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EDITORIAL NOTE

Dear Readers,

With immense pleasure, we present to you the third issue of Enlighten Agriculture (July–September 2025). This edition brings together a rich tapestry of ideas, research, and field experiences that reflect the dynamic spirit of agricultural innovation and sustainability. From the inspiring story of Nanjangudu farmers revolutionizing banana cultivation through grit and green practices, to the scientific exploration of phytohormones as a pathway for regenerative agriculture, this issue is a testament to the resilience and creativity shaping our farming landscapes. The insights into biological nitrification inhibition in banana cultivation and the promise of AI in seed assessment highlight how tradition and technology can converge for lasting impact.

We also feature thought-provoking perspectives on gender equity and feminist agroecologies, reminding us that agriculture is not only about crops and soils but also about people, communities, and inclusivity. Cutting-edge research on ozone treatment for seed quality, the regulatory role of aquaporins, and the potential of LiDAR technology in fostering resilient systems further broaden the scope of innovation discussed in these pages. Complementing these are explorations into the connections between agriculture, environment, and health—such as the role of gut microbiota-derived short-chain fatty acids and raised-bed cultivation techniques for lettuce, which together reflect the deep interlinkages between food production and human well-being.

We extend our heartfelt gratitude to all the authors, reviewers, and contributors who have made this issue possible. As always, we hope these articles spark curiosity, encourage dialogue, and inspire action toward a more sustainable and equitable agricultural future.

Warmly
Editorial Team
Enlighten Agriculture

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EDITORIAL

Envisioning Feminist and Gender-Neutral Agroecologies: Gender, Equity, Intersectionality and Power in Agricultural Innovation

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We must realise and acknowledge that the present-day farming is at one of the crossroads. At least hereafter, our actions should be guided by ecological sustainability, food security and more of social equity as these aspects plays an intersectional role for the development of gender-neutral agriculture. However, agricultural innovation still happens to be an institutionally unequitable sphere, particularly when the issue of gendered asymmetries of power is brought up. Feminist agroecology is a niche theoretical issue, also a framework and pathway to the systematic change, without which we cannot think critically about revolutionary change in agricultural systems, as it is centralizing equity, care and justice. World Health Organization reports that women make up 43 % of the agricultural labour force in developing countries whereas they own less than 15 percent of agricultural land globally (FAO, 2011). The South Asia region results are even lower; women land ownership in India is merely 14 % (Agarwal et al., 2021). Due to this, there have been a systemic-barriers faced by women farmers when they approach formal sources of credit, irrigation facilities, extension services and agri-inputs. The National Sample Survey (NSS 77th Round) indicated that only 5% of female cultivators in India received basic extension service, which is astonishingly lower, this will lead to inaccessibility of innovation by the women farmers (Sah et al., 2015). Such inequalities are not administrative oversights but can be shown to be a direct question of patriarchal and caste-based land tenure systems, legal exclusions and continuing undervaluing of women labour in household and community agroeconomies.

Women-led and Dalit-farmer-centric approach

Among the largest agroecological initiatives in Telangana, India, Deccan Development Society (DDS) advances as a paradigmatic example of women-led and Dalit-farmer-centred agroecology practice. Along with the millet-based cropping complex, seed sovereignty, and the extensive sharing of community seed banks, DDS cultivates and organically manage 50000 acres of rainfed land (Patnaik et al., 2017). More important in its strategy is an epistemic paradox, that DDS does not consider any elite expert-driven models rather it follows only Indigenous knowledge and techniques.

Gender Blindness in Green Revolution

Green Revolution increased food production in India but this strengthened male centric, input intensive, mechanized systems. In Punjab and Haryana, research shows that women were purposefully marginalized while making plans especially, mechanisation replaced all the women-related labour in agriculture, and farm chemicals increased the reproductive-health risks in women (Motwani, 2024). The critiques of feminism continue to argue that technological change without any critical application of gender analysis only brings forth more avenues of marginalization rather than egalitarian agrosociety.

Women SHGs and Climate Smart Agriculture in Odisha

Several government programs (NRLM, Mission Shakti) bring women into group or community farming. However, assessments in Odisha point out that although SHGs expanded more access to training and microfinance, they often replicated elite seizure but also locked out landless women and hindered market autonomic decision-making processes. This reveals that without institutional change, group structures and community led initiatives will become a 'tokenistic approach, not a suffragette one' (Nielsen et al., 2020). Through the analysis of present structural weaknesses in Indian agriculture, there are four interrelated areas which need to be inclined to right away.

1. Land ownership and lawful safeguards

In 2005 the Hindu Succession Act was further amended, which was a visionary dream of Dr. B.R. Ambedkar, and this was a significant progress, though enforcement is slow. Before this amendment, in many jurisdictions, the names of women cannot even be found in the records as a joint property. At the same time, the customary laws in the entire country especially the laws governing the tribal and Muslim governments still discriminate against the female heirs. These needs to be changed to empower the women.

2. Research and design of agro-inputs

The mainstream breeding programs regularly favour traits that confirm to the male food preferences and harder preparation and processing techniques and often overlook the preferences of women. Gender-sensitive breeding can enhance livelihoods like Participatory Varietal Selection involving women in Nepal; however, these innovations should be diffused more broadly (Joshi et al., 1997).

3. Pricing of the free labour

Surveys on time-use reveals that rural women spend between 291–315 minutes (4.8–5.3 hours) daily on unpaid domestic work, and 135–137 minutes (2.25 hours) on unpaid caregiving, totaling about 7–8 hours per day when combined with another unpaid task (Verma, 2025). Though these data highlight the extreme importance of women work, they are not part of mainstream macroeconomic measures that neglect informal work contributions like animal keeping, seed collection, and weeding. Hence, there should be a price for unpaid women for their farm-chore works.

4. Uptake and technological design

The Self-Employed Women's Association (SEWA) has implemented and promoted the use of ergonomically designed farm tools specifically suited for women. Case studies confirm these tools, such as lightweight weeders, improved sickles, hand-driven planters, seed treatment drums, wheel hoes, and grain cleaners have significantly reduced the physical burden and time required for key agricultural operations, while improving productivity and ergonomic safety.

5. Intersectionality and climate resilience

The women farmers tend to be more vulnerable to changes in climate but they are not much represented during adaptation planning. The sustainable agroecological systems such as ZBNF, and SRI should include gendered vulnerability analyses to promote equal risk reduction.

Policy Shifts and the Way Forward

When considered collectively, these statistics indicate some serious flaws in the structure of Indian agriculture, pointing to the necessity of system-wide, cross sectoral and intersectional measures. Over the past few months, there have emerged two important developments in the arena of scholarly and policy discussion in the field of agriculture. Gender main streamer is a long-term strategy which has been recommended by the National Gender Resource Centre in Agriculture (NGRCA) and Revised National Policy for Women in Agriculture (2021) has also reiterated its commitment in this regard. However, despite such commitments, gender-responsive schemes are still allotted below 6.8% of total budget expenditure in the agricultural budget. We thus need to grapple with these problems: (1) the lack of gender disaggregated data systems, (2) the shortfalls in feminist extension model which have credible recognition of plural knowledges, (3) the need to carry out land titling reforms capable of achieving a synergistic combination of land tenure security together with equal access to credit to women cultivators, and (4) the need for intersectional targeting which simultaneously addresses caste and landlessness as well as tribal status in addition to gender.

There is still the perception by the male patriarchal society, so called 'society', that feminist agroecology is an adjunct to scientific agriculture but it is a 'corrective lens'. Though, it is still considered widely not as the ground-breaking central part of the agriculture innovation but as the add-on like a pickles and paapads. However, the analytic framework of feminist agroecology is needed to reclaim the advocacy of women, what it means to challenge the logics of irrational customs, and build agronomic systems that rely on caring, reciprocity, and ecological justice. To achieve transformative innovation, the historical and structural exclusions that have marginalized many genders including women should took part at the epicentre of the process, and recognise them as equal and responsible co-creators of knowledge as agents of systematic revolutionary change rather than so called 'beneficiaries'.

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Nanjangudu farmers boom in banana production a blending grit with green practices for lasting harvests

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Musa sp. var. Nrb, is a tropical plant which is restricted to the region of 30N to 30S of latitude. A unique banana variety native to the Devarasanahalli, Nanjangud region of Karnataka India holds geological importance in its cultivation and growth. Nanjangud rasabale is known for its unique qualities in terms of taste, pulp quality and aroma that are due to the black clay alluvial saline soil. Owing to these properties, it was given the Geographical Indication (GI) protection tag in 2005 under the Goods (Registration and Protection) Act, 1999.The bunches are small to medium in size of below 10kg with 80-120 medium sized fruits weighing around 150g each. (Vedashri et al., 2023)

The fertile soils of the region provide essential minerals and nutrients necessary for the healthy growth of *Musa* sp. var. Nrb, contributing to its distinct flavor and nutritional profile. Additionally, the region favours microclimate, influenced by its geographical location and elevation, plays an important role in regulating temperature and moisture levels, further enhancing the banana's growth and development.

As a result, Musa sp. var. Nrb exemplifies the close relationship between geology, soil composition, and agricultural productivity, nutritional and health benefits, highlighting the geological importance of this unique banana variety.

According to the Horticulture Department data, a total of 180 farmers cultivated rasabale on 100 hectares of land in 2006-07. By 2019-20, the number came down to 15, who were cultivating it on a mere 10 hectares. Growing bananas here isn't easy due to erratic rainfall, stubborn pests and diseases this make the farmer worry about their crop.

Fig. 1. Nanjangud farmer at his farm during the harvest stage of banana

To meet these challenges nanjangudu farmers have learned hands-on methods to coax the most from their lands. While their drive has led to impressive harvests. Based on a recent field study, this story dives into the heart of Nanjangudus banana farms and the farmers hard work while pointing toward a greener, more sustainable pathway.

Nanjangudu Farmers Work on the Land to get Big Bunches of Banana

A close look at villages across Nanjangudu reveals that a patchwork of farming styles a blending old-school of know-how with newer techniques. Farmers here are focused on boosting yields to meet market demands and keep their livelihoods steady. Here's what they're doing:

- Piling on Fertilizers: To grow hefty banana bunches, many farmers pour on chemical fertilizers. So, addition of more nutrients a bigger fruit will it yield. But without soil tests, they're often guessing and blanket application are doing which leads to through off nutrient balance and affect the long-term sustainability.
- Spraying Pesticides against Pests and Disease: Pests like Rhizome weevil, Pseudo stem weevil and Panama wilt, sigatoka leaf spot are constant threats. So farmers rely heavily on pesticides and fungicide application to protect their crops but it kill beneficial insects and pollute water sources and increase the cost of cultivation.
- Precise application of Water: Maximum farmers adopted drip irrigation and sprinkler irrigation a game changer that delivers water straight to the roots. It saves water and helps plants absorb the nutrients leading to stronger yields.
- Going Organic: A few forward-thinking farmers mix in biofertilizers or compost to enrich the soil naturally. These methods are less common but show promise for healthier fields in the long run.
- Mixed Cropping: To stretch their income and make the most of their plots, some farmers grow beans, green chilli, chrysanthemum alongside bananas. This intercropping can cut pest problems and keep the soil fertile.

Fig. 2. Collection of soil samples during field study work at Nanjangud

Fig. 3. Installation of drip irrigation

Fig. 4. Intercropping of chrysanthemum in banana crop

The Hidden Price of Plenty

Nanjangudu farmers are relentless in their pursuit of bountiful harvests but their all-in approach has downsides. Many don't know their soil health condition and apply fertilizers or pesticides based on their instinct rather than science. This can deplete the land, making it less fertile over time. Heavy pesticide use also risks harming pollinators, tainting water,

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Fig. 5. Plastic mulching during planting time

and even affecting farmers health. Along with the costs of these inputs it consumes the hard-earned profit of especially smallholders already stretched thin. The study highlights a farmers feel pressure to prioritize short-term gains over long-term health because of tight finances and limited access to expert advice. Drip/sprinkler irrigation and biofertilizers work wonders, better in field but their installation cost is very high. (Khan et al, 2024)

A Smarter Way to Cultivate

Building a Sustainable farming Nanjangudu farmers are proof of what determination can achieve, but their room to grow smarter. To keep their fields thriving, they need practical, tailored solutions. Here are some ways forward:

- Know Your Soil: Regular soil testing can take the fertility status of soil for fertilizer application and saving money. So farmers utilise government institutions like KVK/University for soil testing at affordable price.
- Smarter Pest Control: Integrated Pest Management (IPM) combines natural predators, crop rotation, and resistant banana varieties to cut pesticide use. Training farmers on IPM could protect crops and the environment.
- Affordable Tech: Subsidies or lowcost loans for drip irrigation and biofertilizers could help more farmers adopt these tools, boosting yields while saving water and enriching soil.
- Sharing the Know How: Farmer groups and workshops could spread success stories, like how one village doubled yields with intercropping. Peer learning builds confidence and skills.
- Backing from Above: Government programs could reward eco-friendly practices, like organicfarming or water-saving techniques, aligning farmers wallets with the planet needs.

Nanjangudu Farmers Work on the Land to get Big Bunches of Banana.

A close look at villages across Nanjangudu reveals that a patchwork of farming styles a blending old-school of know-how with newer techniques. Farmers here are focused on boosting yields to meet market demands and keep their livelihoods steady. Here's what they're doing:

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- Spraying Pesticides against Pests and Disease: Pests like Rhizome weevil, Pseudo stem weevil and Panama wilt, sigatoka leaf spot are constant threats. So farmers rely heavily on pesticides and fungicide application to protect their crops but it kill beneficial insects and pollute water sources and increase the cost of cultivation.
- Precise application of Water: Maximum farmers adopted drip irrigation and sprinkler irrigation a game changer that delivers water

Fig. 6. Harvested Banana in mandis

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A Harvest That Lasts

Nanjangudu banana farmers are a force of nature turning their fields into a hub of productivity through sheer grit and ingenuity. Yet, leaning too hard on chemicals and neglecting soil health puts their success at risk. By embracing tools like soil testing, IPM, and efficient irrigation, they can keep their harvests strong while preserving the land for their kids and grandkids. With a little support through training, funding and policies Nanjangudu's farmers can grow not just bananas, but a model for sustainable farming that others can follow. This story is a salute to the hardworking farmers of Nanjangudu, whose sweat and smarts feed communities far and wide. With the right tweaks their banana boom can keep thriving good for their pockets, their soil and the planet.

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Phytohormones: A way forward for regenerative Agriculture

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Abstract

Modern agriculture demands sustainable practices that enhance productivity while preserving ecological balance. Phytohormones, as pivotal biochemical regulators of plant growth and stress responses, have emerged as critical players in regenerative agriculture. This article explores the synergistic relationship between phytohormones and soil microbial communities, especially under regenerative practices like crop rotation, cover cropping, and reduced chemical inputs. These interactions enhance nutrient cycling, root development, stress resilience, and plant immunity by modulating hormone pathways such as auxins, cytokinins, gibberellins, abscisic acid, salicylic acid, and jasmonic acid. Beneficial microbes, particularly plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, further reinforce plant health by intervening in these hormone productions. The crosstalk and integration of phytohormonal signaling with microbial ecology presents a promising approach to enhance soil health, biodiversity, and climate-resilient crop systems, laying the foundation for a sustainable agricultural future.

Key words: Phytohormones, Regenerative Agriculture, Microbes

Introduction

Modern agriculture stands at the key challenge of increasing productivity while maintaining ecological integrity. Phytohormones, or plant hormones, are key biochemical components that signal and orchestrate plant development and adaptive responses. In recent years, studies of their interactions with rhizospheric microbes have emerged as a critical aspect of plant resilience and productivity. Understanding these interactions is essential for developing low-input, climate-resilient agricultural practices. Phytohormones are low-molecular-weight signaling compounds that regulate plant physiological development even at low concentrations. These phytohormones —such as auxins, cytokinins, gibberellins, abscisic acid (ABA), ethylene, jasmonates, salicylic acid, strigolactones, melatonin, and many more—act as integral signal mediators in plant responses to internal and external stimuli. They regulate key functions, including cell division, cell differentiation, organogenesis, senescence, and defense responses, establishing them as key components in plant adaptability and resilience.

In regenerative agriculture's viewpoint, which emphasizes ecological balance, biodiversity enhancement, and soil health restoration, phytohormones play a pivotal role. One of the most promising dimensions in this regard is the interaction between plant phytohormone signaling pathways and soil microbial, like plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and endophytes. These microorganisms can directly synthesize or modulate phytohormones, thereby influencing plant growth and stress tolerance. For instance, many PGPRs produce indole-3-acetic acid (IAA), a principal form of auxin, which enhances root elongation and lateral root formation, facilitating better nutrient and water acquisition. Certain microbial strains can also influence the levels of cytokinins and gibberellins, promoting shoot development and biomass accumulation. Moreover, microbes contribute to the modulation of stress-related hormones like ABA and ethylene, helping plants adapt to drought, salinity, or pathogen attack.

On the other hand, plants release root exudates that are shaped by their endogenous phytohormonal status. These exudates in turn alter the rhizosphere microbiome's composition and function, creating a dynamic feedback loop that is essential to the effectiveness of regenerative methods. Regenerative agriculture creates a favorable environment for these plant-microbe interactions to flourish by reducing chemical inputs and promoting natural biological processes, which eventually improve soil fertility, nutrient cycling, and plant health.

In line with the objectives of regenerative agriculture, combining our knowledge of phytohormonal signaling with microbial ecology provides a potent framework to promote resilient agroecosystems and sustainable crop output. With important ramifications for climate-resilient agriculture, this interface offers a rich environment for studies in systems biology, functional soil ecology, and plant-microbe interactions.

Phytohormones and Their Role in Agriculture

1. Regulating Plant Growth and Development

Phytohormones such as auxins, cytokinins, and gibberellins are central to the orchestration of plant growth and morphogenesis.

- Auxins, such as indole-3-acetic acid, are essential for organogenesis and vascular differentiation because they control root initiation, apical dominance, and cell elongation.
- Cytokinins, in conjunction with auxins, maintain the equilibrium between root and shoot development by encouraging cell division and shoot commencement.
- By modifying gene expression associated with growth-promoting enzymes, gibberellins affect stem elongation, seed germination, and floral development.

These hormones' antagonistic and synergistic interactions create a complex regulatory network that guarantees plant structures' appropriate temporal and geographical development.

2. Responding to Abiotic Stress

Abiotic stresses such as drought, salinity, and temperature extremes trigger hormonal signaling cascades, which are primarily mediated by abscisic acid (ABA).

- ABA reduces transpirational water loss during drought and encourages stomatal closure, acting as a master regulator of plant water balance.
- Additionally, it alters the expression of genes that respond to stress, osmoprotectants, and antioxidant enzymes that support the preservation of cellular homeostasis. To regulate the plant's physiological reaction to stress, ABA interacts with other hormones like ethylene, brassinosteroids, and melatonin.

3. Enhancing Plant Defense Mechanisms

In response to biotic stressors like pathogens and herbivores, plants utilize salicylic acid (SA) and jasmonic acid (JA) as core signaling molecules in their defense arsenal.

- SA primarily mediates systemic acquired resistance (SAR), enhancing long-term immunity against biotrophic pathogens.
- JA is associated with induced systemic resistance (ISR) and is effective against necrotrophic pathogens and insect herbivores.
- These hormones regulate the production of secondary metabolites, pathogenesis-related proteins, and defense enzymes that fortify plant defense barriers.

4. Microbial Interactions and Hormone Crosstalk

Beneficial soil microbes, especially plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), can produce or modulate plant phytohormones, enhancing both growth and stress tolerance.

- PGPR is known to synthesize IAA, gibberellins, and cytokinins, promoting root architecture modification, nutrient acquisition, and shoot development.
- Some microbes degrade ethylene precursors like ACC (1-aminocyclopropane-1-carboxylic acid) via ACC deaminase, reducing ethylene-induced growth inhibition under stress.
- Microbial signals can prime the host plant's hormonal defense networks, offering enhanced protection through ISR pathways.

Regenerative Agriculture and Phytohormones: A Synergistic Relationship

- Crop rotation, cover crops, composting, and no-till farming are examples of regenerative agriculture techniques that greatly improve soil health and microbial biodiversity, which in turn encourages soil-dwelling microorganisms to produce phytohormones in situ.Plant growth is influenced by these helpful microorganisms, particularly plant growth-promoting rhizobacteria (PGPRs), in two ways:
- Directly by:
    - Fixing atmospheric nitrogen, making it available to plants.
    - Synthesizing key phytohormones such as indole-3-acetic acid (IAA), gibberellins,

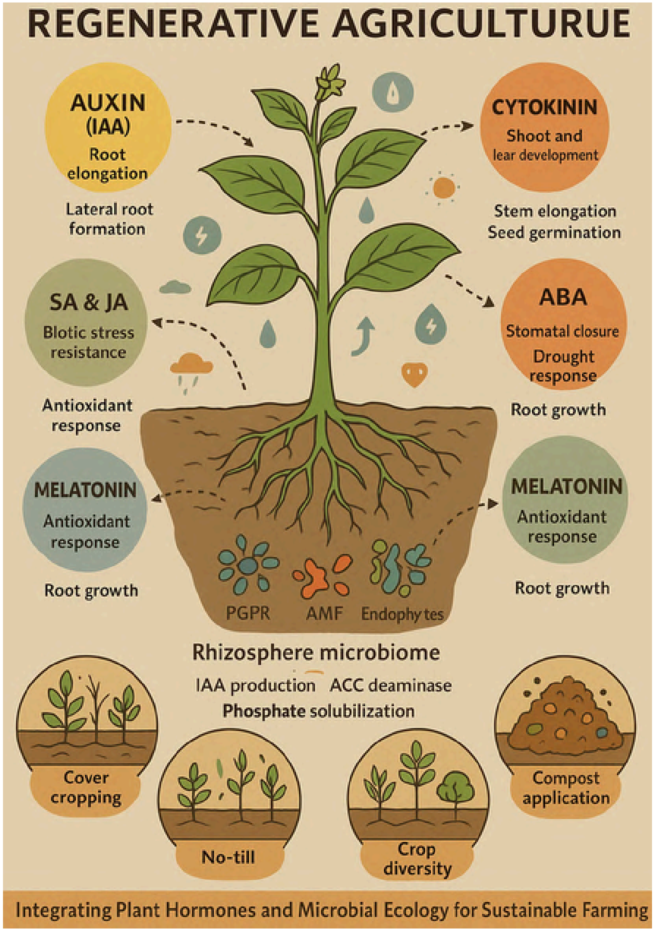

Fig. 1. Integrating Plant Hormones and Microbial Ecology for Sustainable Farming

    - cytokinins, and abscisic acid that regulate root and shoot development.
    - Solubilizing phosphates and other minerals, thereby indirectly modulating hormone pathways through improved nutrient availability.
- Indirectly by:
    - Producing antibiotics and cell wall-degrading enzymes that suppress pathogens.
    - Releasing siderophores (iron-chelating compounds) and hydrocyanic acid, which inhibit harmful microorganisms.
    - Triggering induced systemic resistance (ISR) in plants, which involves phytohormone signaling pathways such as jasmonic acid (JA) and ethylene.
- Enhancing Plant Protection Through microbial and hormonal mechanisms, regenerative agriculture improves plant immunity and stress tolerance. Plants with stronger root systems and more

resilient immune systems grow in biologically active soil. As a result, the plant is less reliant on outside chemical inputs like artificial insecticides and herbicides. Important plant hormones that play a role in these defenses include:

   - Salicylic acid (SA) – crucial for defense against biotrophic pathogens.
   - Jasmonic acid (JA) and ethylene – important for defense against necrotrophic pathogens and insect herbivores.
   - Abscisic acid (ABA) – plays a dual role in abiotic stress response and pathogen defense.
- Crop Diversity and Resource Efficiency: Diverse cropping systems—such as intercropping, polyculture, and cover crops—lead to enhanced functional biodiversity above and below ground level. This diversity contributes to more dynamic and balanced phytohormonal crosstalk among plant species and their associated microbes. Eg.
   - Different plant species release different root exudates, shaping unique microbial communities that produce varied phytohormone profiles.
   - Increased biodiversity leads to enhanced resource use, enhancing nutrient cycling and reducing competition, ultimately leading to optimized hormonal responses that support plant overall development.

Climate Resilience One of the hallmarks of regenerative agriculture is its ability to build soil organic matter, which plays a crucial role in carbon sequestration and water retention. A richer soil organic profile:

- Improves soil structure and root penetration, facilitating deeper water and nutrient uptake.
- Creates an environment for microbial communities that continue to produce growth-promoting phytohormones, even under stressful conditions like drought or heat.

Supports hormonal mechanisms (especially ABA and melatonin pathways) that allow plants to adapt to abiotic stresses like temperature fluctuations, salinity, and limited water availability.

Conclusion

Regenerative agriculture offers a framework for maximizing phytohormones' natural production and activity, resulting in crops that are healthier, more robust, more productive. Regenerative methods support a more resilient and sustainable food system by enhancing the function of phytohormones in plant growth, development, and defense through the promotion of soil health and biodiversity.

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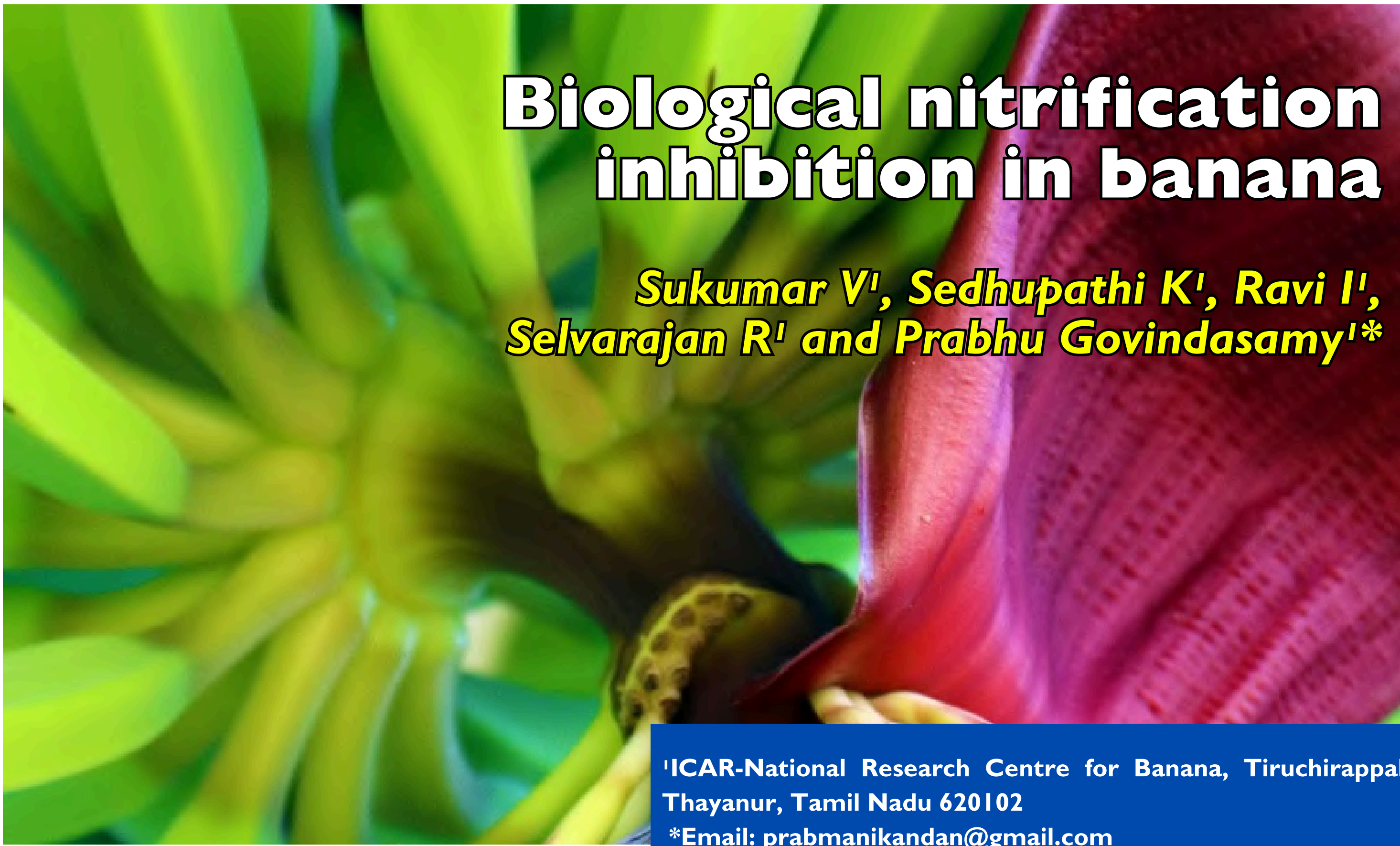

Biological nitrification inhibition in banana

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Abstract

Nitrogen (N) is a vital nutrient for plant growth and development. The most commonly used fertilizers are nitrogenous fertilizers, such as urea and DAP. Typically, only about 50% of applied nitrogen fertilizer is taken up by plants. At the same time, the rest is lost to the environment as ammonia (NH_3), nitrate (NO_3^-), or nitrous oxide (N_2O). Biological nitrification inhibitors (BNIs) help reduce these losses by slowing the conversion of N in soil, thereby enhancing N retention and plant uptake. In the presence of NH_4^+ in the rhizosphere, plant roots rapidly release hydrophilic BNIs, a process associated with the activation of plasma membrane H^+-ATPase. This enzyme establishes membrane potential and generates the proton motive force required for primary and secondary transport of various substances. The release of BNIs is mediated by MATE transporters, which are driven by the proton motive force generated through membrane potential changes induced by voltage-gated anions. Several preliminary studies have screened different banana germplasm lines for BNI activity. These studies suggest the presence of potential BNI activity in bananas; however, further research is needed to confirm and validate these findings.

Key words: Ammonium, Hydrophilic, N, N Use Efficiency, N Loss

Introduction

Nitrogen (N) is a vital nutrient for plant growth and development. It is a key component of chlorophyll and nucleic acids. Nitrogen is fundamental to protein synthesis, which regulates enzymatic activity and metabolic functions within plant cells. It also contributes to the production of nucleotides, thereby enabling the synthesis of DNA and RNA. These processes are vital for cell division and genetic expression. Additionally, N contributes to chlorophyll production, thereby enhancing photosynthetic efficiency and overall energy capture (Figure 1). A deficiency of N often manifests as chlorosis, stunted growth, and reduced biomass accumulation, whereas adequate N availability promotes vigorous vegetative growth, a higher leaf area index, and improved crop ields. Therefore, N is not only vital for structural and functional plant biochemistry but also a key of-

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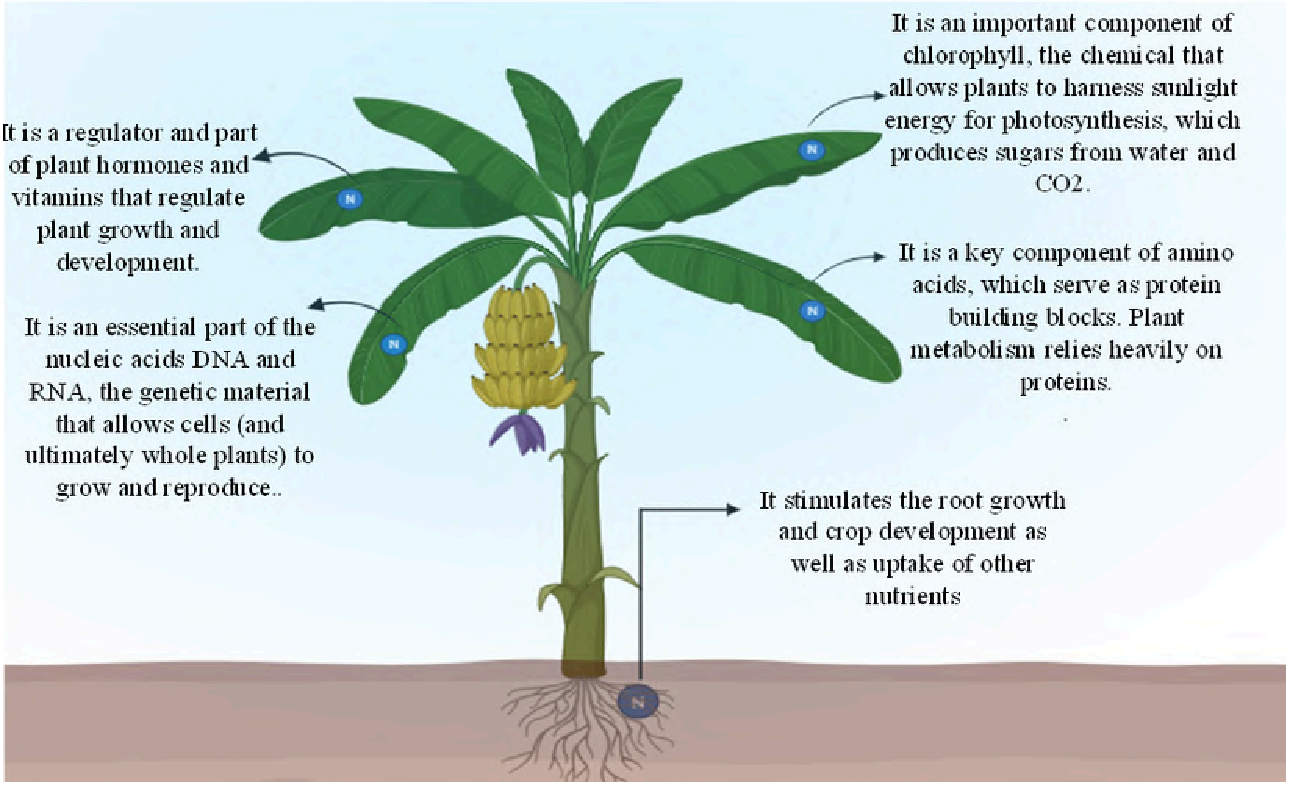

Fig. 1. Role of nitrogen in Banana

agricultural productivity. The N cycle is a biogeochemical process that describes how N moves through different forms in nature (Figure 2). It involves several key steps: nitrification, ammonification, assimilation, denitrification, and N-fixation. Nitrogen fixation is the process by which atmospheric N (N_2) is transformed into ammonia (NH_3). Ammonification is the process by which the organic N from the decomposing materials is converted to ammonia. This can happen through N-fixing bacteria or natural processes such as lightning. Ammonification occurs when organic N from dead organisms or waste products is broken down into ammonia. Nitrification is a two-step oxidation process carried out by nitrifying bacteria. First, ammonia is converted to nitrites (NO_2^-) by Nitrosomonas and Nitrosococcus. Then, nitrites are further converted into nitrates (NO_3^-), which plants can easily use. Assimilation is the step where plants absorb nitrates and nitrites from the soil and use them to build proteins and other essential compounds. Denitrification is the final step, in which nitrates are converted back into N gas (N_2) by denitrifying bacteria such as Pseudomonas and Thiobacillus denitrificans. This is a reduction process that returns N to the atmosphere, completing the cycle.

Nitrogen loss

Nitrogen loss from plants and soil reduces soil fertility and limits plant productivity, while also contributing to environmental degradation. Nitrogen oxides are a major pathway of N loss to the atmosphere, leading to acid rain and indirectly contributing to greenhouse gas emissions. Nitrous oxide released into the atmosphere contributes to global warming and also depletes the ozone layer (Cameron et al., 2013).

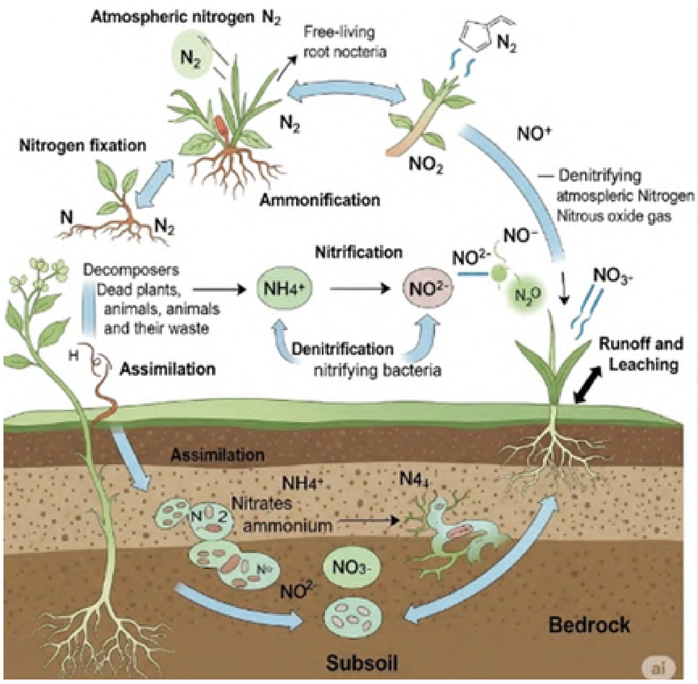

Fig. 2. Nitrogen cycle

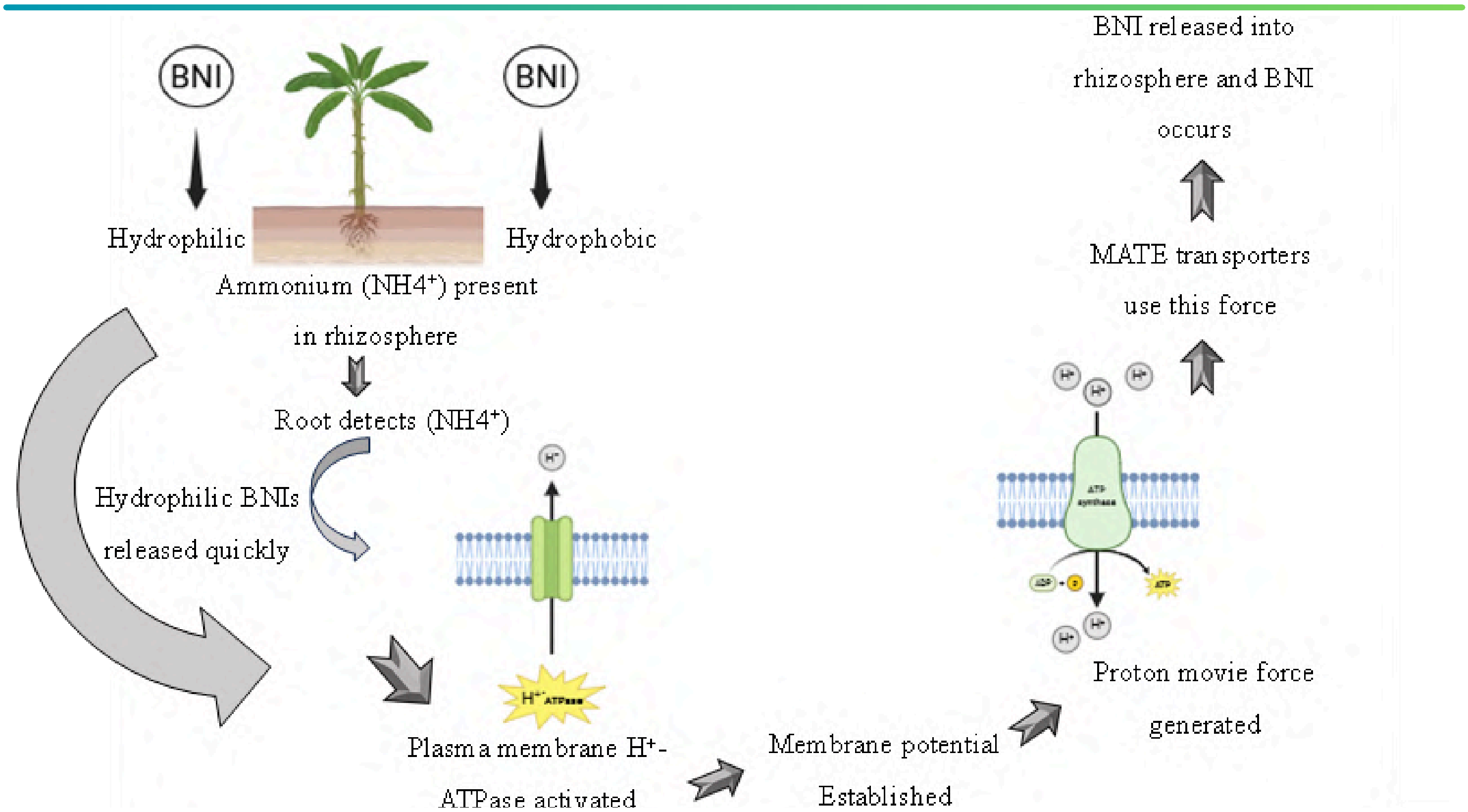

Fig. 3. Occurence of BNI in banana

Other significant forms include nitrate and nitrous oxide. Nitrates are leached into rivers and lakes, causing eutrophication, which reduces fish diversity and poses health risks to humans. Ammonia (NH_3) volatilization accounts for an estimated 10–60% of the losses from applied N fertilizers.

Biological Nitrogen Inhibition (BNI)

Biological nitrification inhibitors (BNIs) released through plant root exudates play a crucial role in suppressing nitrifier activity in agricultural soils. They also enhance nitrogen (N) recovery from fertilizers and improve nitrogen use efficiency in plants.

Occurrence of BNI in plants

Biological nitrification inhibitors (BNIs) are classified as hydrophilic or hydrophobic (Figure 3). In the presence of NH_4^+ in the rhizosphere, plant roots rapidly release hydrophilic BNIs, a process associated with the activation of plasma membrane H^+-ATPase. This enzyme establishes membrane potential and generates the proton motive force required for or primary and secondary transport of various substances. The release of BNIs is mediated by MATE transporters, which are driven by the proton motive force generated through membrane potential changes induced by voltage-gated anions (Zhang et al., 2022).

Why is BNI necessary for plants?

Nitrogen is vital for plant growth, but N use efficiency in crops is generally low. Typically, only about 50% of applied N fertilizer is taken up by plants. At the same time, the rest is lost to the environment as ammonia (NH_3), nitrate (NO_3^-), or nitrous oxide (N_2O). Biological nitrification inhibitors help reduce these losses by slowing the conversion of N in soil, thereby enhancing N retention and plant uptake (Coskun et al., 2017). Several preliminary studies have screened different banana germplasm lines for BNI activity. These studies suggest the presence of potential BNI activity in Bananas; however, further research is needed to confirm and validate these findings (Anonymous, 2025).

Conclusion

Banana offers a unique and valuable opportunity to investigate BNI activity, given its extensive genetic diversity represented by more than 500 germplasm collections worldwide. Harnessing the potential of BNI traits in bananas could significantly reduce the dependence on synthetic nitrogen fertilizers, thereby lowering production costs for farmers while contributing to sustainable nutrient management and environmental protection.

The identification and characterization of BNI activity within this diverse germplasm pool would provide critical insights into natural mechanisms of nitrogen regulation. However, comprehensive and systematic research is required to confirm the presence, extent, and variability of BNI in Banana and to validate its potential for practical applications in agriculture.

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Harnessing AI for seed assessment: A step towards sustainable conservation

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Abstract

The conservation of plant biodiversity has become increasingly critical due to climate change, habitat destruction, and human activities. Seeds are the cornerstone of plant survival, playing an essential role in ecosystem sustainability and food security. Artificial Intelligence (AI) has emerged as a transformative tool for improving seed conservation efforts through advanced assessment techniques. AI-powered seed evaluation can significantly enhance the monitoring, classification, and management of seed banks and agricultural diversity. This paper discusses the significance of AI in seed conservation, its methodologies, and strategies for integrating AI into existing conservation frameworks.

Keywords: AI-driven Seed Assessment, Biodiversity Protection, Sustainable Agriculture, Machine Learning, Automated Seed Classification

Introduction

Seed quality directly impacts agricultural productivity and environmental sustainability. Conventional methods for assessing seeds require significant labor and are prone to inaccuracies.

AI technologies offer an innovative, efficient alternative that ensures precise seed evaluation while minimizing time and human error. The adoption of AI-driven assessment methods promotes sustainable conservation practices by utilizing non-destructive technologies for enhanced accuracy, efficiency, and eco-conscious seed preservation

Key Concepts in Seed Assessment

- **Germination Viability:** The percentage of seeds capable of sprouting in optimal conditions, serving as a key indicator of seed quality.
- **Seed Vigor:** The ability of seeds to germinate rapidly and uniformly, ensuring robust plant development.
- **Seed Integrity:** The physical attributes of seeds, including size, shape, and texture, which influence growth potential.
- **Machine Learning:** A specialized AI approach where algorithms learn from existing data to predict seed classification and viability.

AI Applications in Seed Evaluation

Artificial Intelligence integrates diverse technologies to enhance seed assessment. AI-driven seed analysis relies on pattern recognition, data-driven predictions, and automated sorting techniques. Its impact in agriculture is revolutionizing conservation efforts in several ways:

- Computer Vision for Image-Based Seed Analysis: AI algorithms analyze seed images to assess visual characteristics such as texture, size, and shape, ensuring consistent classification.
- Machine Learning for Predictive Modeling: AI models trained on seed datasets refine predictions regarding germination rates and seed quality. These models improve accuracy with continuous learning.
- Robotic Automation for Seed Sorting: AI-enhanced robotic systems rapidly categorize and process large seed volumes, optimizing quality control while reducing manual effort.
- Continuous Monitoring: AI-powered tracking systems oversee seed storage and preservation, ensuring sustained viability.

AI-Enhanced Seed Assessment Workflow

The integration of AI in seed evaluation follows a structured methodology:

1. Data Acquisition: High-resolution images and spectroscopic data are collected using advanced imaging tools.
2. Algorithm Training: AI models are developed using comprehensive datasets, identifying correlations between seed characteristics and germination success.
3. Seed Classification & Prediction: AI frameworks categorize seed batches and forecast their viability based on learned patterns.
4. Continuous Monitoring: AI-powered tracking systems oversee seed storage and preservation, ensuring sustained viability.

Advantages of AI in Sustainable Seed Conservation

- Enhanced Accuracy: AI mitigates human errors, ensuring superior seed selection, increased yield potential, and optimal resource allocation.
- Efficiency Optimization: AI expedites the assessment process, allowing farmers to swiftly adapt to changing conditions with informed decisions.
- Automated Monitoring: Continuous oversight of seed quality ensures ideal storage conditions and timely conservation interventions.
- Sustainable Resource Utilization: AI-driven predictions improve seed usage, minimize waste, and enhance agricultural productivity.
- Eco-Friendly Solutions: AI-based assessments reduce reliance on harmful chemicals, supporting environmentally conscious farming practices.

Challenges in AI-Based Seed Conservation

Despite its numerous advantages, AI-driven seed assessment faces several challenges:

1. High Initial Investment: Acquiring AI technologies can be costly, particularly for small-scale farmers.
2. Technical Complexity: Operating AI systems demands specialized skills, posing a barrier for those unfamiliar with advanced tools.
3. Data Quality Concerns: AI models require extensive, high-quality datasets for optimal performance, demanding rigorous preprocessing and validation.
4. Integration Difficulties: Existing agricultural infrastructures may struggle to incorporate AI-driven assessments seamlessly.
5. Scalability Constraints: AI model efficacy depends on vast datasets. Limited data availability can hinder model accuracy and generalization.

Conclusion

The incorporation of AI into seed assessment presents a ground-breaking advancement in sustainable conservation practices. AI technologies facilitate efficient, accurate, and eco-conscious seed evaluation, contributing to global food security and biodiversity preservation. Expanding datasets through augmentation techniques and strategic collaborations with research institutions can further refine AI performance in seed conservation. As AI continues evolving, its role in enhancing seed assessment and sustainable agriculture will be indispensable.

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Gut-Microbiota derived Short-chain fatty acids: key players in human health

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Abstract

The human gut microbiota metabolizes dietary fibers into short-chain fatty acids (SCFAs)—primarily acetate, propionate, and butyrate—powerful microbial metabolites that orchestrate a spectrum of physiological processes. These bioactive compounds fortify gut barrier integrity, fine-tune immune modulation, influence host energy dynamics, and mediate intricate gut-brain axis signalling (Fusco et al., 2023). SCFAs thus represent a pivotal nexus linking diet, microbiota, and systemic health. While their roles in enhancing tight junctions, glucose homeostasis, lipid regulation, and anti-inflammatory pathways are well-established, emerging evidence unveils a more nuanced narrative. In certain pathological or dysbiotic conditions, dysregulated SCFA levels may intensify inflammation, disrupt epithelial cohesion, and disturb metabolic balance contributing to the pathophysiology of asthma, obesity, cancer, and neurological disorders (Dan Zhang et al., 2023). Their paradoxical effects beneficial or detrimental depending on dosage, tissue context, and disease state. This topic also explores dietary modulation and SCFA-based therapeutic intervention in bronchial epithelial models. These findings reaffirm the therapeutic promise of microbiota-informed strategies, particularly the Mediterranean diet, in cultivating SCFA-producing microbial diversity (Richards et al., 2020). Looking ahead, personalized nutrition, precision SCFA delivery (such as inhaled formulations for respiratory conditions), and microbiome-targeted therapies offer exciting frontiers in clinical innovation (Garcia et al., 2018). The dual-faced nature of SCFAs positions them as both guardians of homeostasis and harbingers of disease—making them compelling candidates for future translational and precision medicine-research.

Key words: Gut-microbiota, SCFA, Dietary fibre, butyrate paradox

Introduction

The gut microbiota is a vast, diverse community of microorganisms—mostly bacteria, with archaea, fungi, and viruses—that resides along the gastrointestinal

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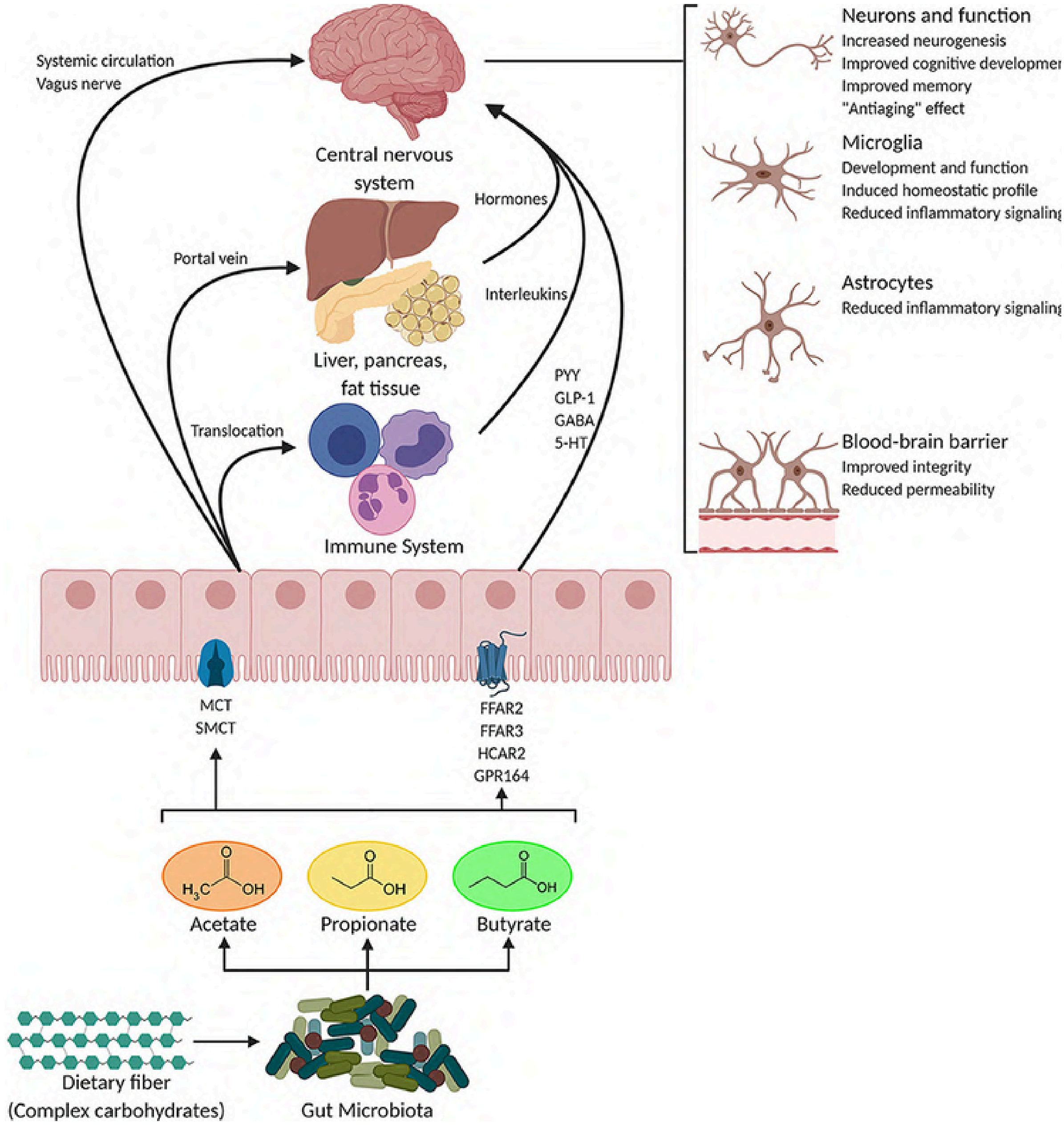

Fig. 1. Gut-microbiota, systemic circulation

tract and contributes essential functions to host physiology. By fermenting otherwise indigestible carbohydrates, microbes generate bioactive metabolites that shape digestion, nutrient harvest, immune education, and epithelial barrier maintenance; disruptions of tight junction proteins such as occludin and claudins are closely tied to inflammation-driven barrier failure and "leaky gut," underscoring how barrier integrity links the microbiota to disease risk and resilience. Among microbial products, short-chain fatty acids (SCFAs)—acetate, propionate, and butyrate—are central outputs of colonic fermentation of dietary fiber. Through epithelial and immune G-protein–coupled receptors and via epigenetic actions, SCFAs strengthen junctional complexes and mucus, dampen pro-inflammatory cascades, and recalibrate cytokine production, including reductions in IL-6 and nitric-oxide–linked signaling, thereby supporting local barrier function and systemic immune balance. In epithelial systems, exposure to balanced SCFA mixtures increases barrier resistance and limits paracellular leak, aligning with improved tight junction organization and reduced permeability under eubiotic conditions. SCFA biology is context-dependent, and pathological milieus can invert expected benefits. In colorectal cancer, butyrate's actions vary with tumor metabolism and exposure: while many datasets show anti-proliferative, pro-apoptotic effects via HDAC

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inhibition and mitochondrial pathways, literature also documents paradoxical scenarios in which butyrate can fuel growth or fail to suppress it, depending on dose, delivery site, and tumor microenvironment—the "butyrate paradox". Likewise, disease priming in airways can turn acetate/propionate signaling toward pro-inflammatory outputs, illustrating how tissue state and receptor expression shape outcomes. Diet powerfully modulates this axis. Adherence to Mediterranean-style patterns—rich in fiber, polyphenols, and minimally processed plant foods—consistently associates with increased SCFA-producing taxa, higher fecal or circulating SCFA levels, and improved inflammatory and metabolic markers, alongside gains in microbial diversity, although effect sizes and proxies (serum vs. fecal SCFAs) vary across studies. In aggregate, fiber-forward dietary habits promote a microbiome that restores barrier integrity, curbs epithelial cytokine signaling such as IL-6/IL-8, and diversifies microbial guilds, translating into better metabolic homeostasis and immune tolerance when host tissues are not overtly diseased.

Future prospects

Future research should prioritize therapeutic exploration of localized SCFA delivery, with immediate emphasis on inhaled formulations for airway inflammation and appropriate rectal, enteric-coated, or topical routes for colonic and epithelial targets, supported by rigorous PK/PD characterization, dose-finding for individual SCFAs and their ratios, and early assessment of safety, tolerability, and synergy with standard therapies. In parallel, personalized nutrition should leverage microbiome profiling to stratify individuals by SCFA-producing capacity and match them with tailored dietary fibers and polyphenol-rich foods, iteratively adjusted using stool SCFA readouts, symptoms, and host biomarkers, and delivered through culturally appropriate, cost-sensitive toolkits and decision-support algorithms. Clinical development should proceed through staged trials, from Phase I safety to Phase II proof-of-concept in prioritized indications such as IBD, IBS, NAFLD, insulin resistance, asthma, and MS adjunct care, culminating in Phase III multicenter studies with

Table .1 Types of SCFA's

SCFA	Carbon Atoms	Approx. % in Colon	Key Microbial Producers
Acetate	2	~60%	*Bifidobacterium, Akkermansia, Bacteroides*
Propionate	3	~25%	*Bacteroides, Veillonella*
Butyrate	4	~15%	*Faecalibacterium prausnitzii, Roseburia*
Valerate	5	<1–3%	*Clostridium, Eubacterium species*

Caproate (Hexanoate)	6	<1%	Some Clostridium species
Formate	1	Variable, usually low	Various anaerobic bacteria
Isobutyrate	4 (branched)	Trace–low	Protein fermentation by Clostridium spp.
Isovalerate	5 (branched)	Trace–low	Protein fermentation by Clostridium, Bacteroides

Clinical development should proceed through staged trials, from Phase I safety to Phase II proof-of-concept in prioritized indications such as IBD, IBS, NAFLD, insulin resistance, asthma, and MS adjunct care, culminating in Phase III multicenter studies with standardized outcomes (fecal/circulating SCFAs, organ-specific function, inflammation, and quality-of-life), responder-enriched designs based on microbial and receptor biomarkers (FFAR2/FFAR3/HCAR2), and head-to-head comparisons of direct SCFA delivery versus dietary, prebiotic, and synbiotic strategies. To enable durable modulation, prebiotic and probiotic integration should focus on selecting substrates that maximize butyrate with minimal GI side effects, engineering robust consortia of high-efficiency SCFA producers with compatible synbiotic formulations, validating persistence and functional impact in bioreactor and gnotobiotic models, and instituting stringent safety, stability, and real-world monitoring frameworks. Underpinning all strands, multi-omics research—combining metagenomics, metabolomics, and host transcriptomics/epigenomics—should map SCFA-receptor signaling to immune and metabolic pathways, apply systems and causal methods to identify leverage points, and build machine-learning models for response prediction and dose optimization, supported by FAIR data infrastructure and reproducible pipelines. Operationally, the roadmap targets short-term formulation finalization, PK/PD protocols, pilot microbiome-guided diets, and Phase I studies; mid-term completion of Phase II trials, validation of responder biomarkers, launch of synbiotic candidates, and deployment of decision-support; and long-term execution of Phase III programs, regulatory approvals for SCFA and live biotherapeutics, integration of personalized nutrition into standard care, and real-world evidence systems. Governance should center on multidisciplinary consortia, ethical and equitable data and recruitment practices, and a learning health system that updates protocols based on accumulating trial and real-world data, ultimately delivering precise, mechanism-driven SCFA interventions that improve inflammatory, metabolic, and neurological outcomes while enabling scalable personalization and reducing overtreatment and costs.

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Exploring the potential of ozone treatment in enhancing seed quality

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Abstract

High-quality seeds provide better plant establishment, increased tolerance to environmental challenges, and eventually enhanced yield. Ozone (O_3) treatment has emerged as a promising eco-friendly method for improving seed quality by breaking dormancy, enhancing germination, controlling storage pests and pathogens. Ozone acts as a powerful oxidizing agent, effectively eliminating fungal spores, bacteria, and viruses from seed surfaces through oxidative damage to pathogen cell walls, without leaving harmful residues (Nedim et al., 2022). Controlled ozone exposure can enhance germination by increasing oxygen availability, altering hormonal balances and stimulating enzymatic activity. Additionally, ozone can break dormancy in seeds with physiological dormancy by modulating abscisic acid (ABA) and gibberellin (GA) levels. However, excessive or prolonged O_3 exposure can lead to oxidative damage, affecting membrane integrity and seed viability (Gad et al., 2021). Therefore, optimizing O_3 concentration & exposure time is essential. This study examines the potential of ozone-induced improvements in seed quality.

Key words: Ozone, eco-friendly, seed treatment, seed health, germination

Introduction

Seed quality is one of the most significant factors of agricultural productivity that has a direct impact on germination rates, seedling vigour, and total crop production. Chemical treatments have been utilized for decades to sterilize seeds and extend their viability, but they often leave hazardous residues that are bad for the environment, human well-being, and soil health. Biological methods are safer but often slower, and physical treatments can be energy-intensive. Advanced approaches like ozone seed treatment may offer a solution to implement eco-friendly and sustainable farming methods. Ozone seed treatment is an innovative chemical-free technique that improves seed quality through the application of ozone gas (O_3). In 1982, the US Food and Drug Administration authorized ozone as a safe method of water purification. Furthermore, it is known for disinfecting seeds, promoting germination, breaking seed dormancy and protecting against pests in storage.

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Ozone leaves no harmful residues after being applied because it breaks down into oxygen (O_2). As a result, it is an eco-friendly substitute that supports organic farming and sustainable agriculture. The effectiveness of ozone treatment in seeds depends on ozone concentration, exposure time, seed type, and application method (gaseous or aqueous). Environmental factors like temperature, humidity, and storage conditions also influence its efficiency. Research is still being done to provide scalable industrial applications and enhance treatment procedures for various seed types.

Ozone

The triatomic molecule known as ozone (O_3) is made up of three oxygen atoms. It originates from the Greek word "Ozein" which means "to smell," and was discovered by Christian Friedrich Schönbein in 1839. In the stratosphere, it exists naturally and is essential for absorbing the hazardous ultraviolet (UV) rays of the sun.

Characteristics of Ozone

Ozone is a highly unstable and reactive gas with strong oxidizing properties, enabling it to decompose both organic and inorganic substances effectively.

Its short lifespan and brief half-life make it an environmentally friendly option, as it leaves no harmful residues after breaking down contaminants.

Ozone Formation

The ozone generation process involves the oxygen source i.e., pure oxygen from concentrators or atmospheric air, a monitoring system which uses sensors to regulate ozone production and prevent excessive exposure and an output control that manages the ozone concentration to optimize treatment effectiveness. In corona discharge ozone generators, a dielectric material (like glass or ceramic) is placed between two electrodes. A dielectric material is an insulating substance that does not conduct electricity but can support electrostatic fields. When high voltage is applied, the dielectric controls and stabilizes the discharge, preventing sparks. This creates a plasma field that breaks down oxygen (O_2) into atomic oxygen (O), which then forms ozone (O_3).

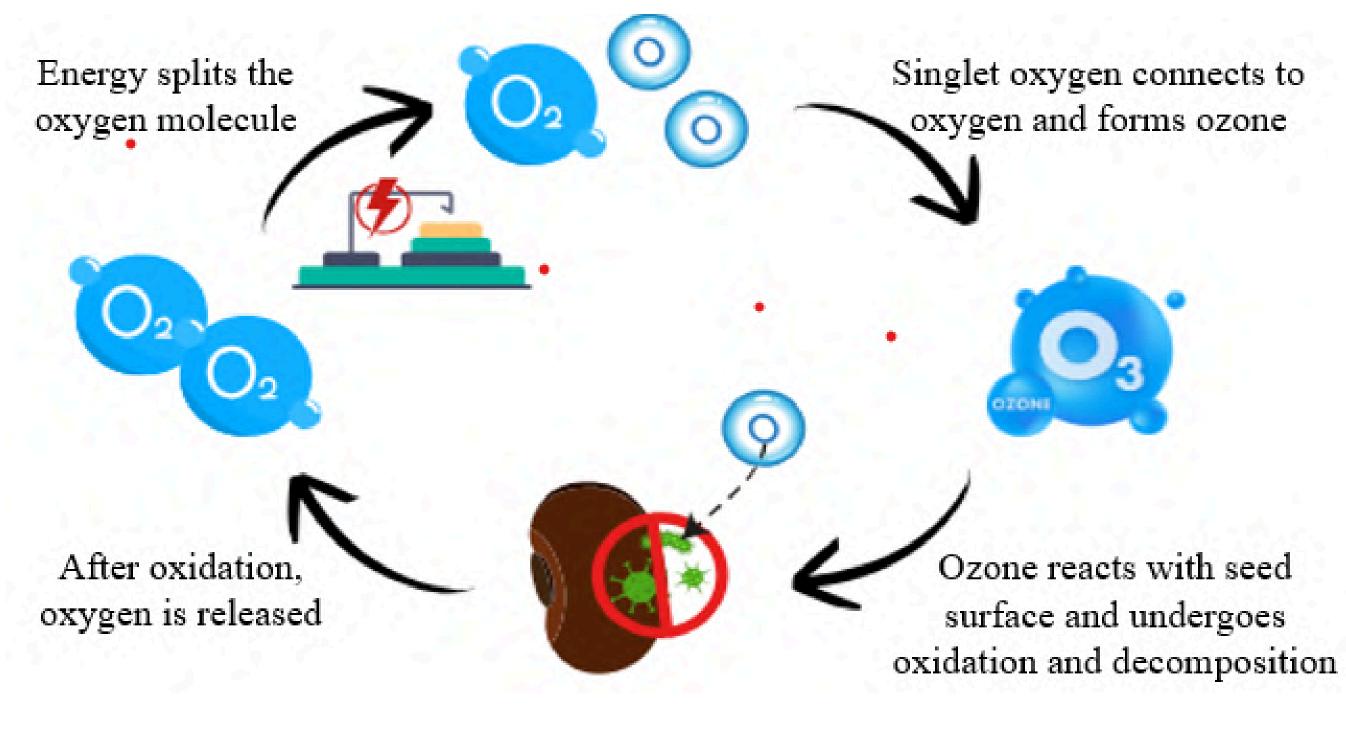

Fig.1. Ozone Formation

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Ozone decomposition

Ozone is highly unstable and decomposes back into oxygen by natural decay where ozone naturally reverts to O_2 due to its short half-life or by reacting with organic matter such as seed surface contaminants by breaking down and oxidizing pathogens while decomposing itself. The other method includes catalytic decomposition where certain catalysts (e.g., manganese dioxide, activated carbon) accelerate ozone breakdown into oxygen (Brodowska et al., 2014).

Methods of ozone seed treatment

The ideal treatment chamber should be constructed from ozone-resistant materials and designed to ensure uniform ozone exposure to seeds. Rotating mechanisms ensure uniform ozone exposure, preventing overexposure or uneven treatment. The choice of method depends on the type of seed, the desired outcome, and the level of disinfection required.

Gaseous Ozone Treatment: In this method, seeds are exposed to ozone gas in a controlled environment. The seeds are placed in an ozone-resistant chamber where ozone is generated and circulated uniformly. The exposure duration and ozone concentration are carefully regulated to achieve optimal disinfection and seed quality enhancement.

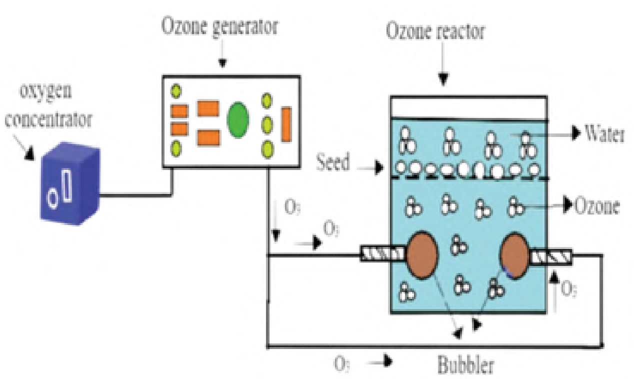

Fig.2. Gaseous Ozone Treatment

Aqueous Ozone Treatment: This involves dissolving ozone in water to create ozonated water, which is then used to treat seeds. Seeds are either soaked in ozonated water for a specified duration or subjected to a continuous flow treatment.

Factors influencing ozone seed treatment

Different seeds have varying coat thicknesses, permeability, and structural compositions, which affect their response to ozone exposure. Hard-coated seeds may require longer treatment durations compared to soft-coated seeds. The time seeds are exposed to ozone significantly affects treatment outcomes. Temperature and humidity influence ozone stability and its interaction with seeds. Warmer conditions accelerate ozone decomposition, reducing its efficacy. Pre-treating seeds (e.g., soaking) can enhance ozone penetration, enhancing microbial inactivation and seed hydration. The concentration of ozone used plays a crucial role in determining treatment success (Pandiselvam et al., 2019).

Mechanism of ozone on seed germination

Ozone treatment plays a significant role in enhancing seed germination by altering the physical and biochemical properties of seeds. One of the primary effects of ozone exposure is the modification of the seed coat, making it more permeable to water and gases. This increased permeability allows for improved water uptake, which is essential for initiating metabolic processes required for germination. At the molecular level, ozone generates reactive oxygen species (ROS) that act as signaling molecules, triggering various physiological changes. These ROS stimulate the breakdown of dormancy by activating genes responsible for gibberellic acid (GA) biosynthesis (GA20ox1) and abscisic acid (ABA) catabolism (ABA8′OH). Additionally, ozone exposure has been found to increase lipid peroxidation, which leads to the breakdown of stored lipids into fatty acids and alcohols. These compounds serve as an energy source for the developing seedling, promoting early growth and vigor. The oxidative effect of ozone also weakens chemical barriers in the seed coat, further facilitating oxygen exchange and enzyme activation.

Limitations of ozone seed treatment

The sensitivity towards different seeds and viability concerns due to excessive exposure led to oxidative stress, such as damage to lipids, proteins, and DNA, which is a major concern.In addition, setting up an ozone seed treatment plant requires high investment

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Table 1. Applications of Ozone in various crops

Crop	Salient features	Reference
Wheat	Significantly reduced total fungal count and Tilletia spp. and Penicillium spp.	Daniela et al. (2025)
Barley	Significant reductions in total fungal count and Fusarium spp.	Daniela et al. (2024)
Black Cumin	Eliminated the Cucumber mosaic virus	Sidika et al. (2023)
Tomato, Cucumber, Tulips, Wheat, Narcissus, Hyacinth	Reduce the incidence of Field and storage fungi	Nedim et al. (2022)
Corn Seeds	Significant increase in plant height	Natasha et al. (2020)
Lettuce	Ozonated sludge had increased weight, plant height and leaf number	Peng et al. (2018)
Winter wheat seeds	Improvement in the germination and germinating energy of the seeds	Picchi et al. (2017)
O. megacantha, O. streptacantha and O. ficus indica	Increase germination rate irrespective of the species	Vázquez et al. (2017)
Lettuce	Increase in the shoot and root biomass	Ybarra et al. (2015)

Conclusion

Ozone seed treatment is a revolutionary technology that enhances seed quality by improving germination, disinfecting seeds, and controlling storage pests. The sterilization success of ozone depends on the type of seed, pathogen, and treatment conditions. The ecofriendly nature and ability to eliminate pathogens make it a viable alternative to conventional chemical treatments. With continued research and technological advancements, it has the potential to agricultural production.

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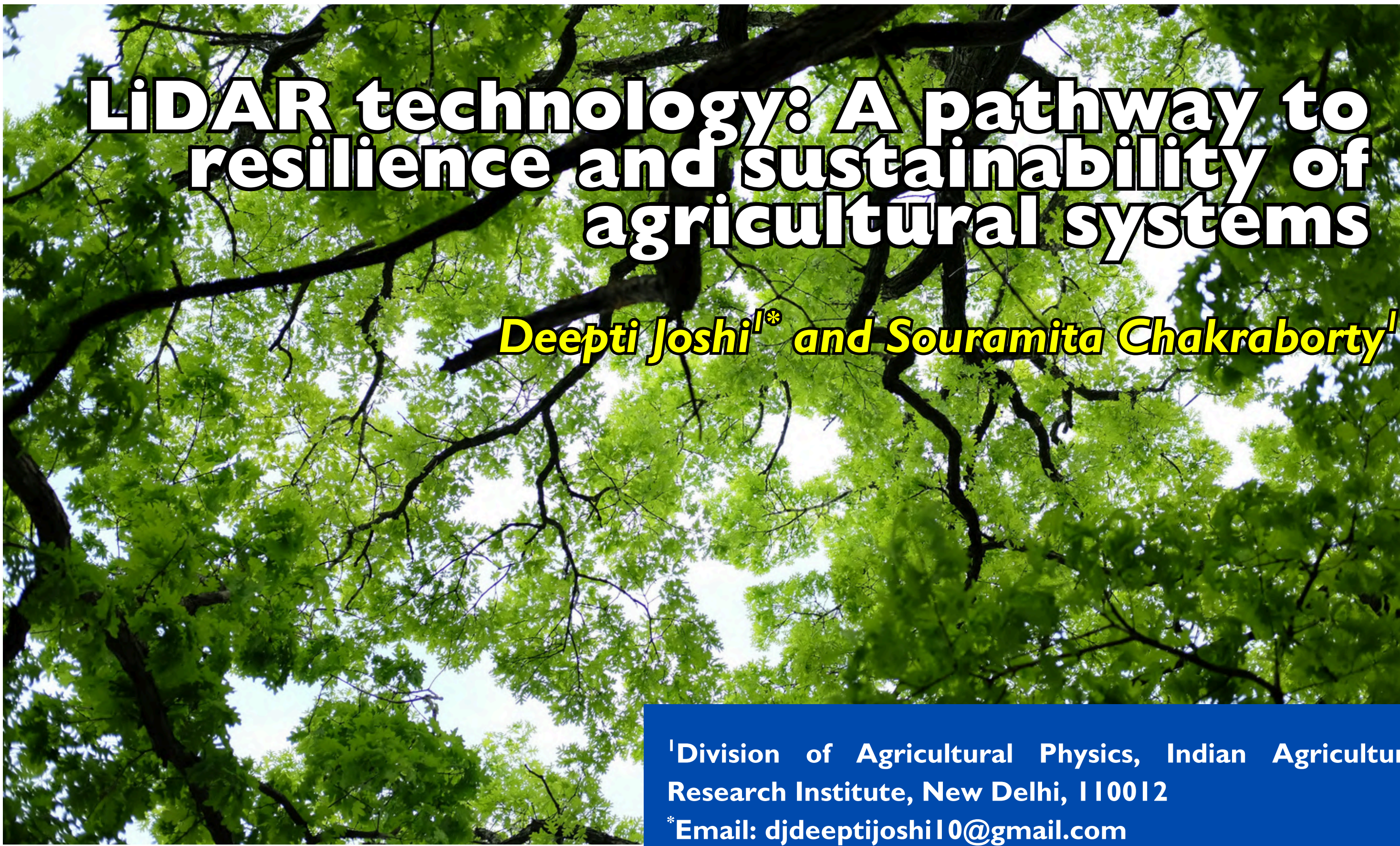

LiDAR technology: A pathway to resilience and sustainability of agricultural systems

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Abstract

One of the greatest challenges of 21st century is to feed the increasing population of the world. Among the advanced technologies used for increasing agricultural production, Light Detection and Ranging (LiDAR) is a transformative technology which provides high resolution 3D maps of the canopy, soil as well as the entire landscape. This enables crop monitoring, input management, pest detection, and yield estimation. This article provides a brief understanding of LiDAR systems and also discusses its applications in agriculture 5.0. Advantages, limitations and future prospects of this technology are also discussed. It shows the importance of LiDAR system as eyes of the agriculture, converting raw data into actionable insights, thus making agricultural systems more resilient and sustainable.

Keywords: LiDAR, Agriculture 5.0, non-destructive and 3D mapping

Introduction

Farmers are facing the dual challenge of adequate food supply as well as ensuring nutritional security for the ever-increasing population with limited and shrinking resources. Present agricultural practices fail to solve this multi-dimensional problem. The history of agricultural revolutions shows how farmers have adapted newer practices to meet the changing demands. From subsistence farming to precision agriculture, we have now entered the era of Agriculture 5.0. It is a human-centered agriculture featuring remote sensing, Artificial Intelligence, Internet-of-things, edge computing with increased resilience and sustainability (Bissadu et al., 2025). Of all the cutting-edge technologies driving agriculture 5.0, LiDAR stands out for its ability to transform the way of farm management by generating high resolution 3-D maps of the farm. LiDAR technology was originally developed in 1960 for geological and military applications, however, in recent years, LiDAR has emerged as a promising technology for agricultural systems as well (Karim et al., 2024). Since its inception, there has been several technological advancements in the technology which are described in table 1.

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Table.1. Advancements in LiDAR technology

Decade	Advancements in technology	Applications
1960s	Pulsed Laser technology	Military and atmospheric studies
1970s	Airborne LiDAR	Topographic mapping, canopy height measurement
1980s	Scanning LiDAR (Oscillating mirrors or rotating prism)	Bathymetry and coastal studies
1990s	GPS and IMU integration with LiDAR	Digital Elevation Models, floodplain mapping
2000	Full waveform LiDAR	Urban 3D mapping, infrastructure planning
2010	Miniaturization (UAV mounted LiDAR)	Precision agriculture
2020	Solid-state and MEMS-based LiDAR	Autonomous vehicles, robotics

Principle and components of LiDAR system

LiDAR- Light Detection and Ranging, is an active remote sensing technology that uses pulsed lasers to measure the distance between the sensor and target. Working principle behind this technology is measuring the distance by calculating the time taken by laser to travel back to the sensor (round-trip time).

Where R is the distance between the sensor and object; c is the speed of light and τ is Time of Flight (Roriz et al., 2021).

Components of LiDAR system includes- source, detector, scanning mechanism, Global Positioning system (GPS), Inertial Measurement Unit (IMU) and a computer. The exact location of each point is determined with the help of GPS and IMU. LiDAR systems are of different types (Fig. 1)

LiDAR system sends laser pulses towards the target surface, which can be soil, crop or any terrain and these pulses return back to the sensor upon hitting hit the target (Backscattering). These reflected pulses are called return signal. Number of return signals depend on the size and structure of the object. When pulse is sent from the air borne sensor, first return is from the top of the canopy. Subsequent returns are from the leaves and branches inside and last return is from the ground surface beneath (Fig. 2) (Debnath et al., 2023).

This process repeats multiple times generating millions of points. These points represent surface features of the target object in 3D. These point clouds can be used to generate maps or 3D models of the scanned surface.

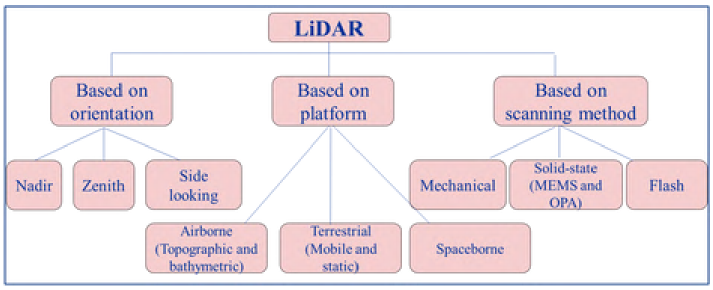

Fig.1. Types of LiDAR system

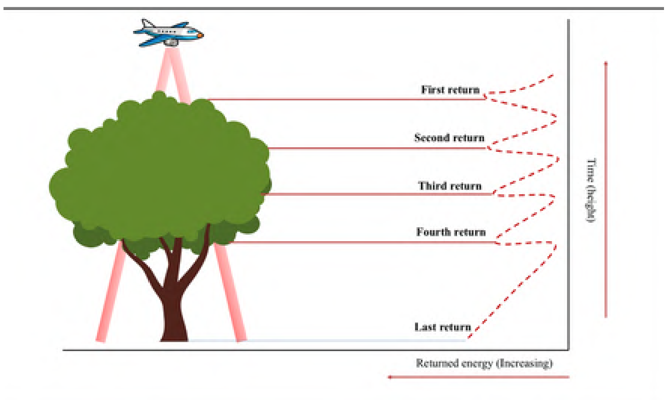

Fig.2. Return signals of LiDAR from the target

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LiDAR and Agriculture 5.0

Agriculture 5.0 shows a shift from yield centric agriculture to data-driven, intelligent, resilient and sustainable systems emphasizing on the resilience and environmental stewardship. LiDAR provides accurate spatial data, which is an indispensable part of automation and intelligent systems. LiDAR provides precise 3D models of crop canopy, facilitating the measurement of plant height, leaf area index and canopy density. This detailed mapping is an absolute necessity for irrigation and fertilizer management as well as yield estimation (Rivera et al., 2023). Furthermore, LiDAR systems can detect subtle changes in canopy structure which is advantageous for monitoring the crop health for moisture stress, nutrient deficiency or pest infestation. Additionally, by generating Digital Elevation Models using LiDAR systems, it is easy to identify slope, drainage pattern and waterlogged areas in the field. This aids in designing irrigation system and optimizing applications. Not only this, LiDAR system also facilitate real-time navigation and obstacle detection and hence can be employed in autonomous vehicles and robots, facilitating operations like weeding, pesticide applications and harvesting (Farhan et al., 2024).

Advantages and disadvantages of LiDAR systems

It facilitates rapid and non-destructive data collection offering minimum hindrance to the crop. Being an active remote sensing technique, it can be used during day as well as night. It provides accurate 3D structure of the canopy. Moreover, LiDAR data can be easily integrated with AI techniques for rapid analysis. Despite these advantages it has certain limitations too. Mutual interference between sensors is a major problem which reduces signal to noise ratio. As LiDAR system has higher resolution and wider field of view, the output point-cloud requires high storage or data compression, which is another major limitation. Besides, LiDAR sensor is highly sensitive to adverse weather conditions like rain, fog etc. which affect the 3D point cloud (Roriz et al., 2021). High initial cost and requirement of skilled persons is another limitation to its application.

Future prospects

Scope of LiDAR system is not limited to crop health monitoring and yield estimation. Its use can be extended to assess the quality of the produce- fruits, vegetables and grains. It can also be used for carbon farming and its 3D models can be used in simulation studies. LiDAR data can also be used in digital twin models. Another prospect is the cost reduction and to make this system more affordable for medium and small-scale farming.

Conclusions

LiDAR technology has proved itself as a promising tool for agriculture 5.0 by providing information on crop health and field conditions and facilitating resource optimization, yield estimation as well as erosion control. It also supports data driven decision-making, thereby increasing the crop yield and reduces cost of cultivation. However, its true potential can be realized only when it is combined with artificial intelligence and edge computing techniques as well as with data from other sensors (thermal, multispectral or hyperspectral). This integration transforms agricultural farms into smart ecosystems enhancing productivity as well sustainability of agricultural systems.

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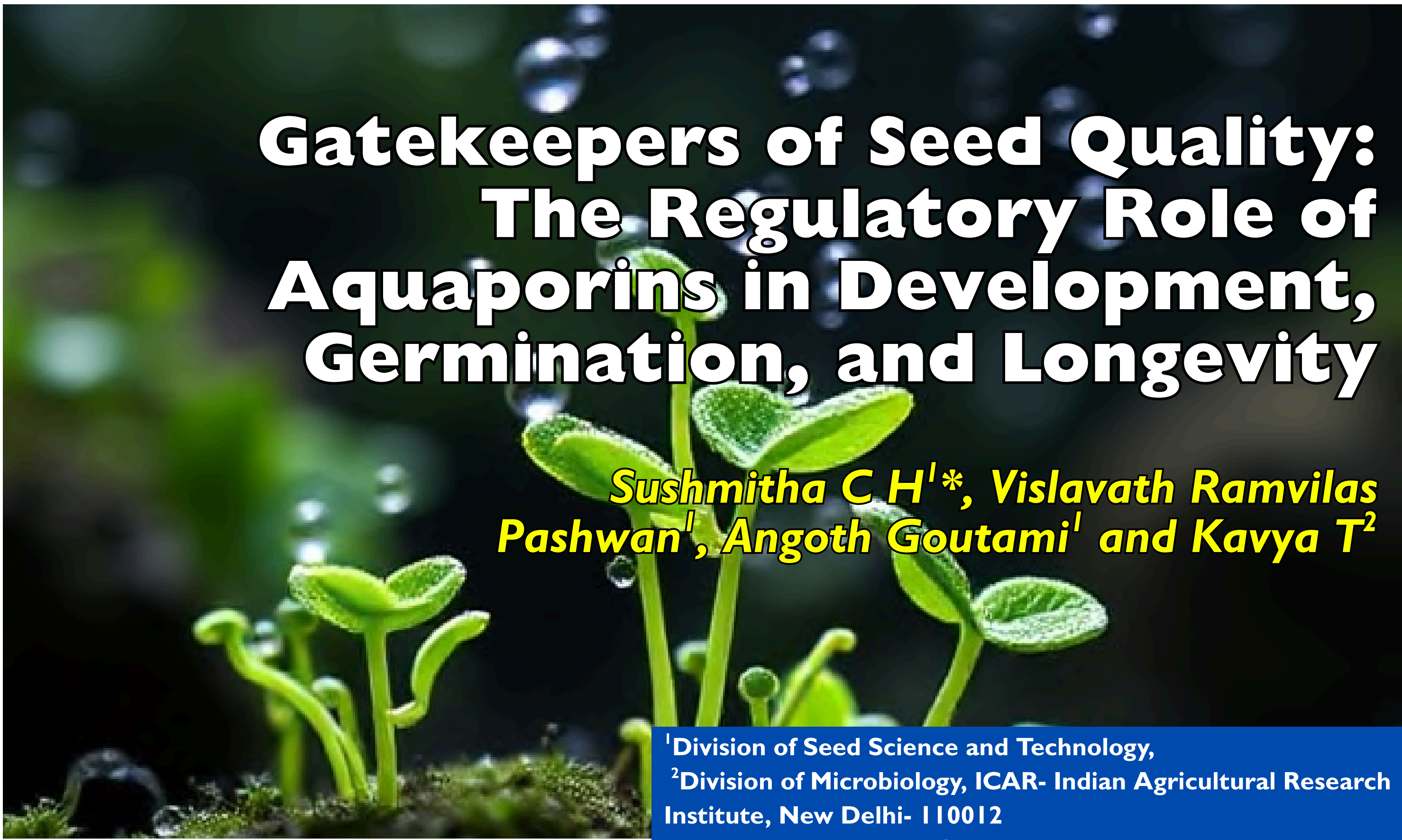

Gatekeepers of Seed Quality: The Regulatory Role of Aquaporins in Development, Germination, and Longevity

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Abstract

Aquaporins (AQPs) are integral membrane proteins that facilitate selective transport of water and small solutes across cellular membranes. In seeds, they play pivotal roles in regulating water relations during development, desiccation, imbibition, germination, and stress responses, all of which are crucial determinants of seed quality. Seed-specific aquaporins, particularly plasma membrane intrinsic proteins (PIPs) and tonoplast intrinsic proteins (TIPs), contribute to desiccation tolerance, uniform hydration, and seedling vigour. Their expression is tightly controlled at transcriptional, post-transcriptional, and post-translational levels, with regulation by hormones such as abscisic acid and gibberellins. Recent studies reveal that aquaporin dynamics also affect seed longevity and storability by maintaining membrane integrity and mitigating oxidative damage during ageing. Understanding aquaporin function not only enhances our knowledge of seed physiology but also offers potential strategies for improving seed vigour, storability, and stress resilience through priming, molecular breeding, and biotechnological approaches.

Key words: Aquaporins, Seed quality, Germination, Desiccation tolerance, Seed vigour

Introduction

Seed quality is a multifaceted trait that determines the success of crop establishment, productivity, and sustainability of agricultural systems. Among the physiological processes governing seed quality, water relations play a central role since imbibition, germination, and seedling establishment depend on efficient water uptake and transport. Aquaporins (AQPs), a family of integral membrane proteins belonging to the major intrinsic protein (MIP) superfamily, are key facilitators of water and small solute transport across biological membranes. Their discovery and functional characterization over the last three decades have significantly expanded our understanding of how plants regulate water homeostasis.

In seeds, aquaporins influence several processes including seed development, desiccation tolerance, imbibition, germination, and stress responses. Regulation of their activity at transcriptional, post-transcriptional, and post-translational levels ensures proper coordination between water flow and metabolic activation. This article highlights the roles of aquaporins in seeds and discusses their regulation in relation to seed quality attributes such as viability, vigour, storability, and stress tolerance.

Aquaporins: Structure and Classification

Aquaporins are typically composed of ~250–300 amino acids forming six transmembrane α-helices connected by five loops, with conserved asparagine–proline–alanine (NPA) motifs critical for selectivity. In plants, aquaporins are grouped into five main subfamilies

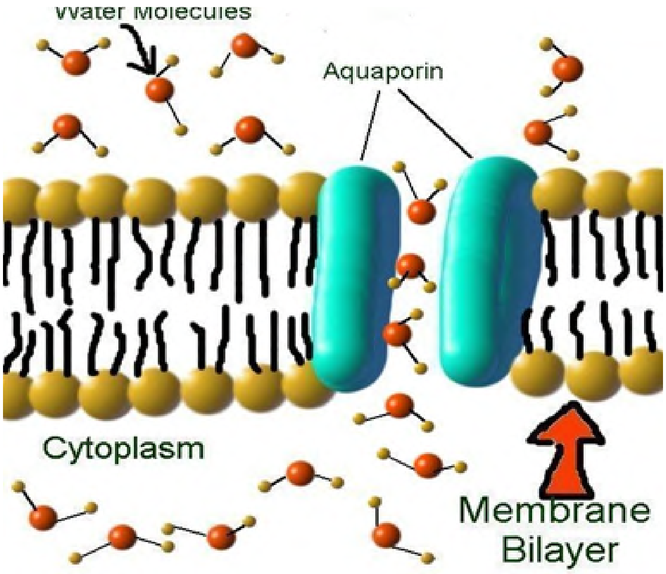

Fig.1. Aquaporins: Structure

- **Plasma membrane intrinsic proteins (PIPs)** localized in the plasma membrane, primarily responsible for water transport during imbibition and germination.
- **Tonoplast intrinsic proteins (TIPs)** located in vacuolar membranes, crucial for maintaining osmotic balance and cell expansion.
- **Nodulin 26** like intrinsic proteins (NIPs) – permeable to small solutes (e.g., glycerol, ammonia, metalloids).
- **Small basic intrinsic proteins (SIPs)** – less characterized, localized to endoplasmic reticulum.
- **X intrinsic proteins (XIPs)** less common, with broader substrate permeability.

In seeds, PIPs and TIPs are the most relevant, as they directly regulate water influx during imbibition and manage intracellular osmotic adjustments. TIP isoforms, especially seed-specific ones such as TIP3 and TIP4, have been shown to play distinct roles in maturation, dormancy, and germination under water stress (Footitt et al., 2019).

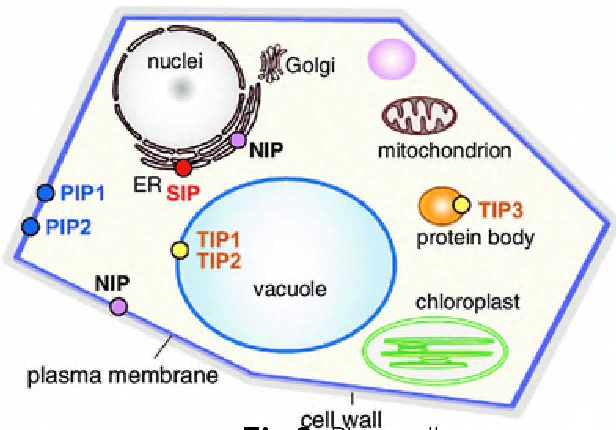

Fig.2. Plant cell

Role of Aquaporins in Seed Physiology and Quality

1. Seed Development and Maturatio

During seed filling and maturation, controlled dehydration ensures desiccation tolerance. Aquaporins, particularly TIP isoforms, help regulate vacuolar water movement and osmotic adjustments, thereby facilitating reserve accumulation and proper seed desiccation. Arabidopsis vacuolar aquaporins (TIP3) have been shown to be under the control of the transcription factor ABI3, which is central in maturation and desiccation tolerance (Mao et al., 2015).

2. Seed Desiccation Tolerance

High-quality seeds withstand drying without losing viability. Aquaporins help maintain cellular homeostasis during desiccation by controlling water efflux and protecting subcellular structures from uncontrolled dehydration. Their interaction with late embryogenesis abundant (LEA) proteins and sugars stabilizes membranes during drying. In Arabidopsis, mutants with reduced seed-specific dehydrins showed significantly reduced seed longevity under storage (Hundertmark et al., 2011).

Similarly, molecular studies have linked desiccation tolerance and seed longevity to regulatory pathways involving aquaporins and ABA (Sano et al., 2016).

3. Imbibition and Germination

Rapid water uptake during imbibition can cause physical damage to membranes (imbibitional injury). Controlled expression and gating of aquaporins prevent excessive water flux, allowing gradual hydration of membranes. PIPs, especially PIP1 and PIP2 isoforms, are upregulated during imbibition, ensuring uniform water distribution and faster reactivation of metabolism. In Arabidopsis, inhibition of aquaporins significantly reduced germination rate, highlighting their importance in early hydration (Vander Willigen et al., 2006).

4. Stress Tolerance During Germination

Seed germination under drought, salinity, or temperature extremes is closely linked to aquaporin activity. For example, TIP3;1 and TIP3;2 act antagonistically in modulating ABA-dependent inhibition of germination, while TIP4;1 is induced under water stress to aid osmotic adjustment (Footitt et al., 2019). External ABA application also alters aquaporin transcription in seeds, impacting their response to environmental stresses (Kapilan et al., 2018).

5. Seed Longevity and Storability

Aquaporins influence seed storability by maintaining structural integrity of membranes during storage. Efficient water transport pathways reduce uncontrolled leakage of solutes during ageing, thereby prolonging viability. Seed-specific TIPs under ABI3 regulation are strongly linked with longevity; mutants lacking these show faster deterioration (Mao et al., 2015). Moreover, aquaporin-mediated regulation of water and reactive oxygen species has been proposed as a mechanism controlling ageing (Sano et al., 2016).

Regulation of Aquaporins in Seeds

1. Transcriptional Regulation

- Seed-specific aquaporin genes such as TIP3;1 and TIP3;2 show distinct expression patterns during maturation and early germination, with roles in ABA-mediated dormancy (Footitt et al., 2019).
- Their expression is controlled by transcription factors including ABI3, LEC1, and FUS3, which regulate seed maturation programs (Mao et al., 2015).
- Hormones such as ABA and gibberellins (GA) differentially regulate aquaporins, with ABA enhancing TIP expression during maturation, while GA promotes PIP activity during germination (Wang et al., 2020).

2. Post-transcriptional and Post-translational Regulation

- mRNA stability ensures temporal control of aquaporin expression during dormancy and germination (Footitt et al., 2019).
- Phosphorylation acts as a reversible switch for gating PIPs, influenced by ABA-mediated signaling (Kapilan et al., 2018).
- pH and calcium changes in the cytosol can rapidly inactivate aquaporins under stress, conserving water (Kapilan et al., 2018).
- Protein–protein interactions, such as heterotetramer formation between PIP1 and PIP2, enhance transport efficiency (Wang et al., 2020).

3. Subcellular Localization and Trafficking

Aquaporins can be relocalized between internal membranes and the plasma membrane in response to developmental or stress signals. For instance, TIP3 isoforms are localized to protein storage vacuoles during dormancy and early germination (Footitt et al., 2019).

Implications for Seed Quality Enhancement

- **Marker for Seed Vigour** – TIP3 isoforms and PIPs can serve as molecular markers, as their expression correlates with vigour and germination under stress (Footitt et al., 2019).
- **Improving Seed Treatments** – Priming techniques such as hydropriming and osmopriming can modulate aquaporin activity, leading to synchronized germination (Kijak & Ratajczak, 2020).

- **Temperature Breeding for Stress-**Resilient Seeds – Genetic manipulation of aquaporins has potential to improve seed performance under stress; overexpression or suppression of TIPs has yielded contrasting effects on seed water relations (Wang et al., 2020).
- **Enhancing Storability** – Targeting TIP regulation, in combination with ABI3 pathways, could improve seed longevity (Mao et al., 2015).
- **Biotechnological Applications** – CRISPR/Cas-based editing of aquaporin genes is a potential tool for developing climate-resilient seeds (Wang et al., 2020).

Future Perspectives

While aquaporins are established as crucial determinants of water relations in seeds, the roles of lesser-known subfamilies such as SIPs and XIPs remain underexplored. Further, cross-talk between aquaporins, ROS signaling, and metabolic regulators needs deeper study. Understanding natural allelic variation in aquaporin genes across crop species could provide targets for breeding high-quality, stress-resilient seeds. Integrating transcriptomics, proteomics, and imaging will help elucidate their spatio-temporal dynamics in seeds.

Conclusion

Aquaporins are central regulators of water transport in seeds, influencing development, desiccation tolerance, germination, stress adaptation, and storability. Their precise regulation ensures balanced hydration and cellular protection, which are fundamental to maintaining seed quality. Harnessing aquaporin biology through breeding, priming, and biotechnological interventions holds promise for enhancing seed vigour, longevity, and resilience in the face of climate challenges'

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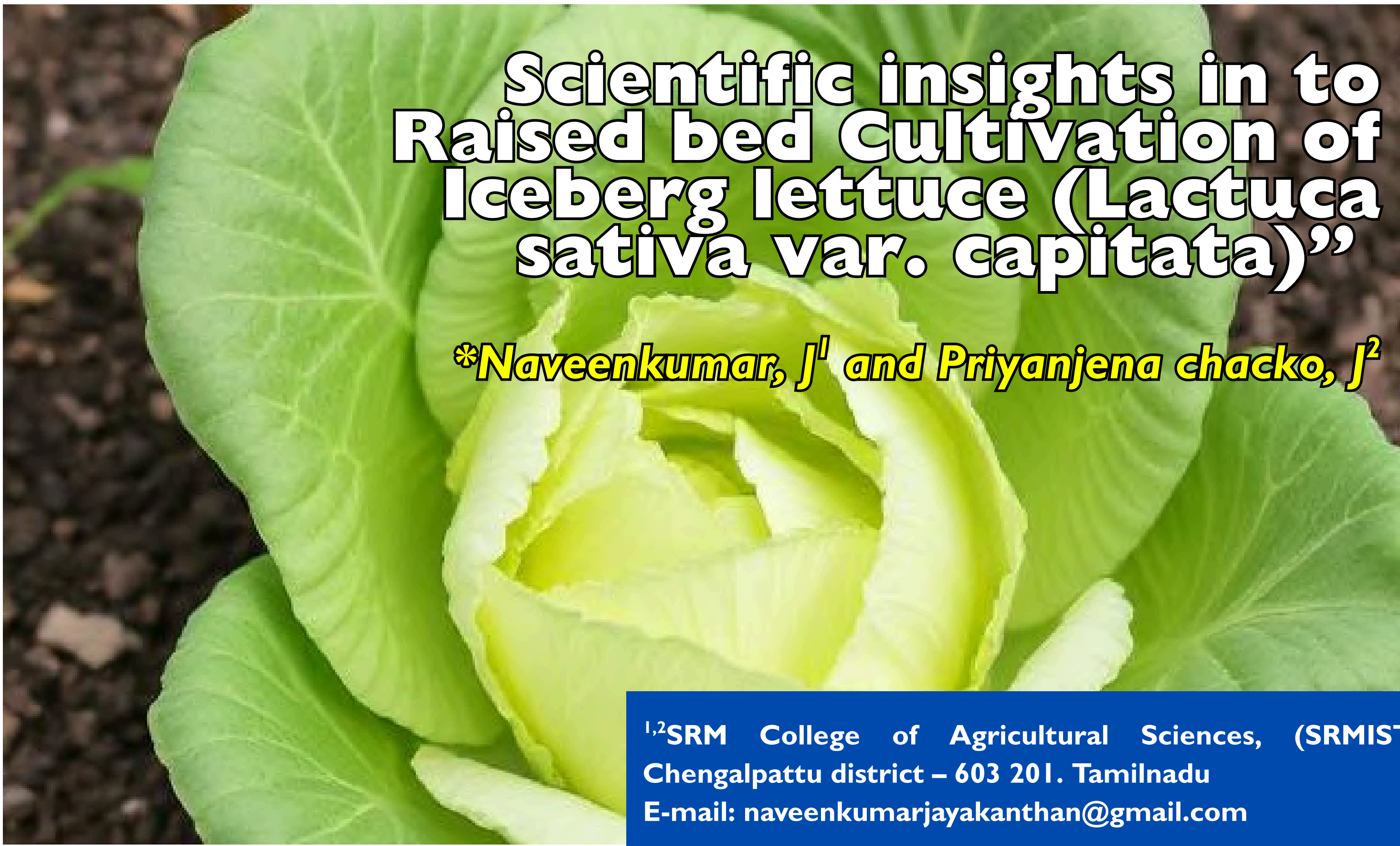

Scientific insights in to Raised bed Cultivation of Iceberg lettuce (Lactuca sativa var. capitata)”

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Abstract

Iceberg lettuce is a highly demanded salad crop, scientifically called Lactuca sativa var. capitata. Lettuce crispness, nutritional quality, and end users appeal in domestic markets as well as international markets. Cultivation of lettuce using raised beds has emerged sustainable approach that allows soil aeration, easy drainage and nutrient use efficiency, hence improving yield and lettuce head quality. This review article shows scientific information on sowing methods, preparation of raised beds, nutrient management, crop husbandry, pest and disease management, harvest, and post-harvest handling of crisphead lettuce. The direct sowing with a cocopeat and vermicompost mixture, bed configuration 48 cm wide, a row-to-row spacing of 10 cm and a plant-to-plant spacing of 23-25 cm spacing have been reported to improve establishment and lettuce head formation. The crisphead required balanced application of fertilizer with micro- and macronutrients, efficient irrigation management through drip or sprinkler irrigation, integrated crop protection, optimum maturity harvest with proper cold chain management, ensures shelf life and market acceptability in this review highlights recent advances and practical perspectives on raised bed cultivation of crisphead lettuce, providing a scientific basis for increasing productivity and profitability.

Key words: Iceberg, Raised bed cultivation, Pest and disease, Nutrient Management, crop husbandry

Introduction

Lettuce is one of the most important leafy vegetables grown worldwide for fresh consumption. Among its types, iceberg lettuce (*Lactuca sativa var. capitata*), also called crisphead lettuce, is highly valued in rural and urban diets owing to its crisp texture, mild flavor, and high market demand in food chains.

Traditionally cultivated on flat beds, the crop is now increasingly grown on raised beds, which provide better soil drainage, enhanced aeration, and improved water and nutrient use efficiency. Iceberg lettuce is emerging as a profitable crop in peri-urban zones.

In India, there are protected cultivation units and regions with cool winter climates. With changing consumer preferences and expanding organized retail, scientific cultivation on raised beds offers a potential pathway for increasing farmer income and ensuring consistent supply of high-quality produce.

Sowing method

Iceberg lettuce can be established either by direct sowing nursery raising or direct sowing. In the direct sowing method, small holes are made in raised beds, seeds are sown, and the holes are covered with a cocopeat and vermicompost mixture in a 3:1 ratio.

This medium ensures water-holding capacity, good aeration, and initial nutrient support for seed germination. Shade nets are often used to protect germinating seedlings from intense sunlight, rainfall, or bird damage.

The transplanting methods, seeds are raised in portrays with soilless media, and 25–30-day-old seedlings are transplanted to the main field. A plant-to-plant spacing of 9-12 inches or 23-30 cm is optimal on raised beds for uniform head development. The crop thrives best under cool-season conditions, with sowing between October and February in India

Fig.1. Sowing method & cultivation

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Raised Bed cultivation in Iceberg lettuce

The Raised bed planting enhances soil tilth and improves irrigation efficiency. In this practice, beds of approximately 48 cm width and length as per the cultivator's convenience are prepared, with a height ranging from 15 to 30 cm (commonly 15, 20, or 30 cm). Such geometry facilitates better field management and ensures a uniform crop stand. In this method, mulching sheets are not used, since the raised bed structure itself provides effective drainage and reduces weed growth. Irrigation is supplied through drip or sprinkler systems to maintain constant soil moisture.

Nutrient Management for lettuce

Nutrient management plays a vital role in achieving optimum crisphead size, firmness, and shelf life.

- **Organic manures** Application of 10–15 ton/ha of well decomposed FYM or compost during field preparation improves soil fertility.
- **Fertilizers** A general recommendation of 100:80:60 kg N:P_2O_5: K_2O per/ha is followed. Entire phosphorus and potassium, along with 50% nitrogen, are applied as basal and the remaining nitrogen is top-dressed or fertigated in two or three splits.
- **Micronutrients** Foliar spray of calcium, boron, and magnesium reduces physiological disorders such as tip burn and improves head compactness.
- **Sustainable Approach** Vermicompost, poultry manure, and biofertilizers can be integrated for organic and ecofriendly cultivation.

Crop management

- **Weed control** 20-25 days after planting manual weeding, supported by raised bed design it also gradually reduces weed pressure
- **pest** cutworms and aphids are both the primary primary pest. Recommended practices are neem-based formulations and integrated nutrient management (INM)
- **Diseases** of leaf spot and downey mildew are most common. The effective management strategies are crop rotation, use resistant varieties and need based fungicide sprays.

Harvesting & yield

The crispheads ready for harvest in 70-80 DAT (day after transplanting), should achieve compactness before bolting. Harvest can do manually, and portion of the stem is usually left attached. Proper trimming and grading are important to meet market requirements. In raised-bed cultivation, yields typically range from 200–250 quintals per hectare, it may vary with the variety and management practices.

Fig.2. Iceberg or crisphead harvest stage

Postharvest handling

Freshly harvested heads are highly perishable and require careful handling and packing in perforated crates or cartons, often wrapped in polyethylene to retain freshness. Cold storage at 0–2 °C with 95% RH extends shelf life up to 2–3 weeks. Maintenance of cold-chain logistics is essential for market distribution and export quality.

Fig.3. Post harvest handling

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Conclusion

Iceberg lettuce Raised bed cultivation offers a sustainable approach for enhancing yield, quality, and resource use efficiency,Practices such as direct sowing in cocopeat along with vermicompost medium, adoption of 9-inch spacing, balanced fertilization, and efficient irrigation contribute to more profitability. With increasing consumer preference for fresh salad crops, adoption of scientific raised bed technologies can strengthen the supply chain and support both domestic consumption and export opportunities.

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Best Article of the Second Issue

Progress and Applications of E-Nose and E-Tongue in Horticultural and Food Industries

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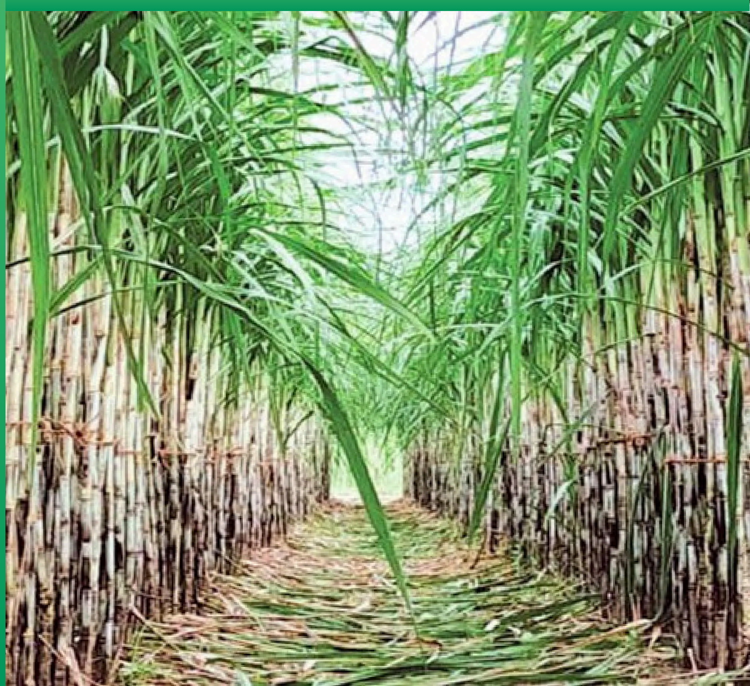
Abstract

E-sensing technologies are current trends in developing digitalized horticulture, food, and other industrial sectors. Mimic human olfaction and taste

consumer trust.

Key words: E-sensing, minimising human error, artificial sensing, product standardization



Dr. Janaki Ammal

INDIAN BOTANIST&
PADMA SHRI AWARDEE

Click on the portrait to read her contributions

Dr. E. K. Janaki Ammal (4 Nov 1897 – 7 Feb 1984) was recognized for her pioneering work in plant breeding, cytogenetics, and phytogeography, with major contributions to sugarcane and brinjal improvement. She co-authored the Chromosome Atlas of Cultivated Plants (1945) with C.D. Darlington and made significant advances in ethnobotany by studying medicinal and economically important plants from Kerala's rainforests. She was honored with the Padma Shri in 1977.

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