OPEN ACCESS Plant Protection, 08 (04) 2024. 803-816 DOI:10.33804/pp.008.04.5524

Check for updates

Available Online at EScience Press
Plant Protection
ISSN: 2617-1287 (Online), 2617-1279 (Print)
http://esciencepress.net/journals/PP

Review Article

BIOTECHNOLOGY FOR SUSTAINABLE AGRICULTURE: INNOVATIONS IN DISEASE MANAGEMENT

[a]Qurban Ali, [b]Tayyaba Akhtar, [b]Naqshe Zuhra, [c]Hasddin, [d]Sarty Syarbiah, [e]Abdul Aman Ega

[a] *Entomological Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan.*
[b] *Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Pakistan.*
[c] *Department of Urban and Regional Planning, Faculty of Engineering, Lakidende University, Unaaha, Indonesia.*
[d] *Faculty of Agriculture, Lakidende University, Unaaha, Indonesia.*
[e] *Southeast Sulawesi Provincial Forestry Service, Kendari, Indonesia.*

A R T I C L E I N F O

Article history
Received: 13th September, 2024
Revised: 17th December, 2024
Accepted: 26th December, 2024

Keywords
Biotechnology
CRISPR-Cas9
Machine learning
Artificial Intelligence
Sustainable agriculture
Biocontrol agents
Pathogens control
Plant pathology

A B S T R A C T

The growing global population, limited natural resources, and climate change necessitate a shift toward environmentally sustainable agriculture. Traditional practices, reliant on chemical fertilizers, pesticides, and poor land management, compromise food safety and environmental integrity, exacerbating plant diseases and weakening crop defenses. Biotechnology offers solutions by enhancing agricultural productivity while reducing pests, diseases, and environmental impacts. This review highlights the role biotechnology in sustainable agriculture, focusing on biosurfactants, genetic engineering, precision agriculture, and biocontrol agents. Gene-editing technologies like CRISPR-Cas9 have enabled the development of disease-resistant crops, improving plant health and mitigating infections. In the future, biocontrol agents such as microbial inoculants and plant-derived antimicrobials may replace traditional pesticides, effectively managing plant diseases caused by bacterial, fungal, and viral pathogens. The present review also explores the potential of machine learning (ML) and artificial intelligence (AI) in optimizing crop management and the growing use of biosurfactants in industrial and environmental applications. Biosurfactants are crucial in suppressing phytopathogens, improving soil health, and fostering beneficial plant-microbe interactions for effective disease management. Although these advancements hold great promise, further research is required to assess their long-term sustainability and ecological impacts. Scaling these technologies, particularly in developing countries, remains a significant challenge. To establish sustainable food systems, an integrated approach combining genetic, environmental, and technological strategies is essential. This study reviews emerging biotechnological solutions, emphasizing their applications in plant pathology to improve crop resilience and ensure global food security.

Corresponding Author: Tayyaba Akhtar
Email: tayyaba.akhtar914@gmail.com

INTRODUCTION

Biotechnology plays a pivotal role in addressing modern agricultural and environmental management challenges (Munawar et al., 2020; Amin et al., 2024; García et al., 2024). The growing global population has increased food consumption, placing immense pressure on soil, water, and biodiversity. Conventional agricultural practices, such as monoculture and the extensive use of chemical pesticides and fertilizers, have degraded ecosystems, compromised soil health, and deteriorated water quality. These issues are further exacerbated by climate change, which intensifies water scarcity, soil erosion, and insect resistance. Consequently, adopting sustainable practices is essential to ensure food security and maintain ecological balance (Munawar et al., 2020; Ali et al., 2023; Amin et al., 2023).

Biotechnology offers solutions for sustainable agricultural practices, environmental conservation, and improved crop productivity. One of the most promising innovations in sustainable agriculture is the development of plant-based biocontrol agents (Hussain et al., 2011; Mukhtar et al., 2013a; Mukhtar, 2018; Ahmed et al., 2024; Badiyal et al., 2024; Tiep et al., 2024). These agents rely on antibacterial and antifungal compounds derived from plants to reduce the reliance on synthetic pesticides. Plant-based biocontrol is particularly significant as it mitigates environmental toxicity, promotes biodiversity, and minimizes health risks to humans and animals caused by pesticide exposure (Kumar et al., 2021; Malik et al., 2024).

Moreover, plant-based biocontrol agents can be integrated into pest management systems to enhance their efficacy across various agricultural systems (Iqbal and Mukhtar, 2020; Azeem et al., 2021; Mukhtar et al., 2021; Khursheed et al., 2022; Bibi et al., 2023; Saeed et al., 2023; Shahbaz et al., 2023; Fatima et al., 2024; Aziz et al., 2024). Advances such as somatic embryogenesis and *in vitro* tissue culture have also revolutionized crop improvement strategies (Chadipiralla et al., 2020). These technologies enable the rapid propagation of high-quality, disease-resistant plants with desirable traits, effectively addressing crop diseases and environmental stress. Moreover, the integration of computational models with tissue culture techniques has optimized regeneration processes, making them more efficient and scalable in resource-intensive breeding programs (Khan et al., 2023a; Todhunter et al., 2024).

Drought- and pest-resistant crop innovations are crucial for helping agriculture adapt to climate change. Biodegradable biosurfactants hold great promise for bioremediation and industrial applications (Jones, 2021). Unlike synthetic surfactants, which harm the environment, biosurfactants effectively degrade oil spills, pesticides, and heavy metals. Microbial strains from mangrove sediments that produce biosurfactants offer a sustainable method for removing pollutants and waste (Gayathiri et al., 2022). Biosurfactants play a vital role in green technologies for ecosystem restoration and cleanup. Another innovative biotechnological approach with significant environmental benefits is phytoremediation, which utilizes plants to absorb, degrade, or detoxify pollutants from soil and water (Kurade et al., 2021; Alimeer et al., 2023). For example, *Vigna unguiculata* (cowpea) can absorb hazardous heavy metals such as cadmium from degraded soils, providing an eco-friendly solution (Patil and Bankar, 2024). The efficiency of plants in removing contaminants can be enhanced through soil microbial associations or genetic modifications, further advancing environmental restoration efforts (Pant et al., 2021; Waheed et al., 2023). Phytoremediation not only restores polluted areas but also improves soil health, ensuring agricultural sustainability (Priya et al., 2023).

Sustainable agriculture and environmental management increasingly rely on biotechnology to enhance productivity, minimize environmental impact, and conserve resources. Innovations such as plant-based biocontrol, tissue culture, biosurfactants, and phytoremediation address global challenges in agriculture and environmental protection (Chaudhary and Kumar, 2022; Breemer et al., 2024; Ebasan et al., 2024). Biotechnology strengthens agricultural systems against climate change, resource depletion, and environmental degradation.

This paper evaluates the applications, challenges, and opportunities presented by these major biotechnological breakthroughs, highlighting their role in sustainable development (Mukhtar et al., 2023, Afzal and Mukhtar, 2024). Specifically, it examines how plant-based biocontrol, biosurfactants, and phytoremediation contribute to sustainable agriculture and environmental restoration. By synthesizing current research and identifying knowledge gaps, this study aims to inform strategies for integrating biotechnology into sustainable agricultural and environmental management.

Biocontrol in agriculture: exploring the potential of plant-derived antibacterial and antifungal agents

Medicinal herbs contain several bioactive compounds with antibacterial effects (Vaou et al., 2022). Coumarins, flavonoids, phenolics, alkaloids, terpenoids, tannins, essential oils, lectins, polypeptides, and polyacetylenes have long been recognized for combating bacterial and fungal infections and aiding in antibiotic production. Many plant species exhibit antibacterial and antifungal properties, making them suitable for agricultural biocontrol applications (Fiaz et al., 2023; Angelini, 2024).

Polygonum persicaria, *P. plebejum*, *Rumex hastatus*, *R. dentatus*, *R. nepalensis*, and *Rheum australe* have been shown to inhibit *Escherichia coli*, *Staphylococcus aureus*, and *Citrobacter freundii* (Batool et al., 2018). In Asia, preparations from *Calotropis gigantea* inhibit pathogenic fungi such as *Candida albicans* and *Aspergillus* species (Parvin et al., 2014). Ethanolic root extracts of *Plumbago zeylanica* demonstrate potent antibacterial activity against *Vibrio cholerae*, *E. coli*, and *Pseudomonas aeruginosa* (Rahman and Anwar, 2007). Aqueous leaf extracts of *Euphorbia hirta* and *Erythrophleum suaveolens*, as well as methanolic leaf extracts of *Thevetia peruviana*, exhibit antibacterial activity against multidrug-resistant strains such as methicillin-resistant *S. aureus* (MRSA) and extended-spectrum beta-lactamase (ESBL)-producing bacteria (Pacheco et al., 2012; Chuah et al., 2014; Sharifi-Rad et al., 2016; Niranjan et al., 2017). These findings highlight the effectiveness of plant extracts against various bacteria, including multidrug-resistant strains that are becoming increasingly difficult to treat with synthetic antibiotics.

Methanol and ethyl acetate extracts of *Anacyclus maroccanus* and *A. radiatus* show lethal effects on *E. coli* and *Trichophyton rubrum* (Niranjan et al., 2017). Angelini (2024) reported that concentrations below 10 µg/ml of roots and leaves from *Lactuca longidentata* effectively inhibit the proliferation of *E. coli* and *T. tonsurans*.

Contributions to plant disease management

The antibacterial properties of plant-derived compounds contribute significantly to managing plant diseases by reducing pathogen infiltration and suppressing harmful microorganisms. These botanical extracts serve as natural biocontrol agents, decreasing reliance on synthetic pesticides and providing safer agricultural alternatives. Table 1 describes all plant species and their active compounds in detail.

Plant-based biocontrol strategies mitigate plant diseases by suppressing bacterial, fungal, and viral pathogens. Extracts from *Cannabis sativa* (cv. Strawberry) exhibit notable antibacterial efficacy against *Bacillus subtilis* and dermatophyte species such as *Arthroderma currey*, a common fungal pathogen (Serventi et al., 2023). Furthermore, aqueous extracts of the *C. sativa* cultivar “Futura 75” have demonstrated antifungal activities (Kayani et al., 2012; Mukhtar et al., 2013b; Iqbal et al., 2014; Orlando et al., 2021; Saeed et al., 2021). These findings underscore the versatility of plant-derived antimicrobial substances in protecting plants against a wide range of diseases.

Enhancing plant immunity and integration into IPM systems

Plant-based compounds can enhance plant immunity, enabling plants to resist and withstand diseases. In IPM systems, plant extracts are used alongside other biocontrol methods to manage disease outbreaks effectively. These extracts not only eliminate pathogens but also induce systemic resistance in plants (Greff et al., 2023).

Table 1. Plant families, scientific names, and medicinal properties (Khameneh et al., 2019).

Family	Scientific Name	Common Name	Active Compound	Effective Against	Delivery Form	Dosage
Berberidaceae	*Berberis vulgaris*	Barberry	Berberine	Bacteria, Protozoa	Soft Gel	1000 mg
Piperaceae	*Piper nigrum*	Black Pepper	Piperine	Fungi, *Lactobacillus*, *Micrococcus*		
Asteraceae	*Arctium lappa*	Burdock		Bacteria, Fungi, Virus	Capsule	475 mg
Apiaceae	*Carum carvi*	Caraway		Bacteria, Fungi, Virus	Capsule	1000 mg
Rhamnaceae	*Rhamnus purshiana*	Cascara Sagrada	Tannins	Bacteria, Fungi, Virus	Capsule	425-450 mg
Asteraceae	*Matricaria chamomilla*	Chamomile	Anthemic Acid	*M. tuberculosis*, *S. typhimurium*, *S. aureus*		
Apiaceae	*Syzygium aromaticum*	Clove	Eugenol	General Use	Capsule	500 mg
Ericaceae	*Vaccinium* spp.	Cranberry	Fructose	Bacteria	Capsule	500 mg

In vitro regeneration

In vitro regeneration has significantly advanced crop development by rapidly replicating high-quality, disease-resistant plants (Ragavendran and Natarajan, 2017). Under controlled laboratory conditions, techniques such as somatic embryogenesis, organogenesis, and callus culture enable the multiplication of selected plant types, accelerating the breeding process. These methods are particularly effective for challenging or disease-prone crops, producing pathogen-free plants while preserving genetic diversity (Halder et al., 2021).

Recent advancements in tissue culture techniques have optimized regeneration protocols for crops like Vigna unguiculata (cowpea), Solanum lycopersicum (tomato), and Capsicum annuum (bell pepper) (Tan and Kuebbing, 2023; Zulfiqar et al., 2024). Researchers have enhanced callus development, shoot and root regeneration, and somatic embryogenesis processes (Chen and Chang, 2000; Noureen et al., 2024). These innovations have expanded *in vitro* crop diversity and improved regeneration efficiency.

For pest resistance, improved nutrition, and environmental stress tolerance, genetic modification combined with regeneration techniques has become a critical tool (Li et al., 2024; Katırcı et al., 2024). Somatic embryogenesis has proven particularly effective for regenerating hard-to-produce crops like cowpea and tomato. By optimizing medium composition, plant growth regulators, and environmental conditions, researchers have significantly increased regeneration rates, making tissue culture scalable for large-scale agricultural production.

Moreover, optimized micropropagation techniques now allow the production of a large number of genetically identical plants, ensuring uniformity in crop varieties and enabling commercial propagation on a wide scale (Kryukov et al., 2022; Abd El-Zaher et al., 2024).

Role of computational models in optimizing plant regeneration

Computational models play a significant role in optimizing plant regeneration, offering valuable applications in agriculture. Parameters such as the concentration of plant growth regulators, humidity, temperature, and light are critical for achieving optimal plant regeneration (Ji et al., 2023). Table 2 provides a detail on plant species used in computational modeling. By using computer models, researchers can simulate the regeneration process and predict outcomes (Pukkala, 1987). Furthermore, machine learning (ML) and artificial intelligence (AI) are increasingly being utilized in crop regeneration (Kirtis et al., 2022). These approaches require large tissue culture datasets to function effectively. ML and AI enable researchers to forecast or predict experimental outcomes, which can enhance the efficiency and accuracy of experiments. According to Niazian and Niedbała (2020), computational models have great potential to improve *in vitro* regeneration, particularly in the fields of commercial breeding and agriculture.

Table 2. Applications of computational models in boosting plant regeneration processes.

Plant Species	Purpose	Model	Output(s)	Reference
Bellevalia sarmatica, Nigella damascene, Echinacea purpurea	Predicting and optimizing the sterilization	MLP and RBF	Lysoformin, biocide, liquid bleach, chloramine B, silver nitrate, and immersion time	Ivashchuk et al. (2018)
Chrysanthemum × grandiflorum	Predicting and optimizing the sterilization	MLP-NSGA-II	NaOCl, $AgCl_2$, Nano-silver, $AgNO_3$, $Ca(ClO_2)$, H_2O_2, and immersion time	Hesami et al. (2018)
-	Predicting temperature inside the culture containers	MLP	Four node temperatures	Murase et al. (1996)
Cuminum cyminum	Predicting and optimizing callogenesis	MLP	Area, minor axis length, feret diameter, weighted density, and perimeter	Mansouri et al. (2016)
Trachyspermum ammi	Predicting and optimizing callogenesis	MLP	Explant age, the concentrations of kinetin, 2,4-D, and sucrose	Niaziain et al. (2018b)
Gyrinops walla	Predicting and optimizing callogenesis	MLP	Different explants, NAA, BAP, coconut water, and different media (MS and WPM)	Munasinghe et al. (2020)
Daucus carota	Predicting and optimizing cell growth	MLP	Time, the initial level of inoculum, the concentration of glucose, fructose, and sucrose	Albiol et al. (1995)

Heavy metal contamination in crops: challenges and biotechnological solutions

Heavy metal pollution in crops poses significant threats to crop yield and food safety. Cadmium (Cd) is particularly hazardous to plants, animals, and humans (Suhani et al., 2021; AlHattali et al., 2024; Zuhra et al., 2024). Cadmium is released into the environment through industrial activities, agricultural runoff, and the use of polluted water and fertilizers (Kubier et al., 2019). Once in the soil, cadmium is easily absorbed by plant roots and can accumulate in edible plant tissues, creating health risks throughout the food chain. Cadmium contamination leads to stunting, chlorosis, and reduced photosynthetic activity, disrupting nutrient intake, enzyme function, and antioxidant defense mechanisms (AlHattali et al., 2024). Crops contaminated with cadmium exhibit lower yields, reduced quality, and impaired metabolic processes, thus threatening agricultural production and food security.

Several biotechnological approaches can help mitigate heavy metal absorption and toxicity in crops. One eco-friendly method of treating heavy metal pollution is phytoremediation, which involves using plants to remove, degrade, or stabilize soil contaminants. Species such as *Helianthus annuus*, *Brassica juncea*, and *Tithonia diversifolia* are known to absorb cadmium from contaminated soils. These plants may either store the metals in their roots or transfer them to above-ground tissues for safe removal. Phytoremediation is a cost-effective and sustainable solution, especially for large-scale agricultural lands affected by contamination.

Genetically modified (GM) crops also hold promise in reducing heavy metal absorption. By modifying genes involved in heavy metal uptake, transport, and detoxification, plants can be made more resistant to toxic elements. Overexpressing genes that produce metal-binding proteins, such as phytochelatins and metal transporters, allows plants to store cadmium and other metals in a non-toxic form (Yan et al., 2018).

To enhance phytoremediation, fungi and bacteria can be employed to degrade or immobilize heavy metals in the soil, limiting their availability to plants. Although biotechnological solutions offer great potential, further research is needed to ensure their feasibility and scalability in agricultural settings.

Reducing heavy metal pollution in agriculture remains challenging. Factors such as plant growth rates, biomass production, and environmental conditions limit the applicability of phytoremediation in heavily polluted areas, though it has shown effectiveness in small-scale trials. The success of phytoremediation depends on factors such as soil metal availability, plant species selection, and the duration of the remediation process. Furthermore, public acceptance, regulatory approval, and environmental concerns have slowed the adoption of genetically modified crops for heavy metal tolerance and removal. Long-term studies are necessary to assess the potential impacts of GM crops on soil health, biodiversity, and ecological stability.

Detection of aflatoxins in crops: integrating advanced technologies for food safety

Aflatoxins, toxic compounds produced by *Aspergillus* species, pose significant risks to crops such as peanuts, tree nuts, and maize. These mycotoxins can cause liver damage, immunosuppression, and even cancer in humans and animals over time through the consumption of contaminated crops (Robens and Richard, 1992; Aggarwal et al., 2024).

Traditional methods for detecting aflatoxins in crops include thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) (Kotinagu et al., 2015). However, these approaches are often impractical in resource-limited settings due to the high cost of equipment, the need for skilled personnel, and the lengthy processing times. Therefore, there is an urgent need for affordable, rapid, and site-based aflatoxin detection technologies.

Recent advancements in nanotechnology, biosensors, and immunoassays have significantly improved the detection of aflatoxins in agricultural products. For example, enzyme-linked immunosorbent assays (ELISAs) enable the rapid screening of large sample volumes with high sensitivity and specificity (Matabaro et al., 2017; Sadimantara et al., 2024a). These tests leverage the interaction between aflatoxin molecules and antibodies for accurate contamination detection (Li et al., 2011). However, the complexity of sample matrices and the specific requirements for reagents can limit the utility of these methods (Sadimantara et al., 2024b).

Biosensors represent a noteworthy advancement, offering real-time, *in situ* detection of aflatoxins. These sensors use biological elements such as enzymes, antibodies, or nucleic acids to identify contaminants (Al-Rubaye, 2019). Their portability makes them ideal for field applications, particularly when integrated into compact devices. Moreover, advancements in nanotechnology have resulted in highly sensitive and selective detectors for aflatoxins. Quantum dots, carbon nanotubes, and gold nanoparticle-based biosensors have demonstrated enhanced sensitivity, enabling the detection of even trace levels of contamination and thereby improving food safety (Eivazzadeh-Keihan et al., 2017; Lv et al., 2018).

Despite these technological advancements, several challenges hinder the widespread adoption of advanced aflatoxin detection methods. Limited research on their application in agricultural contexts, coupled with the high costs of deployment, constrains their use in resource-poor regions. Laboratory techniques like HPLC remain reliable but are unsuitable for field testing, which demands more economical and portable alternatives. Immunoassays and biosensors show promise, but their reliance on specific reagents restricts their applicability in complex sample matrices such as soil and animal feed.

Furthermore, the standardization and certification of emerging detection technologies are still in progress, delaying their integration into mainstream agricultural and food safety management systems. Addressing aflatoxin risks requires a comprehensive approach that combines advanced detection tools with effective preventive measures. These include cultivating *Aspergillus*-resistant crop varieties, implementing pest control strategies, and adopting proper storage practices to minimize aflatoxin contamination.

Finally, educating farmers on the risks of aflatoxins and the benefits of these new detection tools is essential for their successful adoption and utilization. Only through a holistic agricultural strategy can aflatoxin exposure be effectively mitigated, ensuring both food safety and public health.

CRISPR/Cas9 mechanism and applications in agriculture

The innovative gene-editing technique CRISPR/Cas9 offers precise alteration of DNA sequences (Jo et al., 2015). The CRISPR DNA sequence, originally discovered in archaea and bacteria, functions as an adaptive immune system to combat viruses (Ledford, 2022; Shahid et al., 2024). The Cas9 protein and guide RNA (gRNA) work in tandem to accurately cleave target DNA (Doudna and Charpentier, 2014). Once Cas9 identifies a sequence matching the gRNA, it introduces site-specific DNA breaks (Liang et al., 2017). This induces the cell's natural repair mechanisms, which can insert, delete, or modify genes as needed (Liu et al., 2022). Figure 1 describes the flowchart of the CRISPR/Cas9 mechanism and applications in agriculture. The revolutionary CRISPR/Cas9 system has significantly boosted agricultural productivity and resilience. Through genetic engineering, crops benefit from enhanced disease resistance, improved drought tolerance, and increased nutrient content (Wang et al., 2022). For instance, CRISPR technology has been used to modify wheat and rice, improving their ability to withstand extreme weather conditions and mitigating the impact of climate change on global food security (KhokharVoytas et al., 2023).

CRISPR/Cas9 also accelerates the development of pest-resistant crops, reducing reliance on chemical pesticides. This not only minimizes the environmental footprint of agriculture but also increases food production efficiency (Hemalatha et al., 2023; Khan et al., 2023b). Additionally, Koç and Karayiğit (2022) emphasize the potential of CRISPR gene editing to enhance the nutritional quality of crops by fortifying them with essential vitamins and minerals, addressing global hunger challenges.

Advantages of CRISPR/Cas9

Precision

It enables highly targeted edits in the genome, minimizing unintended mutations (off-target effects).

Speed

It facilitates the faster development of improved crops and livestock compared to traditional breeding methods.

Sustainability

It reduces dependence on chemical fertilizers, pesticides, and water, promoting environmentally sustainable farming practices.

Global food security

It improves crop yields and develops climate-resilient crops to combat global malnutrition and food insecurity challenges.

Disadvantages of CRISPR/Cas9

Regulatory challenges

It is subject to stringent GMO regulations in many countries, which can delay adoption.

Public perception

It faces scepticism and ethical concerns regarding the use of genetic modification in food.

Environmental risks

It poses a risk of unintended ecological consequences, such as cross-pollination or genetic drift.

Access and equity

High costs and complexity may restrict access for small-scale farmers in developing countries.

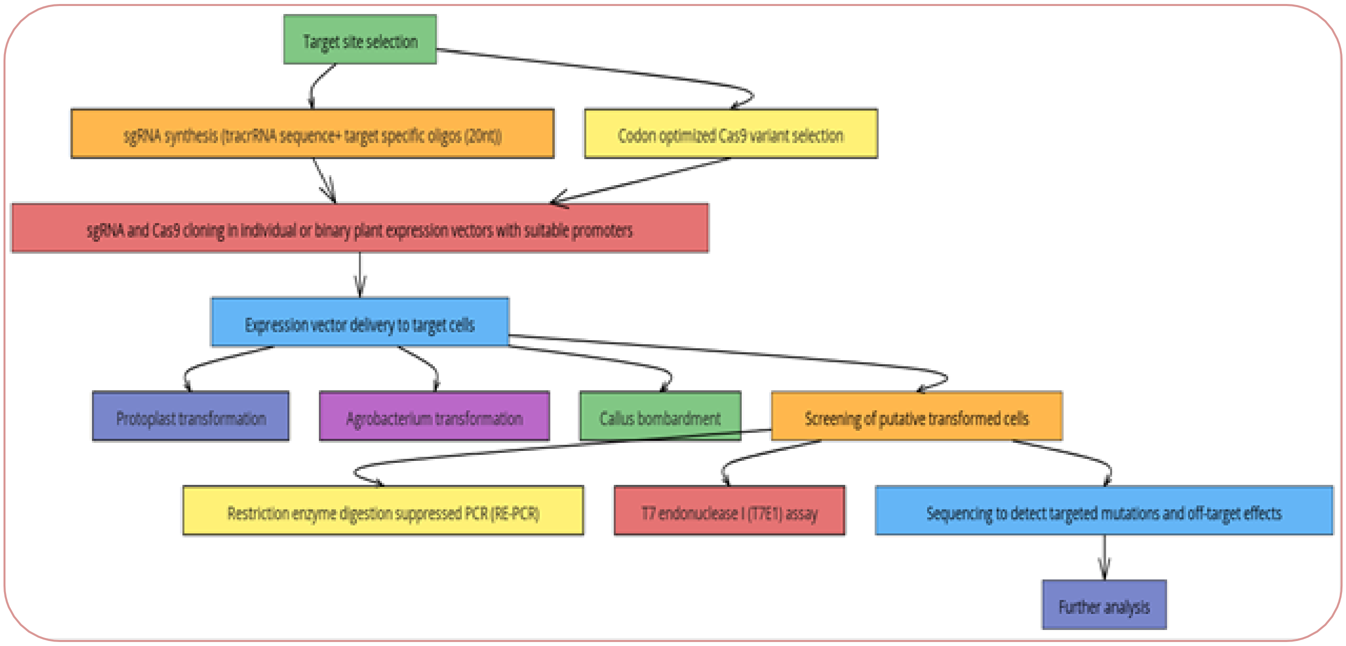

Figure 1. Flowchart of CRISPR/Cas9 mediated plant genome editing.

Biosurfactants: effective replacements for industrial applications and environmental restoration

Biosurfactants are surface-active agents produced by bacteria, fungi, and yeasts. These compounds are biodegradable, non-toxic, and environmentally friendly, making them ideal for various industrial applications and environmental remediation efforts. Their ability to reduce surface and interfacial tension enhances processes such as emulsification, solubilization, dispersion, and foaming. Biosurfactants are recognized as a viable alternative to synthetic surfactants, which are persistent in the environment and often harmful (Rajkhowa and Sarma, 2022; Hamzah et al., 2024).

In environmental restoration, biosurfactants are particularly valuable for the remediation of polluted soils and water. They play a pivotal role in bioremediation, utilizing microorganisms to degrade or detoxify contaminants. Biosurfactants improve the solubility and bioavailability of hydrophobic pollutants such as oils, heavy metals, and pesticides, facilitating microbial degradation. For instance, biosurfactants emulsify oil spills, enabling microorganisms to break them down more effectively. In contaminated soils, they enhance the solubility of metal ions, making them more accessible for bacterial removal. By addressing pollution through natural means, biosurfactants contribute to ecosystem restoration without relying on harmful chemicals (Karlapudi et al., 2018).

Beyond environmental applications, biosurfactants are utilized in industries such as food, pharmaceuticals, cosmetics, and detergents (Moldes et al., 2020). Their biodegradability and low toxicity make them a safer option compared to synthetic surfactants in consumer products (Nagtode et al., 2023). For example, biosurfactants serve as emulsifiers in food products like salad dressings and mayonnaise, improving their stability (Alara et al., 2023). In the pharmaceutical and cosmetic industries, biosurfactants enhance the absorption and efficacy of active ingredients.

The production of biosurfactants is both environmentally sustainable and economically viable. Microorganisms such as *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Candida albicans* can produce biosurfactants using agricultural residues, vegetable oils, and food industry waste as substrates (Gaur et al., 2022; Pinto et al., 2022). This sustainable manufacturing approach not only reduces waste but also underscores the ecological and economic benefits of biosurfactants.

FUTURE DIRECTIONS AND CONCLUSION

Biotechnology will play a pivotal role in sustainable farming by addressing challenges such as rising temperatures, resource shortages, and increasing food demand. Modern genetic technologies like CRISPR-Cas9 offer the potential to develop crop varieties that are drought-, heat-, and salt-tolerant. Current gene-editing techniques can modify specific regions of the genome to enhance nutritional value, abiotic stress tolerance, and pest resistance. By accelerating crop development, genome editing has the potential to mitigate the impacts of climate change and food insecurity, ultimately saving lives.

Emerging biotechnologies such as artificial intelligence (AI) and machine learning (ML) are transforming agriculture. These technologies analyze vast datasets derived from environmental sensors, field observations, and genetic studies to improve crop management. AI and ML can optimize irrigation schedules, predict pest outbreaks, and provide nutrient management solutions, enabling farmers to increase productivity while reducing input costs. By combining biotechnology with precision agriculture, data-driven decision-making can enhance both yields and sustainability.

Eco-friendly farming practices are increasingly incorporating biosurfactants, microbial inoculants, and plant-based antimicrobials. Biocontrol agents not only minimize pollution but also promote biodiversity. As the global demand for organic and sustainable farming grows, the use of biocontrol agents against soil-borne diseases and pests is becoming indispensable. Biosurfactants produced by bacteria have versatile applications, including cleaning oil spills and serving as biodegradable disinfectants.

Research on soil health is advancing with the development of novel microbial inoculants to restore soil microbiomes and improve nutrient availability, thereby reducing the dependence on chemical fertilizers. These innovations strengthen plant-microbe interactions, enhancing both agricultural sustainability and productivity. Moreover, bioremediation techniques employ microbes to cleanse soil and water contaminated by industrial agriculture.

Despite these advancements, resource limitations hinder the adoption of biotechnology in developing nations. Comprehensive regulatory, economic, and ecological studies are required to integrate biocontrol agents, genetic engineering, and AI into traditional agricultural systems. Social acceptance remains a significant barrier to the widespread adoption of biotechnology and genetically modified (GM) crops. Further research is needed to assess the scalability, efficiency, and environmental impact of these systems.

In conclusion, biotechnology offers transformative opportunities to improve agricultural sustainability. Precision farming, gene editing, soil health management, and biocontrol agents collectively contribute to sustainable agriculture. However, limited research has been conducted on the genetic, environmental, and scalable aspects of biotechnology solutions. Addressing these gaps will be crucial for harnessing the full potential of biotechnology to enhance sustainable agriculture. Collaboration among researchers, farmers, governments, and private enterprises is essential to build agricultural systems that are resilient, productive, and environmentally sustainable.

AUTHORS' CONTRIBUTIONS

NZ conceptualized the idea, collected and arranged data; QA and TA collaboratively analyzed information, forming the foundation for this review; H, SS and AAE provided essential guidance throughout the writing, formatting, and publication process.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abd El-Zaher, M.H., Abd El-Wahab, S.M., Saleh, S.S., Al-Maghrabi, N.N.M., 2024. Synthetic seeds production by encapsulated somatic embryo of white olive cultivar.

Afzal, A., Mukhtar, T., 2024. Revolutionizing nematode management to achieve global food security goals - An overview. Heliyon 10, e25325.

Aggarwal, A., Mishra, A., Tabassum, N., Kim, Y.-M., Khan, F., 2024. Detection of mycotoxin contamination in foods using artificial intelligence: A review. Foods 13, 3339.

Ahmed, M.J., Shoaib, A., Fatima, Q., Malik, B., 2024. Biocontrol potential of *Pseudomonas syringae* against emerging phyto-fungal pathogens. Phytopathogenomics and Disease Control 3, 95-100.

Alara, O.R., Abdurahman, N.H., Alara, J.A., Ukaegbu, C.I., Tade, M.O., Ali, H.A., 2023. Biosurfactants as emulsifying agents in food formulation. In Advancements in Biosurfactants Research, Springer, pp. 157-170.

Albiol, J., Campmajó, C., Casas, C., Poch, M., 1995. Biomass estimation in plant cell cultures: a neural network approach. Biotechnology Progress 11(1), 88-92.

AlHattali, Y., AlMaskri, A., AlBusaidi, W., Khan, M.M., Akram, M.T., 2024. Impact of cadmium contaminated growing medium on the growth and physiological responses of tomato seedlings (*Solanum lycopersicum* L.). Journal of Global Innovations in Agricultural Sciences 12, 307-313.

Ali, A., Tabbasum, I., Azeem, H., Ölmez, F., Deveci, G., Khalid, B., Mehtab, M., 2023. Bacterial endophytes, a resilient way toward sustainable agriculture: provide plant growth promotion and biocontrol of plant pathogens. Journal of Global Innovations in Agricultural Sciences 11(2), 153-174.

Alimeer, D.A., Mahmood, N.N., Al-Halbosiy, M.M.F., 2023. Extraction and purification of biosurfactant by locally isolated *Enterococcus faecium* bacteria and study of its antimicrobial activity. Journal of Global Innovations in Agricultural Sciences 11(4), 543-548.

Al-Rubaye, A.G.G., 2019. Development of optical biosensors based on metal nanostructures for pollution (mycotoxins) detection. Sheffield Hallam University.

Amin, H., Sheikh, U., Anjum, F., Ashraf, I., Rizwan, S., Murtaza, G., Khan, N.H., 2024. A multidimensional analysis of food security, health, and ecological situation. Journal of Global Innovations in Agricultural Sciences 12(1), 207-213.

Amin, H., Sheikh, U., Asghar, K., Anjum, F., Bashir, M.K., Malik, N., Hussain Khan, N., Shahid, I., 2023. Community food insecurity and role of agriculture extension in rural development. Journal of Global Innovations in Agricultural Sciences 11, 259-271.

Angelini, P., 2024. Plant-derived antimicrobials and their crucial role in combating antimicrobial resistance. Antibiotics 13, 746.

Azeem, W., Mukhtar, T., Hamid, T., 2021. Evaluation of *Trichoderma harzianum* and *Azadirachta indica* in the management of *Meloidogyne incognita* in tomato. Pakistan Journal of Zoology 53(1), 119-125.

Aziz, S., Jamshed, S.A., Mukhtar, T., Irshad, G., Ijaz, S.S., Raja, M.U., 2024. Evaluation of *Bacillus* spp. as biocontrol agents against chili leaf spot caused by *Xanthomonas vesicatoria*. Journal of Plant Diseases and Protection 131, 987-997.

Badiyal, A., Mahajan, R., Rana, R.S., Sood, R., Walia, A., Rana, T., Manhas, S., Jayswal, D., 2024. Synergizing biotechnology and natural farming: Pioneering agricultural sustainability through innovative interventions. Frontiers in Plant Science 15, 1280846.

Batool, K., Sultana, S., Akhtar, N., Muhammad, H., Naheed, A., 2018. Medicinal plants combating against human pathogens: A review. International Journal of Biotechnology and Food Science 6, 42-51.

Bibi, G., Nayyar, B.G., Ajmal, M., Mehak, A., Seerat W., Shahbaz, M., Mukhtar, T., Akram, A., 2023. Effect of culture filtrates of *Alternaria alternata* on seed germination and seedling growth of sesame. Archives of Phytopathology and Plant Protection 56(8), 625-635.

Breemer, J., Muthalib, A.A., Suriadi, L.O., Lapipi, M., Syarif, M., Gamsir, A.W., Nusantara, A., Balaka, M.Y., 2024. Testing the effects of economic growth, and the role of the agriculture, forestry and fisheries sectors, and other influential factors in forming community welfare. Journal of Global Innovations in Agricultural Sciences 12, 661-669.

Chadipiralla, K., Gayathri, P., Rajani, V., Reddy, P.V.B., 2020. Plant tissue culture and crop improvement. Sustainable Agriculture in the Era of Climate Change, 391-412.

Chaudhary, B., Kumar, V., 2022. Emerging technological frameworks for the sustainable agriculture and environmental management. Sustainable Horizons 3, 100026.

Chen, J.-T., Chang, W.-C., 2000. Efficient plant regeneration through somatic embryogenesis from callus cultures of Oncidium (Orchidaceae). Plant Science 160, 87-93.

Chuah, E., Zakaria, Z., Suhaili, Z., Bakar, S.A., Desa, M.M., 2014. Antimicrobial activities of plant extracts against methicillin-susceptible and methicillin-resistant *Staphylococcus aureus*. Journal of Microbiology Research 4, 6-13.

Doudna, J.A., Charpentier, E., 2014. The new frontier of genome engineering with CRISPR-Cas9. Science 346, 1258096.

Ebasan, M.S., Otadoy, J.B., 2024. Factors influencing agricultural land management practices in Misamis Occidental, Philippines. Journal of Global Innovations in Agricultural Sciences 12, 641-651.

Eivazzadeh-Keihan, R., Pashazadeh, P., Hejazi, M., de la Guardia, M., Mokhtarzadeh, A., 2017. Recent advances in nanomaterial-mediated bio and immune sensors for detection of aflatoxin in food products. Trends in Analytical Chemistry 87, 112-128.

Fatima, S.S., Ali, M.A., Jabran, M., Afzal, M.N., Tanveer, M.H., Nadeem, S.A., Abbas, A., 2024. Comparative study of biocontrol agents against Fusarium wilt in okra caused by *Fusarium oxysporum* pv. *vasinfectum*. Phytopathogenomics and Disease Control 3, 213-220.

Fiaz, N., Sikandar, Z., Shafique, M., Ghaffar, A., Sharif, M.F., Khalid, F., Shahzad, M.K., Saleem, U., Ahmad, H.T., Khokhar, M.I., 2023.

Integrated control of whitefly (*Aleurolobus barodensis*) of sugarcane at its grand growth stage: A sustainable approach. Phytopathogenomics and Disease Control 2, 57-62.

García, M.B., Catasú, W.G., Avalos, D.M.R., Rodriguez, J.A.T., Peña, R.J.H., 2024. Yam biotechnology innovation: A contribution to local food sovereignty. Journal of Global Innovations in Agricultural Sciences 12, 1011-1018.

Gaur, V.K., Sharma, P., Sirohi, R., Varjani, S., Taherzadeh, M.J., Chang, J.-S., Ng, H.Y., Wong, J.W., Kim, S.-H., 2022. Production of biosurfactants from agro-industrial waste and waste cooking oil in a circular bioeconomy: An overview. Bioresource Technology 343, 126059.

Gayathiri, E., Prakash, P., Karmegam, N., Varjani, S., Awasthi, M.K., Ravindran, B., 2022. Biosurfactants: Potential and eco-friendly material for sustainable agriculture and environmental safety-a review. Agronomy 12, 662.

Greff, B., Sáhó, A., Lakatos, E., Varga, L., 2023. Biocontrol activity of aromatic and medicinal plants and their bioactive components against soil-borne pathogens. Plants 12, 706.

Halder, M., Majumder, A., Ray, S., Jha, S., 2021. Medicinal plant research at crossroads: Biotechnological approaches for conservation, production and stability in tissue cultures and regenerated plants. Medicinal Plants: Domestication, Biotechnology and Regional Importance 459-544.

Hamzah, A.H.P., Heryadi, D.Y., Judijanto, L., Pramono, S.A., Lestari, N.C., 2024. Production-optimization of biosurfactant from mangrove sediment bacteria using media salinity, differences in carbon source concentration, and pH levels. Journal of Global Innovations in Agricultural Sciences 12, 391-398.

Hemalatha, P., Abda, E.M., Shah, S., Prabhu, S.V., Jayakumar, M., Karmegam, N., Kim, W., Govarthanan, M., 2023. Multi-faceted CRISPR-Cas9 strategy to reduce plant-based food loss and waste for sustainable bio-economy-a review. Journal of Environmental Management 332, 117382.

Hesami, M., Naderi, R., Tohidfar, M., 2019. Modeling and optimizing medium composition for shoot regeneration of chrysanthemum via radial basis function-non-dominated sorting genetic algorithm-II (RBF-NSGAII). Scientific Reports 9(1), 18237.

Hussain, M.A., Mukhtar, T., Kayani, M.Z., 2011. Efficacy evaluation of *Azadirachta indica*, *Calotropis procera*, *Datura stramonium* and *Tagetes erecta* against root-knot nematodes *Meloidogyne incognita*. Pakistan Journal of Botany 43 (Special Issue), 197-204.

Iqbal, U., Mukhtar, T., 2020. Evaluation of biocontrol potential of seven indigenous *Trichoderma* species against charcoal rot causing fungus, *Macrophomina phaseolina*. Gesunde Pflanzen 72(2), 195-202.

Iqbal, U., Mukhtar, T., Iqbal, S.M., 2014. *In vitro* and *in vivo* evaluation of antifungal activities of some antagonistic plants against charcoal rot causing fungus, *Macrophomina phaseolina*. Pakistan Journal of Agricultural Sciences 51 (3), 689-694.

Ivashchuk, O.A., Fedorova, V., Shcherbinina, N.V., Maslova, E.V., Shamraeva, E., 2018. Microclonal propagation of plant process modeling and optimization of its parameters based on neural network. Drug Invent Today 10(3), 3170-3175.

Ji, B., Xuan, L., Zhang, Y., Mu, W., Paek, K.-Y., Park, S.-Y., Wang, J., Gao, W., 2023. Application of data modeling, instrument engineering and nanomaterials in selected medicinal plant tissue culture. Plants 12, 1505.

Jo, Y.-I., Suresh, B., Kim, H., Ramakrishna, S., 2015. CRISPR/Cas9 system as an innovative genetic engineering tool: Enhancements in sequence specificity and delivery methods. Biochimica et Biophysica Acta (BBA) - Reviews on Cancer 1856, 234-243.

Jones, W.R., 2021. Water resource prospects for the next 50 years on the water planet: Personal perspectives on a shared history from Earth Day, the fourth industrial revolution, and one health to the futures of alternative energy, bioconvergence, and quantum computing. Water International 46, 1158-1186.

Karlapudi, A.P., Venkateswarulu, T., Tammineedi, J., Kanumuri, L., Ravuru, B.K., Dirisala, V.R., Kodali, V.P., 2018. Role of biosurfactants in bioremediation of oil pollution-a review. Petroleum 4, 241-249.

Katırcı, R., Soomro, S.N., Soomro, S.R., Aasim, M., 2024. Optimization of *in vitro* regeneration of cowpea (*Vigna unguiculata* L.) using computational models. Journal of Global Innovations in Agricultural Sciences 12, 285-291.

Kayani, M.Z., Mukhtar, T., Hussain, M.A., 2012. Evaluation of nematicidal effects of *Cannabis sativa* L. and *Zanthoxylum alatum* Roxb. against root-knot nematodes, *Meloidogyne incognita*. Crop Protection 39, 52-56.

Khameneh, B., Iranshahy, M., Soheili, V., Fazly Bazzaz, B.S., 2019. Review on plant antimicrobials: A mechanistic viewpoint. Antimicrobial Resistance & Infection Control 8, 1-28.

Khan, A.H., Parveen, N., Hassan, M., Azmat, M., Amin, M., 2023a. Breeding approaches against climate change and quality enhancement in vegetables. Phytopathogenomics and Disease Control 2, 37-41.

Khan, M.D., Ahmad, B., Ahmed, S.F., Ijaz, M., Abdin, Z.U., Ghafoor, I., Siddiqui, G.M., Adrees, T., Ali, S., Shahzadi, N., Rafa, H.U., Khalid, M.N., Shaukat, S., 2023b. CRISPR-Cas genome editing in crops: A promising frontier for climate-smart agriculture. Phytopathogenomics and Disease Control 2, 71-77.

KhokharVoytas, A., Shahbaz, M., Maqsood, M.F., Zulfiqar, U., Naz, N., Iqbal, U.Z., Sara, M., Aqeel, M., Khalid, N., Noman, A., 2023. Genetic modification strategies for enhancing plant resilience to abiotic stresses in the context of climate change. Functional & Integrative Genomics 23, 283.

Khursheed, A., Rather, M.A., Jain, V., Rasool, S., Nazir, R., Malik, N.A., Majid, S.A., 2022. Plant-based natural products as potential ecofriendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations, and regulatory aspects. Microbial Pathogenesis 173, 105854.

Kirtis, A., Aasim, M., Katırcı, R., 2022. Application of artificial neural network and machine learning algorithms for modeling the *in vitro* regeneration of chickpea (*Cicer arietinum* L.). Plant Cell, Tissue and Organ Culture (PCTOC) 150, 141-152.

Koç, E., Karayiğit, B., 2022. Assessment of biofortification approaches used to improve micronutrient-dense plants that are a sustainable solution to combat hidden hunger. Journal of Soil Science and Plant Nutrition 22, 475-500.

Kotinagu, K., Mohanamba, T., Kumari, L.R., 2015. Assessment of aflatoxin B1 in livestock feed and feed ingredients by high-performance thin-layer chromatography. Veterinary World 8, 1396.

Kryukov, L.A., Vodolazhsky, D.I., Kamenetsky-Goldstein, R., 2022. Micropropagation of grapevine and strawberry from South Russia: Rapid production and genetic uniformity. Agronomy 12, 308.

Kubier, A., Wilkin, R.T., Pichler, T., 2019. Cadmium in soils and groundwater: A review. Applied Geochemistry 108, 104388.

Kumar, J., Ramlal, A., Mallick, D., Mishra, V., 2021. An overview of some biopesticides and their importance in plant protection for commercial acceptance. Plants 10, 1185.

Kurade, M.B., Ha, Y.-H., Xiong, J.-Q., Govindwar, S.P., Jang, M., Jeon, B.-H., 2021. Phytoremediation as a green biotechnology tool for emerging environmental pollution: A step forward towards sustainable rehabilitation of the environment. Chemical Engineering Journal 415, 129040.

Ledford, H., 2022. CRISPR tools from viruses could boost gene editing. Nature 612, 21.

Li, P., Zhang, Q., Zhang, D., Guan, D., Liu, D.X., Fang, S., Wang, X., Zhang, W., 2011. Aflatoxin measurement and analysis. In: Aflatoxins-Detection, Measurement and Control. Citeseer.

Li, Y., Yuan, Y., Hu, Z., Liu, S., Zhang, X., 2024. Genetic transformation of forest trees and its research advances in stress tolerance. Forests 15, 441.

Liang, X., Potter, J., Kumar, S., Ravinder, N., Chesnut, J.D., 2017. Enhanced CRISPR/Cas9-mediated precise genome editing by improved design and delivery of gRNA, Cas9 nuclease, and donor DNA. Journal of Biotechnology 241, 136-146.

Liu, S.-C., Feng, Y.-L., Sun, X.-N., Chen, R.-D., Liu, Q., Xiao, J.-J., Zhang, J.-N., Huang, Z.-C., Xiang, J.-F., Chen, G.-Q., 2022. Target residence of Cas9-sgRNA influences DNA double-strand break repair pathway choices in CRISPR/Cas9 genome editing. Genome Biology 23, 165.

Lv, M., Liu, Y., Geng, J., Kou, X., Xin, Z., Yang, D., 2018. Engineering nanomaterials-based biosensors for food safety detection. Biosensors and

Bioelectronics 106, 122-128.
Malik, N., Sahidin, Muhidin, Fristiohady, A., 2024. Growth response and antibacterial activity test of sintrong plant (*Crassocephalum crepidioides* (Benth.) S. Moore) on different growth media and shade. Journal of Global Innovations in Agricultural Sciences 12, 277-283.
Mansouri, A., Fadavi, A., Mortazavian, S.M.M., 2016. An artificial intelligence approach for modeling volume and fresh weight of callus - A case study of cumin (*Cuminum cyminum* L.). Journal of Theoretical Biology 397, 199-205.
Matabaro, E., Ishimwe, N., Uwimbabazi, E., Lee, B.H., 2017. Current immunoassay methods for the rapid detection of aflatoxin in milk and dairy products. Comprehensive Reviews in Food Science and Food Safety 16, 808-820.
Moldes, A., Vecino, X., Rodríguez-López, L., Rincón-Fontán, M., Cruz, J., 2020. Biosurfactants: The use of biomolecules in cosmetics and detergents. In: New and Future Developments in Microbial Biotechnology and Bioengineering. Elsevier, 163-185.
Mukhtar, T., 2018. Management of root-knot nematode, *Meloidogyne incognita*, in tomato with two *Trichoderma* species. Pakistan Journal of Zoology 50(4), 1589-1592.
Mukhtar, T., Hussain, M.A., Kayani, M.Z., 2013a. Biocontrol potential of *Pasteuria penetrans*, *Pochonia chlamydosporia*, *Paecilomyces lilacinus* and *Trichoderma harzianum* against *Meloidogyne incognita* in okra. Phytopathologia Mediterranea 52 (1), 66-76.
Mukhtar, T., Kayani, M.Z., Hussain, M.A., 2013b. Nematicidal activities of *Cannabis sativa* L. and *Zanthoxylum alatum* Roxb. against *Meloidogyne incognita*. Industrial Crops and Products 42, 447-453.
Mukhtar, T., Tariq-Khan, M., Aslam, M.N., 2021. Bioefficacy of *Trichoderma* species against Javanese root-knot nematode, *Meloidogyne javanica* in green gram. Gesunde Pflanzen 73(3), 265-272.
Mukhtar, T., Vagelas, I., Javaid, A., 2023. Editorial: New trends in integrated plant disease management. Frontiers in Agronomy 4, 1104122. doi: 10.3389/fagro.2022.11041221
Munasinghe, S.P., Somaratne, S., Weerakoon, S.R., Ranasinghe, C., 2020. Prediction of chemical composition for callus production in *Gyrinops walla* Gaetner through machine learning. Information Processing in Agriculture 7(2), 1-12.
Munawar, S., ul Qamar, M.T., Mustafa, G., Khan, M.S., Joyia, F.A., 2020. Role of biotechnology in climate resilient agriculture. Environment, Climate, Plant and Vegetation Growth, 339-365.
Murase, H., Tani, A., Honami, N., Takigawa, H., Nishiura, Y., 1996. Inverse technique for analysis of convective heat transfer over the surface of plant culture vessel. Transactions of the ASABE 39(6), 2277-2282.
Nagtode, V.S., Cardoza, C., Yasin, H.K.A., Mali, S.N., Tambe, S.M., Roy, P., Singh, K., Goel, A., Amin, P.D., Thorat, B.R., 2023. Green surfactants (biosurfactants): A petroleum-free substitute for sustainability-comparison, applications, market, and future prospects. ACS Omega 8, 11674-11699.
Niazian, M., Niedbała, G., 2020. Machine learning for plant breeding and biotechnology. Agriculture 10, 436.
Niranjan, P.S., Kaushal, C., Jain, S., 2017. Pharmacological investigation of leaves of *Polypodium decumanum* for antidiabetic activity. Journal of Drug Delivery and Therapeutics 7, 69-72.
Noureen, S., Akhtar, N., Yang, W., Aziz, A., Saleem, U., Mahmood, T., Yousaf, M.I., Raza, N., Gul, S., 2024. Introgression of sugarcane genotypes × phytohormonal concentrations to speed up *in vitro* somatic embryogenesis and regeneration for development of sugarcane mosaic virus (SCMV)-free saplings. Pakistan Journal of Botany 56, 2027-2036.
Orlando, G., Adorisio, S., Delfino, D., Chiavaroli, A., Brunetti, L., Recinella, L., Leone, S., D'Antonio, M., Zengin, G., Acquaviva, A., 2021. Comparative investigation of composition, antifungal, and anti-inflammatory effects of the essential oil from three industrial hemp varieties from Italian cultivation. Antibiotics 10, 334.
Pacheco, A., Alcântara, A., Abreu, V., Corrêa, G., 2012. Relationships between chemical structure and activity of triterpenes against gram-positive and gram-negative bacteria. In: A Search for Antibacterials Agents. InTech, Rijeka, 1-24.
Pant, G., Garlapati, D., Agrawal, U., Prasuna, R.G., Mathimani, T., Pugazhendhi, A., 2021. Biological

approaches practised using genetically engineered microbes for a sustainable environment: A review. Journal of Hazardous Materials 405, 124631.

Parvin, S., Kader, M.A., Chouduri, A.U., Rafshanjani, M.A.S., Haque, M.E., 2014. Antibacterial, antifungal, and insecticidal activities of the n-hexane and ethyl-acetate fractions of methanolic extract of the leaves of *Calotropis gigantea* Linn. Journal of Pharmacognosy and Phytochemistry 2, 47-51.

Patil, S., Bankar, A., 2024. Development of green approach for environmental decontamination of heavy metals: Soil-microbe-plant interaction. In: Progress in Soil Microbiome Research. Springer, 401-442.

Pinto, M.I.S., Campos Guerra, J.M., Meira, H.M., Sarubbo, L.A., de Luna, J.M., 2022. A biosurfactant from *Candida bombicola*: Its synthesis, characterization, and its application as food emulsions. Foods 11, 561.

Priya, A., Muruganandam, M., Ali, S.S., Kornaros, M., 2023. Clean-up of heavy metals from contaminated soil by phytoremediation: A multidisciplinary and eco-friendly approach. Toxics 11, 422.

Pukkala, T., 1987. Simulation model for natural regeneration of *Pinus sylvestris*, *Picea abies*, *Betula pendula*, and *Betula pubescens*. Silva Fennica 21, 37-53.

Ragavendran, C., Natarajan, D., 2017. Role of plant tissue culture for improving the food security in India: A review update. In: Sustainable Agriculture towards Food Security, 231-262.

Rahman, M.S., Anwar, M.N., 2007. Antimicrobial activity of crude extract obtained from the root of *Plumbago zeylanica*. Bangladesh Journal of Microbiology 24, 73-75.

Rajkhowa, S., Sarma, J., 2022. Biosurfactant: An alternative towards sustainability. In: Innovative Bio-Based Technologies for Environmental Remediation. CRC Press, 377-402.

Robens, J., Richard, J., 1992. Aflatoxins in animal and human health. Reviews of Environmental Contamination and Toxicology: Continuation of Residue Reviews, 69-94.

Sadimantara, M.S., Argo, B.D., Sucipto, S., Al Riza, D.F., Hendrawan, Y., 2024a. The classification of aflatoxin contamination level in cocoa beans using fluorescence imaging and deep learning. Journal of Robotics and Control (JRC) 5, 82-91.

Sadimantara, M.S., Argo, B.D., Sucipto, S., Al Riza, D.F., Hendrawan, Y., 2024b. Prediction of aflatoxin contamination in cocoa beans using UV fluorescence imaging and artificial neural networks for enhanced detection. Journal of Global Innovations in Agricultural Sciences 12, 315-325.

Saeed, M., Mukhtar, T., Ahmed, R., Ahmad. T., Iqbal, M.A., 2023. Suppression of *Meloidogyne javanica* infection in peach (*Prunus persica* (L.) Batsch) using fungal biocontrol agents. Sustainability 15(18), 13833.

Saeed, M., Mukhtar, T., Haq, M.I., Khan, M.A., 2021. Assessment of nematicidal potential of *Cannabis sativa* and *Azadirachta indica* in the management of root-knot nematode (*Meloidogyne javanica*) on peach. Pakistan Journal of Agricultural Sciences 58(5), 1555-1561.

Serventi, L., Flores, G.A., Cusumano, G., Barbaro, D., Tirillini, B., Venanzoni, R., Angelini, P., Acquaviva, A., Di Simone, S.C., Orlando, G., 2023. Comparative investigation of antimicrobial and antioxidant effects of the extracts from the inflorescences and leaves of *Cannabis sativa* L. Cv. Strawberry. Antioxidants 12, 219.

Shahbaz, M., Akram, A., Raja, N.I., Mukhtar, T., Mehak, A., Fatima, N., Ajmal, M., Ali, K., Mustafa, N., Abasi, F. 2023. Antifungal activity of green synthesized selenium nanoparticles and their effect on physiological, biochemical, and antioxidant defense system of mango under mango malformation disease. PLoS ONE 18(2): e0274679.

Shahid, R., Mehmood, A., Shah, S.S., 2024. CRISPR and agriculture: Transforming crop science through precision genetics and sustainable practices-a review. Journal of Global Innovations in Agricultural Sciences 12, 1147-1157.

Sharifi-Rad, J., Mnayer, D., Roointan, A., Shahri, F., Ayatollahi, S., Sharifi-Rad, M., Molaee, N., 2016. Antibacterial activities of essential oils from Iranian medicinal plants on extended-spectrum β-lactamase-producing *Escherichia coli*. Cellular and Molecular Biology 62, 75-82.

Suhani, I., Sahab, S., Srivastava, V., Singh, R.P., 2021. Impact of cadmium pollution on food safety and human health. Current Opinion in Toxicology 27, 1-7.

Tan, S.S., Kuebbing, S.E., 2023. A synthesis of the effect of regenerative agriculture on soil carbon sequestration in Southeast Asian croplands. Agriculture, Ecosystems & Environment 349, 108450.

Tiep, N.V., Thinh, N.V.D., Tuan, L.Q., 2024. Assessing and enhancing sustainable rice straw management for environmental conservation in Yen Thanh district, Nghe An Province, Vietnam. Journal of Global Innovations in Agricultural Sciences 12, 555-561.

Todhunter, M.E., Jubair, S., Verma, R., Saqe, R., Shen, K., Duffy, B., 2024. Artificial intelligence and machine learning applications for cultured meat. Frontiers in Artificial Intelligence 7, 1424012.

Vaou, N., Stavropoulou, E., Voidarou, C., Tsakris, Z., Rozos, G., Tsigalou, C., Bezirtzoglou, E., 2022. Interactions between medical plant-derived bioactive compounds: Focus on antimicrobial combination effects. Antibiotics 11, 1014.

Waheed, U., Iftikhar, Z., Mudassir, M., Rani, S., Raza, H., Noor, Z., Amina, M.H., Butt, M.H., Naveed, H., Batool, S., Hassan, A., Rehman, Z., Naveed, M., 2023. Enhancing wheat crop yield and quality through genetic engineering technologies: A comprehensive review. Journal of Global Innovations in Agricultural Sciences 11(4), 481-489.

Wang, Y., Zafar, N., Ali, Q., Manghwar, H., Wang, G., Yu, L., Ding, X., Ding, F., Hong, N., Wang, G., 2022. CRISPR/Cas genome editing technologies for plant improvement against biotic and abiotic stresses: Advances, limitations, and future perspectives. Cells 11, 3928.

Yan, B.-F., Nguyen, C., Pokrovsky, O., Candaudap, F., Coriou, C., Bussiere, S., Robert, T., Cornu, J.-Y., 2018. Contribution of remobilization to the loading of cadmium in durum wheat grains: Impact of post-anthesis nitrogen supply. Plant and Soil 424, 591-606.

Zuhra, N., Akhtar, T., Yasin, R., Ghafoor, I., Asad, M., Qadeer, A., Javed, S., 2024. Human health effects of chronic cadmium exposure. In: Cadmium Toxicity Mitigation. Springer, 65-102.

Zulfiqar, F., Moosa, A., Ali, H.M., Bermejo, N.F., Munné-Bosch, S., 2024. Biostimulants: A sufficiently effective tool for sustainable agriculture in the era of climate change? Plant Physiology and Biochemistry 108699.