharmacologically viable lead candidates that warrant further in vitro and in vivo validation for managing peanut-induced hypersensitivity.

Keywords: Peanut allergy; Ara h1; Ara h2; IgE-binding epitopes; Food hypersensitivity

***Citrullus colocynthis*: From Traditional Medicine to Functional Food**

Mumtaz Hussain¹, Aliza Batool², Maria Fiaz¹, Muhammad Aqeel¹, Muhammad Riaz^{1*}

¹Department of Food Safety and Quality Management, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

²Department of Food Science and Technology, Faculty of Food and Home Science, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** riaz@bzu.edu.pk

Abstract

Citrullus colocynthis, a member of the Cucurbitaceae family, is an underutilized plant with a rich phytochemical composition and recognized traditional use as a nutraceutical and functional food ingredient. It contains bioactive compounds, including carotenoids, phenols, esters, steroids, isooctyl phthalate and bioactive peptides, which confer significant antioxidant, antimicrobial, antidiabetic and lipid-lowering activities. Recent studies show that protein hydrolysates from *C. colocynthis* have multi-target antidiabetic potential through concurrent inhibition of α -amylase, α -glucosidase and dipeptidyl peptidase-IV, with efficacy comparable to or exceeding that of single-target drugs such as acarbose and sitagliptin. The plant also shows potent antioxidant activity, with DPPH and ABTS radical scavenging of up to 77.04% and 76.97%, respectively, and significant hypoglycemic efficacy (blood glucose reductions of 46–65 mg/dL per application) in patients with type 2 diabetes. Despite this promising bioactivity profile, *C. colocynthis* remains significantly underexploited in modern functional food development. This review synthesizes evidence on its phytochemical composition, bioactive mechanisms, extraction technologies and regulatory pathways, with the aim of positioning *C. colocynthis* as a sustainable and efficacious ingredient for next-generation functional foods targeting metabolic and inflammatory disorders, bridging traditional ethnobotanical use with contemporary food and nutrition science.

Keywords: *C. colocynthis*; Phytochemicals; Functional foods; Nutraceuticals; Antidiabetic activity; Ethnopharmacology

Tomato Production under Environmental Stresses: A Review of Challenges and Sustainable Management Strategies

Muhammad Usman, Muhammad Sadam, Hasan Sardar*, Fakhar ul Huda

Department of Horticulture, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: hasan.sardar@bzu.edu.pk

Abstract

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop valued for its nutritional composition, economic significance and contribution to food security, and maintaining its production under environmental stress is a key concern for sustainable horticulture. This narrative review examines the effects of major abiotic stresses, including high temperature, drought, salinity and waterlogging, on tomato growth, reproductive development, yield and fruit quality. It considers physiological and biochemical responses related to plant water relations, photosynthetic performance, nutrient balance and antioxidant defense, with particular attention to the vulnerability of flowering, fruit set and fruit development, linking stress responses with production outcomes. The review also evaluates management approaches, including stress-tolerant cultivars, grafting, irrigation and nutrient management, mulching, biochar amendments and biostimulants, in relation to stress type, crop developmental stage and growing conditions. It emphasizes the need to distinguish controlled-environment findings from field evidence and to examine combined stresses alongside individual stress factors. By connecting crop responses with practical management options, this review aims to identify research priorities and support the development of resilient tomato production systems within sustainable food systems.

Keywords: *Tomato; Abiotic stress; Climate resilience; Sustainable horticulture; Stress management; Food security*

Jamun Extract and Marination: A Non-Thermal, Natural Preservation Strategy for Safe and Value-Added Beef

Muhammad Asad Ali Khan, Raheel Suleman*, Dur-e-Shahwar Sattar

Department of Food Science and Technology, Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: dr.raheel@bzu.edu.pk

Abstract

Climate change, through higher temperatures and cold-chain disruption, increases spoilage and food loss in perishable foods such as beef, where lipid oxidation and microbial growth degrade quality. Growing consumer resistance to synthetic antioxidants (BHA, BHT) also makes natural preservatives an environmentally friendly alternative. Recent studies have shown that a methanolic extract of jamun (*Syzygium cumini*) seeds has potent antioxidant activity (DPPH IC₅₀ 9.23 µg/mL) and produces inhibition zones of about 16 mm against *E. coli* and *Salmonella enteritidis*, and that *Rhodiola rosea* extract extended the shelf life of refrigerated beef by up to 7 days. In this study, jamun concentrate (48.4 mg GAE/mL phenolics, 28.3 mg QE/mL flavonoids and 77.1% DPPH scavenging) was used as a natural marinade for beef for 1, 2 and 3 h, with unmarinated beef as the control. After 9 days of refrigerated storage, marinated beef had lower TBARS (1.4 vs 2.6 mg MDA/kg), total plate count (4.4 vs 5.4 log CFU/g), *E. coli* (1.5 vs 2.3 log CFU/g) and *S. aureus* (2.1 vs 3.3 log CFU/g) than the control. Marination also reduced cooking loss (21.4 vs 31.4%), increased water-holding capacity (70.9 vs 58.3%) and improved texture; SEM and FTIR indicated muscle fiber loosening and protein conformational changes, respectively, consistent with a more tender product. Sensory acceptance was highest after 2 h of marination, whereas preservation was best after 3 h, and principal component analysis (79% of variance explained) separated marinated beef from the spoilage indicators. These effects are consistent with the antioxidant and antimicrobial action of jamun anthocyanins, flavonoids and phenolics and with the lower pH from its acidity, which limits microbial growth. Jamun concentrate could thus serve as an indigenous, sustainable and value-added preservation method that helps reduce food loss and valorizes a highly perishable fruit in a changing climate.

Keywords: Jamun (*Syzygium cumini*); Ultrasonication; Natural preservatives; Beef shelf life; Sustainable food processing

Integrating Allometric and Machine Learning Models for Aboveground Biomass and Carbon Estimation in Semi-Arid Agroforestry Systems of Pakistan

Ghulam Yasin^{1*}, Syed Amir Manzoor¹, Abdul Manan¹, Muhammad Farooq Azhar¹, Muhammad Zubair¹, Muhammad Farrakh Nawaz²

¹Department of Forestry and Range Management, Bahauddin Zakariya University, Multan, Pakistan

²Institute of Environmental Studies, University of Karachi, Karachi, Pakistan

*Corresponding author's e-mail: ghulam.yasin@bzu.edu.pk

Abstract

Agroforestry is one of the most important practices for mitigating the harmful impacts of climate change worldwide. However, estimating aboveground biomass (AGB) and carbon stocks in agroforestry systems is challenging because tree growth, structure and performance vary widely in the field. This study compared traditional allometric equations with machine learning models for estimating growth characteristics, AGB and aboveground carbon stocks (AGCS) in a semi-arid region of Pakistan. A total of 7,855 trees of 11 agroforestry species were measured for diameter at breast height (DBH) and height. AGB was calculated using species-specific and general biomass equations, and AGCS was computed as 48% of AGB. Mean tree height ranged from 4.37 m in *Albizia lebbeck* to 8.21 m in *Populus deltoides*, and mean DBH from 7.27 cm in *A. lebbeck* to 14.90 cm in *Bombax ceiba*. Mean AGB was highest in *P. deltoides* (72.49 Mg ha⁻¹), followed by *Dalbergia sissoo* (64.94 Mg ha⁻¹), and lowest in *A. lebbeck* (8.71 Mg ha⁻¹). Machine learning models generally outperformed the allometric models. Gradient Boosting (GB) was the best model for most species, with R² values of 0.999, 0.956, 0.989, 0.999, 0.996, 0.992 and 0.978 for *Acacia nilotica*, *A. lebbeck*, *Azadirachta indica*, *D. sissoo*, *Morus alba*, *Syzygium cumini* and *Ziziphus mauritiana*, respectively. Random Forest performed best for *P. deltoides* and *B. ceiba* (R² = 0.998) and Support Vector Regression for *Eucalyptus camaldulensis* (R² = 0.997), while XGBoost showed strong and stable performance for almost all species. SHAP analysis showed that DBH was the most important predictor for most species across all models, with height as an important secondary variable. Overall, machine learning can improve biomass and carbon estimation in semi-arid agroforestry systems and provides a useful basis for carbon assessment and better tree management in Pakistan.

Keywords: Agroforestry; Aboveground biomass; Climate change; Allometric equations; Carbon stocks; Semi-arid region

Physicochemical, Phytochemical, Antioxidant, and Microbiological Evaluation of Mango Peel Essential Oil-Incorporated Ice Cream

Attiya Arooj, Tariq Ismail*

Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: tariqismail@bzu.edu.pk

Abstract

Functional foods have gained considerable attention owing to growing consumer awareness of health-promoting ingredients. Mango (*Mangifera indica*) peel is a rich source of bioactive compounds and volatile constituents, including monoterpenes, sesquiterpenes, alcohols, aldehydes, ketones, esters and lactones, which contribute to its characteristic aroma and biological properties. Mango peel essential oil is therefore a promising natural ingredient for value-added functional foods, and its incorporation into dairy ice cream may enhance functionality while providing a distinctive aroma and flavor. This study aimed to develop mango peel essential oil-enriched ice cream at two concentrations, T1 (0.05%) and T2 (0.1%). Sensory attributes, physicochemical properties, phytochemical composition, antioxidant activity and microbiological stability were evaluated and compared with a control without essential oil. Essential oil significantly ($P \leq 0.05$) influenced the sensory, physicochemical, functional and microbiological properties of the ice cream. The 0.05% treatment had the highest overall sensory acceptability. Essential oil slightly reduced pH and total soluble solids (TSS) while increasing overrun from 60.12% in the control to 65% at 0.1%, and it decreased the melting rate to 0.48 g/min. Total phenolic and flavonoid contents and antioxidant activity increased with increasing essential oil concentration, with the highest antioxidant activity at 0.1% (63.99% vs 28.21% in the control). Microbial counts decreased from 5.0 to 2.7 log CFU/g with increasing concentration, indicating the potential of the oil to improve the functional and microbiological quality of ice cream. Further studies should optimize the oil concentration and investigate its encapsulation, storage stability, bioaccessibility and consumer acceptance.

Keywords: *Mango peel; Essential oil; Ice cream; Antioxidant activity; Total phenolic content; Sensory evaluation; Value-added dairy products*

Guar Gum Fiber as Fat Replacer in Low-Fat Cheddar Cheese

Shamas Murtaza^{1*}, Aysha Sameen², Anjum Murtaza³, Nighat Raza¹, Umar Farooq¹

¹Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan

²Department of Food Science and Technology, Government College Women University Faisalabad, Pakistan

³Institute of Food Science and Nutrition, University of Sargodha, Sargodha, Pakistan

*Corresponding author's e-mail: shamas.murtaza@mnsuam.edu.pk

Abstract

Low-fat Cheddar cheese is in demand today but often lacks the quality and functionality of the full-fat product. Guar gum is stable during freeze–thaw cycles and can retard ice crystal growth by slowing mass transfer across solid–liquid interfaces, and it can help low-fat cheese retain texture and rheology like full-fat cheese. Guar gum was added at 0.15, 0.30 and 0.45% to Cheddar cheese made from milk with 2% fat. Analysis of variance showed highly significant ($p < 0.01$) effects on gumminess and chewiness, significant ($P \leq 0.05$) effects on hardness, meltability and yield, and non-significant effects on cohesiveness, springiness and flowability. Increasing the guar gum level made the cheese softer, with maximum hardness at the lowest gum concentration; gumminess and chewiness decreased, while meltability and flowability increased. The decrease in hardness was probably due to a less compact protein matrix, since guar gum increases the water-binding capacity of the protein matrix. Reducing fat with fat-mimetic ingredients may also strengthen protein–water interactions and enhance adhesiveness. Scanning electron microscopy showed that cheese with guar gum had a more homogeneous structure and better texture than the other samples. Adding guar gum as a fat replacer improved the sensory characteristics of low-fat cheese at levels up to 0.45%.

Keywords: Cheddar cheese; Gumminess; Chewiness; Meltability; Flowability

Valorization of Vegetable and Fruit Waste for the Development of Functional Instant Soup Mix

Nida Firdous^{1*}, Bisma Israr¹, Muhammad Waqar²

¹Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan

²School of Agricultural Technology and Food Industry, Walailak University, Thai Buri, Tha Sala, Thailand

*Corresponding author's e-mail: nida.firdous@mnsuam.edu.pk

Abstract

In Pakistan, a substantial proportion of fruits and vegetables is wasted every year, a serious problem that must be addressed for sustainable development. Carrot peel, potato peel, mushroom stem and pumpkin seed are rich in dietary fiber, protein, minerals and bioactive antioxidants but are routinely discarded during processing, whereas commercially available instant soup mixes are poor in these nutrients. This study aimed to use these four by-products to develop a functional instant soup mix that meets consumer needs in Pakistan while reducing food waste and nutritional deficiencies. Six formulations (T0–T5) were designed using a systematic substitution gradient, with carrot peel and potato peel increasing from 0% to 50% and mushroom stem and pumpkin seed decreasing from 50% to 0%. Proximate composition, mineral content (atomic absorption spectrophotometry), antioxidant activity (DPPH assay), total phenolic content (TPC; Folin–Ciocalteu method), functional properties and color (CIE L*a*b*) were determined, and microbial stability was monitored over 90 days of storage. Crude fiber increased 7.3-fold, from 0.84% (T0) to 6.14% (T5). The highest antioxidant activity (59.77% DPPH inhibition) and TPC (6.82 mg GAE/g), three to four times those of the control, were found in T2 (20% carrot peel, 20% potato peel, 30% mushroom stem and 30% pumpkin seed), suggesting synergy between the hydrophilic phenolics of carrot peel and the lipophilic phenolics of pumpkin seed. Peel incorporation significantly increased calcium content. All formulations remained microbiologically safe after 90 days. T2 was also the best formulation for flavor (7.45/9) and overall acceptability (7.80/9), statistically equivalent to T3. This study demonstrates that fruit and vegetable by-product powders can be used in nutritionally enriched, sensorially acceptable and microbiologically safe functional instant soup mixes, with T2 identified as the optimal formulation for scale-up and commercialization.

Keywords: Food waste valorization; Instant soup mix; Carrot peel; Potato peel; Mushroom stem; Pumpkin seed; Dietary fiber; Antioxidant

Convergence, Stagnation and Decline in Pakistan's Crop Yield Trajectories (1990–2024) and Their Implications for Food Security

Amar Razzaq^{1*}, Muhammad Asad-ur-Rehman Naseer²

¹Business School, Huanggang Normal University, Huanggang, China

²Department of Agribusiness and Marketing, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

*Corresponding author's e-mail: amar.razzaq@hgnu.edu.cn

Abstract

Food-security debates in Pakistan often treat crop agriculture as a single sector, yet its major crops have followed very different paths. This study tracks the yields of seven crops from 1990 to 2024 against world, Indian and peer-country yields, using FAOSTAT data cross-checked against the Pakistan Economic Survey. It identifies when each crop's yield trend changed, ranks Pakistan against other producing countries, separates output growth into the contributions of more land and higher yields, and estimates how much of today's imports the missing yield growth could have replaced. Three trajectories emerge. Maize converged: its yield rose from 39% to 104% of the world level, the fastest growth among 79 major producers, and potato and sugarcane also closed most of their gaps. Cotton stagnated: seed-cotton yield in 2019–23 was no higher than in the early 1990s, slipping from 109% to 76% of the world level. Chickpea declined: its yield fell from 63% to 34% of the world level, the slowest growth among 12 major producers. Wheat and rice kept pace with world growth but remain near 80% of the world level. Higher yields explained 58% of the 71% rise in the real value of crop output, and more land 27%. The lagging crops carry a food-security cost: between 1991–95 and 2019–23, self-sufficiency fell from 112% to 67% in cotton lint and from 86% to 49% in chickpea. Had their yields grown at benchmark rates since the early 1990s, the extra output would equal 60–90% of average lint imports in 2019–23 (about US\$1.3 billion a year) and 77–130% of chickpea imports, although the cotton share is smaller when measured from 2005–09. Lagging productivity therefore accounts for much of Pakistan's dependence on these imports. Stronger seed systems, pest management and climate-resilient varieties could bring sizeable food security and foreign exchange gains.

Keywords: Yield gap; Convergence; Import dependence; Self-sufficiency; Cotton; Pakistan

From Farm to Fork: Climate-Resilient Integrated Pest Management for Sustainable Food Systems in Pakistan

Hamza Naeem

Entomologist, Urban Pest Management Pakistan

Corresponding author's e-mail: hamza@upmpk.com

Abstract

Climate change is adding to food security and safety challenges by altering pest behavior, distribution and seasonal pressure. Pests threaten not only agricultural production but also storage, transport, processing, retail and food service settings. This talk emphasizes the need for a farm-to-fork Integrated Pest Management (IPM) approach to build resilient and sustainable food systems in Pakistan. It examines how urbanization, infrastructure, waste, water, sanitation and climate interact to shape pest hazards. Digital IPM (DIPM) systems can strengthen traceability, real-time alerts, trend analysis and data-driven decision-making. Integrated pest-risk management is therefore a crucial component of safe, sustainable and climate-resilient food systems in Pakistan.

Keywords: *Integrated pest management; Climate change; Food safety; Digital IPM; Farm-to-fork; Pakistan*

Cereal Polysaccharides: Sustainable Ingredients for Next-Generation Functional Foods

Muhammad Tahir Nadeem*, Hafiza Saima, Muhammad Zubair Khalid

Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

*Corresponding author's e-mail: mt.nadeem@gcuf.edu.pk

Abstract

Cereal grains are a major source of polysaccharides such as arabinoxylan, β -glucan and resistant starch, which are valued for their nutritional and functional properties. Arabinoxylan, the main non-starch polysaccharide in cereal bran, is a promising ingredient for healthier and more sustainable foods. As dietary fibers, cereal polysaccharides can support beneficial gut bacteria, help regulate glucose and lipid metabolism and provide antioxidant effects; arabinoxylan from wheat bran and other cereals shows prebiotic potential. Its functionality depends on molecular structure, degree of branching, molecular weight and extraction method. Cereal processing by-products such as bran are abundant, underused sources of these compounds, and enzymatic, ultrasound-assisted and other greener extraction methods are being explored to improve recovery while reducing environmental impact. Recovering polysaccharides from by-products supports the circular economy by turning agricultural residues into valuable food ingredients. In foods, cereal polysaccharides can increase dietary fiber content and provide technological benefits such as water retention, viscosity and improved texture. Applications include bakery, beverage and dairy products, where balancing functionality with sensory quality is important for consumer acceptance. By combining health benefits, food innovation and sustainable resource use, cereal polysaccharides are promising candidates for next-generation functional foods. Clean extraction methods and structure-based ingredient design can further expand their use in sustainable food systems.

Keywords: *Cereal polysaccharides; Arabinoxylan; β -glucan; Dietary fiber; Prebiotic; Functional foods; Cereal by-products; Sustainable food systems*

Climate Change and Global Food Security: Impacts, Vulnerabilities, and Pathways toward Sustainable Food Systems

Hassan Ali^{1*}, Muhammad Akram Kharral^{2,3}

¹*Institute of Agronomy, Bahauddin Zakariya University, Multan 60800, Punjab, Pakistan*

²*Indiana Wesleyan University, 8415 Georgia St, Merrillville, IN 46410, United States of America*

³*Food, Agriculture and Climate Change Section, Ministry of Planning, Development and Special Initiatives, Government of Pakistan, Pakistan*

***Corresponding author's e-mail:** virkchhassan@gmail.com

Abstract

Climate change poses a growing threat to global food security by disrupting agricultural production, food availability, accessibility and nutritional quality. This study aimed to examine the effects of rising temperatures, changing precipitation patterns and extreme weather events on food security and to identify strategies for strengthening the resilience of food systems. A systematic review was conducted to synthesize evidence from peer-reviewed research articles, international agricultural reports and global food security assessments. It focused on climate-related production losses, food price fluctuations, nutritional insecurity, vulnerable populations and adaptation strategies, including climate-smart agriculture, diversified food systems, improved storage infrastructure and sustainable water management. Global assessments indicate that approximately 673 million people (8.2% of the world population) experienced hunger in 2024. The World Meteorological Organization reported 2024 as the warmest year on record, with global mean surface temperature about 1.55°C above the pre-industrial level. Climate-related droughts, floods and heatwaves threaten crop productivity, disrupt food supply chains and increase price instability, particularly in regions dependent on rain-fed agriculture. Expanding climate-resilient agricultural practices, reducing post-harvest losses and improving early-warning systems offer important opportunities to reduce these risks. Climate change and food insecurity are interconnected global challenges that require coordinated action across agriculture, water management, public policy and food distribution systems. Strengthening climate adaptation, investing in resilient infrastructure and ensuring equitable access to nutritious food are essential for protecting vulnerable communities and achieving long-term food security.

Keywords: *Adaptive capacity; Extreme weather; Food supply chains; Nutritional vulnerability; Sustainable development*

Innovations and Opportunities for Climate-Resilient Food Systems

Ghulam Sabir Hussain

Fatima Sugar Research and Development Center, Fatima Sugar Mills Limited, Lahore, Pakistan

Corresponding author's e-mail: sabir.hussain@fatima-group.com

Abstract

Climate change increasingly threatens global food security through rising temperatures, irregular rainfall, prolonged droughts, floods, soil degradation, water scarcity and a higher incidence of crop pests and diseases. These challenges are particularly significant in agriculture-dependent regions, where sustainable crop production and efficient resource management are essential for food security and farmers' livelihoods. Sustainable food systems offer an integrated approach by improving agricultural productivity, conserving natural resources, reducing environmental impacts and strengthening resilience throughout the food supply chain. This work highlights innovative strategies and emerging opportunities for developing climate-resilient food systems, with emphasis on sustainable agricultural practices, soil health management, water-use efficiency and technological advances. Climate-smart agriculture, conservation tillage, crop diversification, improved climate-resilient varieties, integrated nutrient management, biofertilizers and biological pest control can enhance productivity and environmental sustainability. Precision agriculture and remote sensing offer further opportunities to optimize inputs, monitor crop conditions and improve responses to climate-related risks, while integrated soil fertility management, efficient irrigation and reduced post-harvest losses strengthen resource-use efficiency and minimize food-system waste. Successful implementation requires coordinated efforts among researchers, farmers, policymakers, agricultural industries and development organizations. In conclusion, developing sustainable food systems requires an integrated approach that combines technological innovation, ecological sustainability, economic viability and social equity to address the growing challenges of climate change effectively.

Keywords: *Sustainable food systems; Climate-smart agriculture; Food security; Soil health; Precision agriculture; Resource-use efficiency; Biofertilizers; Climate resilience*

Agricultural Drone Adoption and Food Security in Pakistan: The Role of Farm Productivity and Climate Resilience

Noreen Safdar

Department of Economics, The Women University Multan, Multan, Punjab, Pakistan

Corresponding author's e-mail: noreen.safdar@wum.edu.pk

Abstract

Agricultural drones offer potential routes to strengthening food security in Pakistan through improved farm productivity and climate resilience, but their contribution depends on agronomic effectiveness, affordability, and local operating conditions. This focused narrative review examines selected online research and policy publications from 2024–2026 on crop spraying, stress monitoring, and adoption constraints, with evidence organized around food availability, economic access, and production stability. A 2025 field study of direct-seeded rice in India found that UAV herbicide application reduced labor requirements by 50%, application costs by 18% and total weed-management costs by 13% compared with backpack spraying; effective sequential herbicide treatments gave the highest grain yields under both methods, highlighting the importance of treatment strategy rather than an inherent drone yield advantage. A 2024 wheat phenotyping study used UAV multispectral imagery and machine learning to evaluate water-stress responses and support drought-tolerant variety selection. Together, these findings suggest complementary pathways through more economical crop protection and better-informed adaptation decisions. For Pakistan, a 2025 study of 450 wheat farmers in Multan, Vehari and Khanewal associated climate-smart practices and access to credit and extension with higher net returns, although it did not evaluate drones, and the September 2026 PIDE policy viewpoint recommends service-based drone pilots with independent assessment before expansion. The review interprets productivity gains as potential support for food availability and farmer purchasing power, while stress monitoring may strengthen production stability when linked to effective field responses. However, direct Pakistan-specific causal evidence connecting drone adoption to household food security remains insufficient in the reviewed sources. Adoption should therefore be accompanied by affordable rental services, trained operators and locally validated application protocols, and comparative multi-season evaluations of yield, net returns, resource use, and household food security are needed to establish whether operational gains translate into sustained resilience and food-security benefits.

Keywords: *Agricultural drones; Food security; Farm productivity; Climate resilience; Pakistan*

Impact of Soil Organic Carbon Verification Using AI and Satellite Remote Sensing on Crop Nutrition

Nighat Raza*, Alina Sadaf

Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: nighat.raza@mnsuam.edu.pk

Abstract

Soil organic carbon (SOC) strongly influences soil health, nutrient cycling, water-holding capacity and microbial activity, and thereby crop nutrition. As carbon markets and regenerative agriculture programs expand, rigorous, low-cost and credible tracking of SOC change is needed. Existing verification methods rely on intensive field sampling and laboratory analysis, which are costly and have limited spatial coverage. Satellite remote sensing data (Sentinel-2, Landsat and hyperspectral missions such as EnMAP) combined with machine learning models (random forests, convolutional neural networks and other deep learning approaches) have recently been used to estimate SOC from field to regional scales. These studies report moderate to good predictive performance (R^2 frequently 0.4–0.8), but accuracy declines in heterogeneous landscapes, under crop cover and for small year-to-year changes. Hybrid approaches that combine remote sensing, process-based modeling and site-specific soil sampling can improve prediction reliability and uncertainty quantification. Evidence suggests that the availability of micronutrients, especially zinc, iron and magnesium, and the nutrient-mobilizing capacity of soil microbes are linked to higher SOC and better soil health, and that long-term organically managed soils are associated with higher levels of some minerals and phytochemicals. However, results are context-dependent, and the effect of SOC gains on nutrient levels in grains and vegetables is inconsistently quantified because carbon and nutrition outcomes are not always measured together. We conclude that AI- and satellite-based verification is a viable and cost-effective way to scale up soil carbon monitoring and to link soil health with food quality outcomes. Combining remote sensing, targeted soil nutrient sampling and crop nutrient testing would improve validation, reduce uncertainty and clarify the connection between soil carbon and human nutrition.

Keywords: *Soil organic carbon; Process-based modeling; Satellite remote sensing; AI; Regenerative agriculture*

Climate Exposure and Bilateral Agricultural Adaptation Finance: Evidence on Commitment Intensity during 2011–2024

Muhammad Asad ur Rehman Naseer*, Amar Razzaq, Shoaib Akhtar, Saher Jabeen

Department of Agribusiness and Marketing, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** asadrehman@bzu.edu.pk

Abstract

This paper examines whether the intensity of bilateral agricultural adaptation-related commitments varies with agricultural climate exposure among observed positive donor–recipient-year records. Its contribution is to combine annual weather exposure over fixed harvested-area geography with separate ten-year prior histories and immediately preceding shocks. OECD Creditor Reporting System activities marked with a principal adaptation objective are linked to CHIRPS version 3 rainfall, NASA POWER temperature, and SPAM 2010 crop weights. The descriptive sample comprises 1,336 positive records covering 25 donors and 121 recipients during 2011–2024, totaling USD 4,994.619 million in current-dollar original commitments. The preferred log-commitment model uses 1,308 complete cases, lagged recipient controls, and donor-year and recipient fixed effects. Prior heat has a coefficient of -0.154 (95% confidence interval -0.414 to 0.106), and prior rainfall deficit has a coefficient of 0.140 (-0.080 to 0.361). Recent-shock point estimates are close to zero. Completed accounting exclusions leave the interpretation unchanged, whereas an isolated negative heat coefficient under an inverse-hyperbolic-sine outcome remains sensitive to scale. The evidence establishes no robust exposure–intensity association within this selected sample, although its uncertainty permits economically meaningful differences. The policy implication is to distinguish commitment amounts, access, delivery and measured need when assessing finance alignment. These observational estimates do not demonstrate misallocation or adaptation effectiveness.

Keywords: *Agricultural adaptation; Climate finance; Bilateral commitments; Crop-area exposure; Selected positive sample; Fixed effects*

Value Addition of Flatbreads: Impact of Corn-Derived Resistant Starch (RS4) on Rheology, Texture and Glycemic Index Reduction of Chapatti

Faiza Shaikh¹, Tahira Mohsin Ali², Saqib Arif³, Natasha Abbas Butt⁴, Muhammad Waqar^{5*}

¹Department of Biosciences, Faculty of Life Sciences, SZABIST University, Karachi, Pakistan

²Department of Food Science and Technology, University of Karachi, Karachi, Pakistan

³Food Quality and Safety Research Institute, Pakistan Agricultural Research Council (PARC), University of Karachi, Karachi 75270, Pakistan

⁴Food Science and Technology, Department of Biomedical Engineering, Ziauddin Faculty of Engineering, Science, Technology and Management, Karachi, Pakistan

⁵Food Technology and Innovation Research Center of Excellence, School of Agricultural Technology and Food Industry, Walailak University, Thai Buri, Tha Sala, Nakhon Si Thammarat, Thailand

*Corresponding author's e-mail: mwaqarvet@gmail.com

Abstract

Functional food reformulation and value addition in cereal-based staples are vital pathways toward sustainable nutrition and public health resilience. While dietary fibers enhance nutritional profiles, conventional sources often compromise the sensory and rheological quality of staple foods. This study investigated the value addition of wheat flatbread (chapatti) by incorporating corn-based resistant starch type 4 (RS4, starch citrate) at substitution levels of up to 15%. Rheological evaluation showed that RS4 supplementation produced stronger dough with enhanced shear resistance and dominant elastic behavior ($G' > G''$) across the dynamic frequency sweep. Critical strain values at 10% and 15% replacement were significantly higher than in the control, indicating improved structural integrity. The resulting chapattis had soft, extensible textures and sensory acceptance equivalent to conventional whole wheat chapattis. Notably, RS4 incorporation reduced the predicted glycemic index (pGI), from 57.25 (medium GI) to 47.39 (low GI). These findings demonstrate that corn-derived RS4 is an effective functional ingredient for value-added flatbreads, yielding low-glycemic, consumer-acceptable staple foods for diabetic management and health-conscious populations without sacrificing processing quality.

Keywords: Value addition; Functional foods; Resistant starch (RS4); Glycemic index; Food processing; Rheology; Chapatti

Mulberry-Based Functional Beverages: Nutritional and Antioxidant Perspectives

Muhammad Sibt-e-Abbas^{1*}, Muhammad Shahbaz¹, Shabbir Ahmad¹, Kashif Razzaq²

¹Department of Food Science and Technology, Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan

²Department of Horticulture, Faculty of Agricultural and Environmental Sciences, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: sibte.abbas@mnsuam.edu.pk

Abstract

Functional beverages are gaining popularity because of their health-enhancing properties, convenience and pleasant flavor, and mulberry-based beverages have good nutritional and antioxidant potential. In this study, a ready-to-serve (RTS) functional beverage was prepared from white (*Morus alba*) and black (*Morus nigra*) mulberry fruit powder. The proximate composition, mineral profile, physicochemical properties, and antioxidant potential of the powders were analyzed, and the beverages were prepared and analyzed by standard procedures. White mulberry had higher moisture (4.92%) and fat (4.64%), whereas black mulberry had higher antioxidant activity (DPPH 45.5%) and vitamin content (131.1 mg/100 g). Protein content was similar (0.63–0.69%), and crude fiber was absent from both samples because of the clarification process. White mulberry had slightly higher ash (11.08%), indicating higher total mineral content, while black mulberry was higher in potassium, calcium, and sodium and in functional potential. The pH and total soluble solids (TSS) of both beverages were within permissible ranges (pH 6.6–6.9; TSS 4.7–5.3 °Brix), and total phenolic content was higher in white mulberry (458 mg GAE/100 g). Sensory evaluation showed significant differences ($P \leq 0.05$) among treatments for all attributes; mean overall acceptability scores were T0 (6.15 ± 0.58), T1 (6.72 ± 0.61), T2 (7.28 ± 0.59), T3 (7.54 ± 0.62), T4 (7.90 ± 0.60) and T5 (8.15 ± 0.57), with T5 the most acceptable. Both beverages had good nutritional and antioxidant content; however, black mulberry was higher in functional attributes, whereas white mulberry was higher in energy density and mineral content. Both show potential as natural health-promoting ingredients in the functional food sector.

Keywords: Mulberry powder; Functional beverage; Antioxidants; Phenolic content

Probing the Effect of Multigrain Crackers against Type 2 Diabetes Mellitus

Komal Abbas^{1*}, Muhammad Sibte-Abbas², Noshaba Fiaz²

¹Department of Human Nutrition and Dietetics, Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan

²Department of Food Science and Technology, Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan

*Corresponding author's e-mail: komalabbas080@gmail.com

Abstract

Type 2 diabetes mellitus (T2DM) is a growing public health crisis in Pakistan, affecting an estimated 33–50 million people and driven by high consumption of refined carbohydrates and sedentary lifestyles. Functional foods enriched with dietary fiber and bioactive phytochemicals are a cost-effective, culturally acceptable dietary strategy for T2DM management. This study developed and evaluated multigrain crackers containing wheat flour, oat flour, and chickpea husk powder (CPH) in three successive experiments. In Experiment I, five composite flour blends (0–20% CPH, oat fixed at 10%) were characterized. CPH had the highest crude fiber (38.4%) and mineral content among the raw materials, and its incorporation progressively increased crude fiber (3.1% to 8.8%), mineral density and water absorption capacity while reducing digestible carbohydrate and starch peak viscosity in dough rheology. In Experiment II, an 8-week feeding trial in streptozotocin-induced diabetic Wistar rats showed dose-dependent reductions in fasting blood glucose (302.6 to 138.4 mg/dL), progressive recovery of serum insulin, improved lipid profile and significantly reduced liver enzymes across CPH groups, with a hepatoprotective ceiling at 15% CPH. In Experiment III, baked crackers were fully characterized: total dietary fiber increased from 3.8 to 10.4 g/100 g and glycemic index decreased from 78.4 (high) to 46.4 (low) with increasing CPH. Sensory acceptability remained above 7.0 up to 15% CPH. T4 (15% CPH) was the optimal formulation, with a low GI (54.8), high fiber (8.6 g/100 g), and the highest consumer acceptability among low-GI formulations. These findings demonstrate that chickpea husk-enriched multigrain crackers at 15% CPH are a nutritious, bioactive, sensory-acceptable and glycemically beneficial functional food made from low-cost, locally available ingredients and an underutilized agricultural by-product, and a scientifically grounded, readily actionable candidate for the dietary management of T2DM in Pakistan.

Keywords: Type 2 diabetes mellitus; Functional food; Dietary fiber; Legume by-product; Oat β -glucan

Valorization of Citrus Fruit Processing Waste for Biodegradable Packaging: A Circular Economy Approach

Noshaba Fiaz*, Muhammad Sibt-e-Abbas, Umar Farooq, Muhammad Shahbaz, Nida Firdous

Department of Food Science and Technology, Faculty of Food and Home Sciences, MNS University of Agriculture, Multan, Pakistan

***Corresponding author's e-mail:** noshi15fst366@gmail.com

Abstract

Citrus fruits are among the most widely cultivated fruit crops worldwide. Their consumption and processing into products such as juices, marmalade and jelly generate waste (peel, seeds, and pomace), raising economic, health and environmental concerns. Petroleum-based plastics, meanwhile, resist degradation and persist in the environment for a long time; plastic food packaging is a major route by which microplastics enter the human food chain, where they can accumulate in the cells and tissues of living organisms and pose risks to human health and long-term biological effects. To address this problem, citrus fruit processing waste (CFPW) is being investigated as a promising bioresource for biopolymers such as cellulose, hemicellulose, pectin, and lignin, and for bioactive compounds with potent antibacterial and antioxidant properties. This review summarizes the use of CFPW in developing biodegradable packaging films for food products. It covers both the direct addition of powdered citrus peel and the secondary extraction of valuable compounds from these residues, primarily pectin, essential oils, and seed extracts. The functional properties of citrus-based packaging systems, including mechanical strength, barrier performance, thermal stability and bioactivity, are critically evaluated. Valorization of CFPW has significant potential to reduce agro-industrial waste, minimize dependence on synthetic plastics and enhance resource efficiency. By integrating waste management with sustainable material innovation, this approach contributes to zero-waste strategies and supports the transition toward more resilient and environmentally responsible food packaging systems.

Keywords: *Citrus fruit; Food chain; Microplastics; Food waste*

Development and Characterization of Instant Cupcake Premix: Evaluation of Physicochemical, Sensory and Storage Stability

Haleema Amjad¹, Shabbir Ahmad^{1*}, Sadaf Yaqoob², Mamoon Amir²

1 Department of Food Science and Technology, MNS University of Agriculture, Multan, Pakistan

2 Faculty of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan

***Corresponding author's e-mail:** shabbir.ahmad@mnsuam.edu.pk

Abstract

Growing demand for convenience foods calls for ready-to-use products that combine acceptable sensory quality and nutritional value with easy preparation. This study therefore aimed to develop and characterize an instant cupcake premix, using all-purpose flour and sugar as constant ingredients and optimizing functional ingredients for product quality and storage stability. The nutritional and rheological characteristics of the all-purpose flour were first determined. Three premix formulations (T0, T1 and T2) were prepared with constant amounts of all-purpose flour and sugar (40:45) and varying amounts of egg powder, skimmed milk powder, baking powder, and guar gum. Physicochemical properties, water absorption capacity, density, and viscosity of the premixes were determined, and the nutritional composition, sensory acceptability, moisture, and total plate count of the cupcakes were evaluated at 15-day intervals during 60 days of storage. T2 had higher ash (0.6%) and crude fiber (2.3%) than T0 (0.2% ash; 2.0% crude fiber), whereas T1 had better sensory scores for color, texture, taste, and overall acceptability, with slight change during storage. Microbial counts increased during storage without differences between treatments, and T2 had a bitter aftertaste. The T1 premix (40:45:5:3:3:1) was identified as the most suitable formulation because of its balanced quality, functionality, and acceptability.

Keywords: Bakery products; Cake mix; Cupcake; Shelf stability; Wheat flour