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ROOTNET: THE FASCINATING PLANT UNDERGROUND NETWORK

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ABSTRACT

Once considered inert, plants are understood to participate in underground communication networks, termed "RootNet." Emerging evidence shows that roots exchange resources, signal chemically, and interact with symbiotic fungi, forming internet-like biological systems across ecosystems. This review explores mechanisms such as root exudates and mycorrhizal links that support kin recognition, pathogen defense, and cooperative nutrient transfer. Beyond ecology, RootNet informs innovations in plant-based sensors, bio-digital interfaces, and sustainable agriculture, including soil monitoring and restoration. Despite promise, uncertainties remain regarding specificity and human impacts, while future research may enable biofeedback systems enhancing food security and climate resilience.

KEYWORDS: Mycorrhizal Networks, Plant Languages, RootNet, Sustainable Agriculture, Underground Communication

INTRODUCTION

We have underestimated the complexity and intelligence of the silent, invisible world beneath our feet. According to recent findings in plant biology, roots communicate in addition to absorbing nutrients and water. Often compared to an underground plant internet, this "RootNet" allows plants to communicate, alert others to threats, and even work together. This covert network upends conventional wisdom on intelligence and communication, creating novel opportunities for bio-inspired technology, ecosystem monitoring, and sustainable agriculture.

THE STUDY OF PLANT COMMUNICATION

In the past, plants were thought to be passive beings that mechanically reacted to outside stimuli. Studies conducted since the early 2000s, however, have significantly changed this viewpoint. According to research, plant roots perceive changes in their surroundings, release chemical signals, and modify their activity accordingly (Baluska et al., 2009).

Chemical substances released by roots, known as root exudates, are essential for underground communication. These substances aid in kin identification, disease defense, and symbiotic relationships—particularly with fungi. The mycorrhizal network, sometimes known as the "Wood Wide Web," which links the roots of several plant species via fungal filaments, is among the more intriguing instances (Simard et al., 1997). This network allows plants and trees to send chemical signals, water, and nutrients over long distances.

ROOTNET: A NETWORK OF NATURAL INFORMATION

The name "RootNet" aptly describes the characteristics of this covert communication technology. Similarly, how the internet connects computers all over the world, RootNet creates a cooperative network out of individual plants. Before the threat spreads, plants use mycorrhizal fungus to relay distress signals to nearby plants when they are attacked through pests or diseases (Song et al., 2010).

It's interesting to note that this system seems to favor particular species or individuals over others, much like network bandwidth distribution, suggesting some sort of biological hierarchy or decision-making at the plant level. In a forest, for example, "mother trees" are known to transfer more carbon to their progeny than to unrelated trees (Simard and Durall, 2004). This brings up philosophical issues regarding the intelligence of plants and even their "social behavior."

INSPIRATION FOR ENGINEERING: BIO-DIGITAL INTERFACES

Not only do ecologists find the RootNet concept fascinating, but technologists have also been motivated to reconsider networking purposes, biosensors, and eco-feedback technology. If plants are able to build robust, flexible networks without centralized management, might this lead to new computer techniques or Internet of Things (IoT) networks?

In an effort to create plant-based sensors, researchers have begun to experiment with bio-electrical detection of signals in plants. For example, live environmental monitors are being designed using the electrical reactions of plants to surrounding changes (light, moisture, and pollutants) (Tanaka et al., 2020). Future smart farms may be able to use plants as sensors to monitor soil conditions and crop health without the need for electronic equipment by utilizing RootNet-like systems.

USES IN ECOLOGY AND AGRICULTURE

There are several uses for comprehending and utilizing RootNet:

Agricultural Sustainability: By guiding precision agriculture, RootNet can lessen the demand for chemical pesticides and fertilizers. It may be possible to design interconnected crops to "warn" one another about infections, enabling prompt and focused action.

Monitoring of Soil Health: Farmers can more accurately evaluate the nutrient cycles and soil microbial health by researching root exudates or plant-fungi interactions.

The ecology of restoration: Restoring plant communication networks in damaged settings through the introduction of specific mycorrhizal fungus or "hub plants" may hasten the recovery of forests or grasslands (van der Heijden and Horton, 2009).

PHILOSOPHICAL AND ETHICAL CONSIDERATIONS

Long-held beliefs about plants must be reexamined in light of RootNet's recognition. Does this imply that plants are intelligent if they can share, interact, and even make decisions? Their intricate signaling networks imply a decentralized type of knowledge or problem-solving, despite the fact that they lack brains and consciousness (Baluska et al., 2006).

The way that people treat and use plants may be affected ethically by this insight. It promotes the idea that plants are active members of ecosystems rather than only passive resources.

OBSTACLES AND POTENTIAL RESEARCH

There are still a lot of unsolved questions despite significant progress:

- To what extent are the communications transmitted via RootNet specific?
- Can human activity alter or interfere with this network?
- Could these natural systems be improved or replicated in other fields through genetic engineering?

Future studies may reveal more intricate plant-to-plant “languages,” which could lead to real-time biofeedback systems for enhancing food security and climate resilience.

CONCLUSION

RootNet is a fundamental reality that lies under the soil and is changing our perception of the plant life. It is not merely a metaphor. The subterranean internet of plants exhibits a biological sophistication comparable to digital networks, from inter-root interaction to forest-scale networks. RootNet provides a preview of a future in which plants are active, intelligent components in an alive network rather than passive green backgrounds as science and technology merge with ecology.

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BEE BEHAVIOUR AND COMMUNICATION

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ABSTRACT

Honey bees exhibit highly organized behavioural patterns and sophisticated communication systems essential for colony survival. This article explores key aspects of bee behaviour, including swarming, queen replacement, division of labour, and reproductive regulation. Special emphasis is given to their unique communication mechanisms such as dance language, pheromones, and tactile signals, which enable efficient resource utilization and colony coordination. Understanding these complex interactions provides valuable insights into social organization, ecological adaptation, and pollination biology. Such knowledge is crucial for improving beekeeping practices, ensuring pollinator conservation, and enhancing agricultural productivity in changing environmental conditions.

KEYWORDS: Honey bees, Pheromones, Pollination, Swarming, Waggle dance

INTRODUCTION

Honey bees are far more than producers of honey and wax; they are highly organized social insects and efficient communicators. To sustain their colonies, forager bees have evolved a sophisticated "dance language" that encodes precise information about the distance and direction of food sources. This remarkable behaviour was first decoded by Karl von Frisch, revealing one of the most advanced non-human communication systems. These behaviours provide deep insights into animal communication, cooperative behaviour, and the evolution of symbolic signalling.

BEE BEHAVIOUR

SWARMING

Swarming is the natural reproductive process of a honey bee colony, in which a large group of bees, led by the old queen, leaves the original hive to establish a new colony. This usually occurs due to overcrowding and rapid colony growth. Worker bees prepare for swarming by constructing queen cells for rearing new queens. Typically, swarming takes place during late spring or early summer.

STAGES OF SWARMING:

1. *Instinct and Preparation*: Strong colonies develop a natural tendency to reproduce through swarming.
2. *Scouting*: Scout bees search for suitable nesting sites before departure.
3. *Departure*: After queen cells are sealed, the old queen leaves with a large group of workers.
4. *Initial Cluster*: Bees temporarily cluster on a nearby surface such as a tree branch.
5. *Final Migration*: The swarm relocates to the selected nesting site and establishes a new colony.

EMERGENCY QUEEN REPLACEMENT

When the queen dies unexpectedly, the colony initiates emergency queen rearing. Worker bees select very young larvae and convert worker cells into queen cells by enlarging them. These larvae are fed royal jelly, which enables their development into queens. Multiple queen cells are formed, but the first emerging queen eliminates rivals. After mating flights, she becomes the new fertile queen responsible for colony reproduction.

WORKER POLICING AND REPRODUCTIVE SUPPRESSION

In queenless colonies lacking suitable brood, some workers develop the ability to lay unfertilized eggs, producing drones. However, other workers often remove these eggs through a process known as worker policing, which maintains genetic stability. Colonies with laying workers usually decline due to lack of proper reproductive organization.

DIVISION OF LABOUR

Honey bee colonies exhibit a well-defined division of labour based on age. Younger workers perform tasks such as cleaning and nursing, while older workers forage for food and defend the hive. The queen regulates colony organization through pheromones that maintain unity and reproductive control.

BLOSSOM FAITHFULNESS

Honey bees exhibit floral constancy, meaning they repeatedly visit the same type of flower until resources are depleted. This behaviour increases pollination efficiency and enhances plant reproduction.

SUPERSEDURE (NATURAL QUEEN REPLACEMENT)

Supersedure is a natural process in which a colony replaces an aging or less productive queen without swarming. Worker bees rear a new queen, who takes over after mating, ensuring continuity and colony stability.

BEE COMMUNICATION

Honey bees communicate through a combination of movement, chemical signals, and physical interactions, enabling efficient coordination within the colony.

MOVEMENT-BASED COMMUNICATION

Bees perform specific dances to convey information about food sources:

- *Round Dance*: Indicates food sources located nearby (within ~50 meters).
- *Waggle Dance*: Communicates distance and direction of distant food sources using a figure-eight pattern relative to the sun's position.

CHEMICAL COMMUNICATION (PHEROMONES)

Pheromones play a crucial role in regulating colony behaviour, including reproduction, alarm signalling, and foraging. These chemical signals help maintain colony organization and social cohesion.

TACTILE COMMUNICATION (TOUCH)

Bees use antennae and body contact to recognize nestmates and exchange information. Touch also helps in sensing environmental changes and coordinating activities within the hive.

VIBRATION AND SOUND

Bees produce vibrations and buzzing sounds that serve as signals for mating, alarm, and colony coordination. These signals are particularly important in maintaining social interactions within the hive.

TYPES OF BEES IN A COLONY

- *Queen*: The single reproductive female responsible for laying eggs and producing pheromones.
- *Worker*: Sterile females that perform all essential tasks such as foraging, nursing, and hive maintenance.
- *Drone*: Male bees whose primary role is to mate with a queen; they do not participate in other colony activities.

HOW HONEY BEES LOCATE FLOWERS?

Honey bees perceive light differently from humans and can detect ultraviolet patterns on flowers. These patterns act as visual guides, directing bees to nectar and pollen sources efficiently. This adaptation enhances foraging success and improves pollination efficiency.

CONCLUSION

Honey bees represent highly advanced social organisms with complex behavioural and communication systems. Their dance language, pheromonal signalling, and cooperative interactions ensure efficient resource utilization and colony survival. Understanding these mechanisms is essential for improving beekeeping practices, conserving pollinators, and supporting sustainable agriculture. As research continues, deeper insights into bee communication may further reveal the sophistication of their social systems, reinforcing their ecological importance and their vital role in global food security.

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EXPLORING THE POWER OF TREE SPICES

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ABSTRACT

Tree spices are important perennial crops obtained from woody plants, where bark, buds, fruits, seeds, or leaves are valued for aroma, flavour, and medicinal uses. Major examples include clove, cinnamon, nutmeg, allspice, star anise, garcinia, and bay leaf, which have supported global trade, traditional medicine, and culinary systems. Their lifespan, suitability for agroforestry, and market demand enhance rural livelihoods, exports, and sustainability. Rich in essential oils and bioactive compounds, they offer antioxidant and therapeutic benefits, while modern processing and value addition have increased their commercial and nutritional importance.

KEYWORDS: Agroforestry, Bioactive compounds, Essential oils, Sustainable agriculture, Therapeutic properties

INTRODUCTION

Spices have occupied a central place in human history, culture and civilization, valued not only for their ability to enhance the flavor, aroma and color of foods but also for their preservative, medicinal and ritualistic uses. Among the diverse groups of spices, tree spices form a unique and highly valuable category due to their perennial woody nature, long productive lifespan and high concentration of aromatic and bioactive compounds.

Tree spices are derived from woody perennial plants in which the economically important parts may include bark, flower buds, fruits, seeds, arils or leaves. Unlike annual or herbaceous spices, tree spices require several years to reach economic bearing but continue to produce for decades, often exceeding 40–60 years under favourable management. This perennial characteristic makes them particularly suitable for plantation agriculture, homestead gardens and agroforestry systems. Prominent examples of tree spices include clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum* spp.), nutmeg (*Myristica fragrans*), allspice (*Pimenta dioica*), star anise (*Illicium verum*) and bay leaf (*Laurus nobilis*).

Beyond their economic importance, tree spices have been deeply embedded in traditional systems of medicine, including Ayurveda, Unani, Siddha and Traditional Chinese Medicine. Various parts of tree spices have been used for centuries to treat digestive disorders, respiratory ailments, infections, inflammation and metabolic diseases. The medicinal value of these spices is largely attributed to their rich phytochemical composition, particularly essential oils, phenolic compounds, flavonoids and terpenoids. Compounds such as eugenol in clove, cinnamaldehyde in cinnamon, myristicin in nutmeg and anethole in star anise exhibit strong antioxidant, antimicrobial, antifungal, anti-inflammatory and carminative properties.

In recent decades, there has been a renewed global interest in tree spices driven by increasing consumer awareness of health, nutrition and sustainability. The shift toward natural flavours, clean-label foods, herbal remedies and plant-based products has significantly increased the demand for spices and spice-derived ingredients. Tree spices are now widely used not only in household cooking but also in food processing industries, bakery and confectionery products, beverages, pharmaceuticals, nutraceuticals, cosmetics and perfumery. Essential oils and oleoresins extracted from tree spices are highly valued ingredients in flavoring, aromatherapy and medicinal formulations.

ORIGIN AND GEOGRAPHICAL DISTRIBUTION

Most economically important tree spices originated in the tropical regions of Asia, the Caribbean and Central America. Clove and nutmeg are native to the Maluku Islands of Indonesia, cinnamon originated in Sri Lanka and parts of South India, allspice is native to the Caribbean region, and star anise is indigenous to southern China and Vietnam. Over centuries, these crops spread to other tropical regions including India, Madagascar, Tanzania, Sri Lanka, Indonesia and parts of Latin America.

India is one of the leading producers, consumers and exporters of tree spices, particularly cinnamon (Indian cassia), clove, nutmeg and bay leaf. The Western Ghats, North-Eastern states, Andaman and Nicobar Islands and coastal regions provide favourable agro-climatic conditions for their cultivation.

NUTRITIONAL COMPOSITION OF MAJOR TREE SPICES

Tree spices, though consumed in small quantities, contribute important dietary components such as minerals, dietary fiber and bioactive phytochemicals. Many tree spices are rich in calcium, iron, potassium, magnesium and manganese, which play essential roles in human metabolism. Their antioxidant compounds help neutralize free radicals, thereby reducing oxidative stress and lowering the risk of chronic diseases. Regular inclusion of spices in the diet has been associated with improved digestion, enhanced immunity and better metabolic health.

MAJOR TREE SPICES AND THEIR BOTANICAL DESCRIPTION

Clove (*Syzygium aromaticum*)

Clove is a slow-growing, medium-sized evergreen tree belonging to the family Myrtaceae. Under cultivation, the tree generally attains a height of 10–15 m, though it may grow taller under natural forest conditions. The trunk is straight with smooth greyish bark and the crown is dense, pyramidal to conical in shape. The root system is moderately deep.

Leaves are opposite, simple, elliptic to obovate, thick, leathery and glossy dark green in color, measuring 8–15 cm in length. Young leaves are reddish in color and gradually turn green as they mature. Inflorescences are terminal or axillary cymes bearing numerous flower buds. Each flower bud consists of a long hypanthium with four thick sepals and four small petals enclosing numerous stamens. The unopened flower buds, harvested at the pink bud stage and dried, constitute the commercial clove spice. Clove trees usually commence bearing after 6–8 years and reach full production by 15–20 years, continuing to yield for over 50 years under proper management.

Cinnamon (*Cinnamomum verum*, *C. cassia* and related species)

Cinnamon is obtained from several species of the genus *Cinnamomum* belonging to the family Lauraceae. The most commercially important species are *Cinnamomum verum* (true or Ceylon cinnamon), C. *cassia*, *C. burmannii*, and *C. loureiroi*. These are evergreen trees or shrubs that may grow up to 10–15 m in height under natural conditions but are maintained as coppiced bushes of 2–3 m height under cultivation to facilitate bark harvesting.

Leaves are simple, opposite or sub-opposite, ovate to lanceolate, thick, leathery and aromatic, with three to five prominent longitudinal veins arising from the base, a characteristic feature of the genus. The economically important part is the inner bark. After harvesting, the outer corky layer is scraped off and the inner bark is dried, during which it curls into quills. True cinnamon (*C. verum*) produces thin, light-colored, highly aromatic quills, whereas cassia types yield thicker, darker and more pungent bark. Cinnamon plants respond well to coppicing, producing multiple shoots that enhance bark yield.

Nutmeg (*Myristica fragrans*)

Nutmeg is a dioecious evergreen tree belonging to the family Myristicaceae. The tree is medium to large in stature, attaining heights of 15–20 m with a straight trunk and spreading crown. The bark is greyish-brown, smooth when young and slightly fissured with age.

Leaves are simple, alternate, oblong-lanceolate, dark green, leathery and glossy, measuring 10–20 cm in length. Flowers are small, pale yellow, waxy and borne in axillary clusters. The fruit is a fleshy, yellow drupe, which splits open at maturity to reveal a shiny brown seed (nutmeg) enveloped by a bright crimson, lace-like aril known as mace. Both nutmeg (seed) and mace (aril) are economically valuable spices. Nutmeg trees have a long juvenile phase and begin bearing after 7–9 years, reaching peak productivity after 15–20 years.

Allspice (*Pimenta dioica*)

Allspice is an evergreen tree belonging to the Myrtaceae family, attaining a height of 8–12 m. The leaves are opposite, oval and aromatic when crushed. Flowers are small, white and borne in axillary clusters. The spice is obtained from the dried unripe berries, which resemble peppercorns. The characteristic aroma of allspice combines flavors reminiscent of clove, cinnamon and nutmeg, hence the name.

Star Anise (*Illicium verum*)

Star anise is a small to medium-sized evergreen tree of the Schisandraceae famil. Leaves are simple, lanceolate and glossy. Flowers are solitary, pale yellow to pinkish. The fruit is a distinctive star-shaped aggregate consisting of 6–8 carpels, each containing a single seed. The dried fruits are used as a spice and are a major source of anethole.

Bay Leaf (*Laurus nobilis*)

Bay leaf is obtained from *Laurus nobilis*, an evergreen aromatic tree or large shrub belonging to the family Lauraceae, native to the Mediterranean region. Under cultivation, the tree grows to a height of 8–12 m with a dense, rounded canopy and smooth grey bark. It possesses a well-developed root system and exhibits good tolerance to pruning.

Leaves are simple, alternate, lanceolate to oblong, thick, leathery and glossy dark green on the upper surface with a lighter underside. The leaf margins are slightly wavy and oil glands impart a characteristic aroma when crushed. Leaves measure 5–10 cm in length and retain their aroma even after drying. The dried leaves constitute the commercial bay leaf spice, widely used for flavoring soups, curries, sauces and meat preparations as well as in traditional medicine for digestive and respiratory ailments.

Garcinia (*Garcinia spp*.)

Garcinia comprises a group of evergreen tree species belonging to the family Clusiaceae, widely distributed in the tropical regions of South and Southeast Asia. Important spice-bearing species include *Garcinia cambogia* (Malabar tamarind), *Garcinia indica* (kokum) and *Garcinia gummi-gutta*. These medium-sized trees typically attain a height of 10–20 m and possess a dense, spreading canopy. Leaves are simple, opposite, dark green, glossy and leathery in texture.

Flowers are unisexual or bisexual, borne in axillary clusters and are yellow to greenish in color. The fruit is a globose to pumpkin-shaped berry with a thick, fleshy rind, which turns yellow, orange, red or purple upon maturity depending on the species. The dried rind of the fruit constitutes the economically important spice, widely used as a souring agent in culinary preparations. Garcinia fruits are rich in organic acids, particularly hydroxycitric acid (HCA), along with garcinol and xanthones, which impart significant medicinal and nutraceutical properties.

CONSTRAINTS AND FUTURE PROSPECTS

Major constraints in tree spice production include long juvenile periods, limited availability of quality planting material, pest and disease incidence and price fluctuations. Future research should focus on genetic improvement, climate-resilient varieties, organic production, mechanization and post-harvest value addition. Increasing demand for natural products, essential oils and functional foods offers significant opportunities for the expansion of tree spice cultivation.

CONCLUSION

Tree spices are vital perennial crops that contribute to culinary, nutritional, medicinal and economic benefits. Spices like clove, cinnamon, nutmeg, allspice, star anise, bay leaf and *Garcinia* spp. are rich in bioactive compounds and adaptable to agroforestry systems, supporting sustainable agriculture. Improved cultivation practices and value addition can enhance productivity and profitability, highlighting their importance in modern agriculture and food systems.

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WHO REALLY PAYS FOR CHEAP FOOD? THE SILENT CRISIS LINKING FARMERS & CONSUMERS

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ABSTRACT

Many people expect food to be plentiful, reasonably priced, and accessible all year long. Low-cost food benefits customers, but the hidden consequences of this affordability are not acknowledged. A quiet catastrophe that connects farmers' suffering with long-term threats to consumers and the environment has been brought about by the drive to provide inexpensive food. By looking at the difficulties farmers confront, inefficiencies in the agri-food system, environmental externalities, and growing consumer concerns about food quality and safety, this article investigates who really pays the price for inexpensive food. Developing a more resilient, equitable, and sustainable agricultural future requires an understanding of this interwoven system.

KEYWORDS: Agri-food supply chain, Environmental externalities, Farmer livelihood crisis, Food quality and safety, Low-cost food systems

INTRODUCTION

Low food prices are frequently regarded as a sign of agricultural development success in contemporary food systems. But behind every reasonably priced meal is a complicated web of farmers, middlemen, customers, and natural resources. In the face of growing input costs, unpredictable weather, and unstable markets, farmers are expected to produce more with less resources. At the same time, people want food that is affordable, secure, and nourishing.

A crucial question is brought up by this contradiction: Who actually pays for inexpensive food? The solution exposes a latent crisis in which consumers face long-term health and food security threats, farmers suffer financial losses, and ecosystems sustain environmental harm. These interrelated issues are closely examined in this article.

FARMERS' FINANCIAL BURDEN

A. GROWING CULTIVATION COSTS

Due to rising expenses for labour, energy, fertiliser, pesticides, and seeds, farmers in both industrialised and developing nations must contend with rising production costs. Farm-gate prices frequently stagnate or fluctuate erratically, despite annual increases in input costs. This disparity lowers profit margins and makes farmers more reliant on loans.

B. MARKET INEFFICIENCIES AND INTERMEDIARIES

Farmers only get a small portion of the final consumer price in many agri-food systems. Farmers' bargaining strength is diminished by the existence of several middlemen, poor storage facilities, and a lack of direct market access. Farmers are therefore forced to sell food at distressed prices, particularly for perishable goods.

C. UNCERTAINTY IN INCOME AND DISTRESS FOR FARMERS

Chronic farmer misery is exacerbated by low profitability and unstable revenue. Market crashes, pest outbreaks, and unpredictable weather all make matters worse. Prolonged economic hardship can have severe societal repercussions, including migration, debt, and a decline in young people's enthusiasm in agriculture.

THE ENVIRONMENTAL COSTS OF LOW-COST FOOD

A. OVERUSE OF NATURAL RESOURCES

Intense farming methods are frequently used to maintain high yields at low prices. Overuse of irrigation water and chemical fertilisers causes salinisation, nutrient imbalance, soil deterioration, and groundwater depletion. These methods jeopardise ecosystem stability and long-term soil fertility.

B. CLIMATE CHANGE AND FARMING

Climate change affects and is exacerbated by agriculture. Land-use changes, livestock, and synthetic fertilisers all contribute significantly to greenhouse gas emissions. In the meantime, farmers deal with unpredictable rainfall, harsh temperatures, and more frequent droughts and floods, all of which raise production risks and expenses.

C. DECREASE IN BIODIVERSITY

On-farm biodiversity is decreased by monocropping systems that are encouraged for uniformity and market demand. The progressive replacement of indigenous knowledge systems and traditional crop varieties makes food systems more susceptible to diseases, pests, and climate shocks.

THE CONSUMER ASPECT OF LOW-COST FOOD

A. THE DELUSION OF AFFORDABILITY

The full cost of food remains concealed, despite customers enjoying low retail pricing. Government subsidies, public health spending, and environmental deterioration all indirectly transfer the burden to society. Therefore, inexpensive food at the market does not always translate into low national costs.

B. CONCERNS ABOUT FOOD SAFETY AND QUALITY

Agrochemical abuse or overuse may be encouraged by pressure to lower production costs. Concerns regarding food safety and long-term health effects are raised by pesticide and contaminant residues in food. Transparency, traceability, and food produced responsibly are becoming more and more important to consumers.

C. DIETARY TRANSITIONS AND NUTRITION

Nutritious foods are frequently more difficult to obtain than inexpensive, high-calorie foods. This leads to lifestyle-related illnesses and vitamin deficiencies, among other forms of malnutrition. A significant public health concern is the gap between nutrition and affordability.

CHALLENGES IN POLICY, SUBSIDIES, AND STRUCTURE

A. SUBSIDIES BASED ON INPUTS

To help farmers and maintain low food costs, governments frequently provide subsidies for irrigation, energy, and fertilisers. Although these subsidies offer temporary respite, they could promote wasteful resource usage and put a burden on public coffers.

B. SUPPORT FOR PRICES AND GAPS IN PURCHASES

Only a small number of crops and regions benefit from minimum support prices and procurement procedures. Market instability still affects a lot of farmers who cultivate pulses, fruits, and vegetables. Income disparity in the farming community is sustained by the absence of inclusive price support measures.

C. SYSTEMIC REFORMS ARE NECESSARY

It is crucial to implement structural changes that prioritise supply chain efficiency, value addition, farmer-producer organisations, and market access. The full cost of sustainable manufacturing must be reflected in fair pricing arrangements.

ROUTES FOR A JUST FOOD SYSTEM

A. INCREASING FARMER-CONSUMER CONNECTIONS

While providing consumers with fresh produce, direct marketing strategies, farmers' markets, community-supported agriculture, and internet platforms can lower middlemen and enhance price realisation for farmers.

B. ENCOURAGING SUSTAINABLE FARMING

It is possible to lower environmental costs without sacrificing output by using sustainable techniques including integrated fertiliser management, water-efficient irrigation, with diverse cropping systems.

C. CONSUMER CONSCIOUSNESS AND ACCOUNTABILITY

Consumers with knowledge are essential to changing food systems. Farmers' livelihoods and environmental preservation can be supported by a willingness to pay reasonable prices for food produced sustainably.

CONCLUSION

There is a significant hidden cost associated with cheap meals. Consumers confront long-term health and food security issues, ecosystems suffer from resource misuse and pollution, and farmers carry the financial burden due to low wages and high risks. The need to reconsider how food is priced, produced, and consumed is highlighted by the quiet crisis that exists between farmers and consumers.

Farmers must be acknowledged as important players rather than cost absorbers in a just and sustainable food system. True affordability should take into consideration nutritional security, environmental sustainability, and economic viability. The real cost of food can only be fairly balanced by shared responsibility among farmers, consumers, markets, and legislators.

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DRONES IN AGRICULTURE: PRECISION, MONITORING, AND MANAGEMENT

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ABSTRACT

The integration of drone technology into agriculture is transforming traditional farming into a data-driven and highly efficient system. Unmanned aerial vehicles (UAVs) enable real-time monitoring, precision input application, and improved resource management across diverse cropping systems. By capturing high-resolution imagery and field data, drones assist farmers in making informed decisions related to crop health, irrigation, nutrient management, and pest control. Their ability to perform targeted spraying and mapping reduces labour costs and enhances operational efficiency. As agriculture faces increasing challenges from climate variability and resource constraints, drones are emerging as vital tools for sustainable and precision farming.

KEYWORDS: Crop monitoring, Drones, Precision agriculture, Smart farming, UAV

INTRODUCTION

The rapid advancement of digital technologies has significantly reshaped agricultural practices, with drones emerging as one of the most impactful innovations in recent years. Also known as unmanned aerial vehicles (UAVs), drones are increasingly being deployed in agriculture to enhance productivity, efficiency, and sustainability. Their ability to collect high-resolution spatial and temporal data allows farmers to gain deeper insights into field variability and crop performance.

Unlike conventional methods, which often rely on manual observation and generalized input application, drone-based systems enable site-specific management. By operating at different altitudes and capturing real-time data, drones help optimize decisions related to sowing, irrigation, fertilization, and crop protection. As a result, they play a crucial role in precision agriculture, where inputs are applied based on the specific needs of crops and soil conditions. This technological shift is particularly important in the context of increasing food demand, climate change, and the need for efficient resource utilization.

MONITORING FIELD CONDITIONS

One of the primary applications of drones in agriculture is the assessment of field conditions. Equipped with advanced sensors and imaging systems, drones can generate detailed maps that provide valuable information about soil variability, topography, and crop distribution. Elevation mapping helps identify uneven terrain, waterlogging-prone areas, and zones with poor drainage, enabling farmers to take corrective measures.

In addition, multispectral and thermal sensors allow indirect assessment of soil properties, including moisture levels and nutrient status. By identifying variations in soil fertility, farmers can adopt site-specific nutrient management strategies, thereby improve input efficiency and reduce environmental impacts. Drones also help detect problem areas within fields, such as patches with poor crop growth, allowing timely interventions to enhance productivity.

PLANTING AND SEEDING APPLICATIONS

Drone technology is increasingly being explored for planting and seeding operations, particularly in challenging terrains and large-scale forestry projects. Automated drones can disperse seeds or seed pods with precision, ensuring uniform coverage and optimal spacing. This approach is especially beneficial in areas that are difficult to access using conventional machinery, such as hilly landscapes or degraded lands.

In forestry and ecological restoration programs, drone-based seeding has demonstrated remarkable efficiency. A coordinated fleet of drones can plant thousands of seeds within a short period, significantly reducing labour requirements and operational costs. Although still evolving, this application holds great promise for large-scale afforestation and reforestation initiatives, contributing to environmental sustainability and carbon sequestration.

SPRAY APPLICATION AND INPUT MANAGEMENT

The use of drones for spraying fertilizers, pesticides, and herbicides has gained considerable attention in recent years. Traditional spraying methods often involve manual labour or tractor-mounted equipment, which can be time-consuming, labour-intensive, and sometimes inefficient. In contrast, drone sprayers enable precise and uniform application of agrochemicals, ensuring that inputs are delivered exactly where needed.

Drones can be programmed to follow predefined flight paths, minimizing overlaps and reducing wastage. Their ability to operate at low altitudes allows for targeted spraying, which enhances the effectiveness of crop protection measures while reducing chemical usage. This not only lowers production costs but also minimizes environmental contamination and health risks to farm workers.

Furthermore, drone-based spraying is particularly advantageous in crops with dense canopies or in waterlogged fields where traditional machinery cannot operate effectively. By improving efficiency and precision, drones contribute to sustainable input management and better crop outcomes.

IRRIGATION MANAGEMENT

Efficient water management is a critical challenge in agriculture, especially under conditions of increasing water scarcity and climate variability. Drones offer innovative solutions for irrigation management by providing real-time information on soil moisture and crop water stress. Thermal imaging sensors can detect variations in canopy temperature, which are indicative of plant water status.

Based on this information, farmers can implement precise irrigation schedules, ensuring that water is applied only where and when it is needed. This approach helps conserve water resources, reduce energy consumption, and prevent issues such as over-irrigation and nutrient leaching.

In advanced systems, drones can be integrated with automated irrigation technologies, enabling dynamic adjustments in water application. Such smart irrigation practices are essential for enhancing water-use efficiency and ensuring the sustainability of agricultural systems in drought-prone regions.

MONITORING PLANT HEALTH

Crop health monitoring is one of the most significant advantages of drone technology. Equipped with high-resolution cameras and multispectral sensors, drones can capture detailed images that reveal subtle changes in plant physiology. Techniques such as the Normalized Difference Vegetation Index (NDVI) are widely used to assess vegetation health by analyzing differences in light reflectance.

These insights enable early detection of stress factors such as nutrient deficiencies, pest infestations, and disease outbreaks. Unlike traditional scouting methods, which are labour-intensive and often limited in scope, drones can cover large areas quickly and provide comprehensive data.

Early identification of problems allows farmers to take timely corrective actions, thereby minimizing yield losses and preventing the spread of pests and diseases. Additionally, drones can identify gaps in plant population or uneven crop growth, enabling replanting or targeted interventions to improve field uniformity.

ADVANTAGES AND FUTURE PROSPECTS

The adoption of drones in agriculture offers numerous benefits, including improved efficiency, reduced labour dependency, and enhanced decision-making capabilities. By providing accurate and timely data, drones enable farmers to optimize resource use and increase productivity. They also contribute to environmental sustainability by reducing the excessive use of water, fertilizers, and pesticides.

As technology continues to advance, drones are becoming more affordable and accessible to farmers of different scales. Integration with artificial intelligence, machine learning, and geographic information systems (GIS) is expected to further enhance their capabilities. These advancements will enable predictive analytics, automated decision-making, and more precise farm management practices.

However, challenges such as regulatory restrictions, technical expertise, and initial investment costs need to be addressed to ensure widespread adoption. Training programs and supportive policies can play a crucial role in overcoming these barriers and promoting the use of drone technology in agriculture.

CONCLUSION

Drone technology is revolutionizing agriculture by introducing innovative solutions to longstanding challenges. From field monitoring and crop health assessment to precision spraying and irrigation management, drones are enhancing efficiency and productivity across farming systems. Their ability to provide real-time, high-resolution data empowers farmers to make informed decisions and adopt site-specific management practices.

As agriculture moves towards sustainability and climate resilience, the role of drones is expected to become increasingly significant. With continued advancements and supportive policies, drones will not only improve farm profitability but also contribute to resource conservation and environmental protection. Embracing this technology is essential for the future of modern, precision-based agriculture.

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PLANT MICROBIOMES AND CLIMATE RESILIENCE

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ABSTRACT

Plant microbiomes, comprising diverse communities of bacteria, fungi, and archaea, play a vital role in enhancing plant resilience under changing climatic conditions. These microorganisms, particularly in the rhizosphere, form mutualistic associations with plants and contribute to nutrient acquisition, hormonal regulation, and stress mitigation. Climate change, characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme events, significantly influences plant–microbe interactions. Understanding these dynamic relationships is essential for developing climate-resilient agricultural systems. Advances in microbiome research, including microbial consortia design and metagenomics, offer promising strategies for sustainable crop production under environmental stress.

KEYWORDS: Abiotic stress, Climate resilience, Plant microbiome, Rhizosphere, Sustainable agriculture

INTRODUCTION

Plants do not exist in isolation but interact continuously with complex microbial communities that inhabit their immediate environment. These communities, collectively referred to as the plant microbiome, include bacteria, fungi, and archaea that colonize plant surfaces and the rhizosphere. Among these, rhizosphere microorganisms are particularly significant due to their close association with plant roots and their direct influence on plant growth and health.

In recent years, plant microbiomes have gained considerable attention for their role in enhancing plant tolerance to abiotic stresses such as drought, salinity, and temperature extremes. As climate change intensifies these stresses, understanding plant–microbe interactions has become increasingly important for ensuring food security and sustainable agricultural production. These microbial communities function as an extension of the plant system, contributing to nutrient cycling, stress tolerance, and overall plant resilience.

ROLE OF PLANT MICROBIOMES IN ENHANCING STRESS TOLERANCE

Plant-associated microorganisms contribute significantly to plant adaptation under adverse environmental conditions. In the rhizosphere, plants release root exudates comprising sugars, amino acids, and organic acids—that serve as energy sources for microbial communities. In return, these microorganisms establish mutualistic relationships that benefit plant growth and survival.

One of the primary mechanisms through which microbiomes enhance plant resilience is improved nutrient acquisition. Under stress conditions, nutrient availability often becomes limited due to reduced soil moisture or altered soil chemistry. Beneficial microbes facilitate nutrient solubilization and mobilization, thereby improving plant access to essential nutrients.

Microbial communities also regulate plant hormonal pathways, which are crucial for stress adaptation. For instance, abscisic acid (ABA), a key stress hormone, plays an essential role in regulating stomatal closure during drought conditions. Certain microbes can influence ABA synthesis and signalling, thereby enhancing plant water-use efficiency. Additionally, microorganisms produce secondary metabolites such as osmoprotectants and antioxidants that help plants cope with stress-induced damage.

Another important contribution of microbiomes is the induction of systemic tolerance. Rather than confining their effects to localized regions, beneficial microbes can trigger whole-plant responses that improve resilience across different tissues. Furthermore, rhizosphere microorganisms enhance root architecture by promoting the formation of lateral roots and root hairs, which increases the plant's ability to absorb water and nutrients under stress conditions.

Beyond direct plant interactions, microbial activity also improves soil health by enhancing soil structure, organic matter content, and nutrient cycling. These indirect effects further contribute to plant growth and resilience in challenging environments (Trivedi et al., 2022).

CLIMATE CHANGE AND ITS IMPACT ON PLANT–MICROBE INTERACTIONS

Climate change is significantly altering the dynamics of plant–microbe interactions. Rising temperatures, shifting precipitation patterns, and increased frequency of extreme weather events are influencing both plant physiology and microbial community structure. As a result, the stability and functionality of plant-associated microbiomes are being affected (Muhammad et al., 2025).

Temperature is a major factor influencing microbial diversity and activity. Warmer conditions tend to favor heat-tolerant microbial species while suppressing those sensitive to temperature fluctuations. This shift can disrupt microbial diversity and reduce the availability of essential ecosystem services such as nutrient cycling and disease suppression.

Changes in rainfall patterns also play a crucial role in shaping microbial communities. Extended dry periods can reduce microbial activity, whereas excessive rainfall may lead to oxygen depletion in soils, negatively affecting aerobic microorganisms. Such fluctuations influence microbial growth rates, metabolic activity, and the production of secondary metabolites. Consequently, the balance between beneficial and harmful microorganisms in the rhizosphere may shift, potentially affecting plant health (Ullah et al., 2025).

Another important aspect is the alteration of root exudation patterns under climate stress. Plants often modify the composition and quantity of root exudates in response to environmental changes. These exudates act as chemical signals that influence microbial recruitment and community composition. As a result, climate-induced changes in plant physiology can indirectly reshape the rhizosphere microbiome.

These interactions highlight the complex and dynamic nature of plant–microbe relationships under climate change, emphasizing the need for a deeper understanding of their ecological and functional implications (Afkhami et al., 2026).

MICROBIOME-MEDIATED MECHANISMS OF CLIMATE RESILIENCE

The ability of plant microbiomes to enhance climate resilience is based on multiple interconnected mechanisms. One of the most critical functions is the improvement of nutrient uptake efficiency. Under stress conditions, root function is often compromised, limiting nutrient absorption. Microbial symbionts compensate for this limitation by facilitating nutrient acquisition and transport.

Microorganisms also play a key role in regulating plant stress hormones. By modulating hormonal pathways, particularly those involving ABA, they help plants maintain water balance and adapt to drought conditions. Additionally, microbes produce osmoprotectants such as trehalose and proline-like compounds, which protect plant cells from dehydration and osmotic stress.

Another important mechanism is the enhancement of antioxidant defense systems. Under abiotic stress, plants generate reactive oxygen species (ROS), which can cause cellular damage. Beneficial microbes stimulate the production of antioxidant enzymes that neutralize ROS, thereby protecting plant tissues.

Furthermore, microbial communities contribute to improved root development, enabling plants to explore a larger soil volume for water and nutrients. This is particularly advantageous in arid and semi-arid regions where resource availability is limited. Collectively, these mechanisms demonstrate the crucial role of microbiomes in supporting plant adaptation to climate stress.

RISKS AND CHALLENGES UNDER CHANGING CLIMATE

While plant microbiomes offer significant benefits, climate change also introduces risks that can disrupt these interactions. Extreme weather conditions, such as prolonged droughts or excessive rainfall, can alter microbial community composition and reduce the abundance of beneficial microorganisms.

In some cases, these changes may favor opportunistic pathogens, leading to increased disease incidence and reduced crop productivity. The delicate balance between beneficial and harmful microbes is therefore at risk under changing environmental conditions.

Another challenge lies in the variability of field conditions. Microbial inoculants that perform well under controlled conditions may not always function effectively in diverse agricultural environments. Factors such as soil type, climate, and crop species influence microbial survival and activity, making it difficult to ensure consistent results.

Addressing these challenges requires a comprehensive understanding of microbial ecology and the development of robust strategies for microbiome management.

FUTURE PERSPECTIVES AND EMERGING APPROACHES

Recent advances in microbiome research are opening new avenues for enhancing climate resilience in agriculture. One promising approach is the development of synthetic microbial communities (SynComs), which are carefully designed consortia of beneficial microorganisms with complementary functions.

Metagenomic and genomic tools are being used to identify stress-resilient microbial strains and understand their functional roles in plant systems. These insights enable the selection and optimization of microbial inoculants for specific environmental conditions.

In addition, emerging technologies such as gene editing and precision microbiome engineering are being explored to enhance beneficial traits in microorganisms. These approaches aim to create stable and efficient microbiome solutions that can perform reliably under field conditions.

The integration of microbiome-based strategies with other climate-smart agricultural practices has the potential to reduce dependence on chemical inputs while improving crop productivity and sustainability (Fadiji et al., 2025).

CONCLUSION

Plant microbiomes represent a critical component of climate-resilient agriculture. Through their roles in nutrient acquisition, hormonal regulation, and stress mitigation, these microbial communities enhance plant adaptability to adverse environmental conditions. However, climate change poses significant challenges by altering microbial diversity and disrupting plant–microbe interactions. Future research should focus on understanding these complex interactions and developing innovative strategies for microbiome management. By harnessing the potential of beneficial microorganisms, it is possible to build sustainable agricultural systems capable of withstanding the impacts of climate change while ensuring food security.

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HIGH-DENSITY PLANTING SYSTEM (HDPS) FOR TRANSFORMING COTTON CULTIVATION IN INDIA

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ABSTRACT

The High-Density Planting System (HDPS) represents a significant advancement in cotton cultivation in India, aimed at improving productivity and sustainability. This system involves cultivating early-maturing, compact cotton hybrids at closer spacing, thereby increasing plant population per unit area. HDPS has demonstrated yield advantages of 30–40% in several cotton-growing states while reducing labour dependency and enabling mechanization. The approach integrates improved agronomic practices, including nutrient management, canopy regulation, and pest control. By enhancing resource-use efficiency and supporting rainfed agriculture, HDPS offers a viable pathway to strengthen farmer livelihoods and boost India's competitiveness in the global cotton sector.

KEYWORDS: Bt cotton, Cotton productivity, HDPS, Precision farming, Sustainable agriculture

INTRODUCTION

Cotton is one of the most important fibre and cash crops in India, playing a crucial role in the global textile industry and supporting the livelihoods of millions of farmers. India contributes approximately 19.35% of global cotton production, with an estimated output of 294.25 lakh bales (about 5.0 million metric tonnes). Despite having the largest area under cotton cultivation—nearly 40% of the global acreage—India ranks relatively low in productivity (Ministry of Textiles, 2025). This disparity highlights the urgent need for innovative production strategies that can enhance yield while ensuring sustainability.

The High-Density Planting System (HDPS) has emerged as a promising solution to address these challenges. By optimizing plant population, utilizing compact hybrids, and adopting improved crop management practices, HDPS aims to increase productivity, reduce labour requirements, and improve resource-use efficiency. This system is particularly relevant under rainfed conditions, where variability in rainfall and limited resources often constrain yields.

CONCEPT OF HDPS

The High-Density Planting System (HDPS) is an advanced agronomic approach in which cotton is cultivated at a higher plant population using narrow row spacing and compact plant architecture. Unlike conventional cotton cultivation, which typically accommodates 7,000–8,000 plants per acre with wider spacing, HDPS increases plant density to approximately 21,000–22,000 plants per acre through closer spacing arrangements.

This system relies on early-maturing, semi-compact cultivars characterized by shorter plant height, reduced leaf size, and a pyramidal canopy structure. Such traits allow better light interception, improved resource utilization, and suitability for mechanical harvesting. Growth regulators such as mepiquat chloride are often used to manage plant height and prevent excessive vegetative growth.

HDPS is particularly suitable for rainfed regions, where optimal plant population helps maximize yield under limited moisture conditions (Dandu et al., 2025; Ingle et al., 2024). The adoption of spacing such as 90 × 15 cm or 90 × 30 cm depends on soil depth and moisture availability, ensuring flexibility across diverse agro-ecological conditions.

SELECTION OF SUITABLE CULTIVARS

The success of HDPS largely depends on the selection of appropriate cotton cultivars. Ideal varieties should possess traits such as compact growth habit, short fruiting branches, and high boll retention at the first fruiting position. Early maturity and synchronous boll development are also desirable to facilitate uniform harvesting.

In addition, cultivars suitable for HDPS should have larger boll size (greater than 4 g), small leaves, and tolerance to major pests and diseases. Resistance to sucking pests is particularly important, as dense planting can create favourable conditions for pest proliferation.

Several Bt cotton hybrids have been developed specifically for HDPS, including those released under coordinated research programs. Private sector initiatives, such as the development of hybrids by seed companies in collaboration with research institutions, have further accelerated the adoption of HDPS in states like Maharashtra, Gujarat, Telangana, and Tamil Nadu (CICR, 2025).

Table 1. Cotton varieties and *Bt* hybrids released for HDPS (Source: Central Institute of Cotton research, Regional Station, Coimbatore).

Name	**Year**	**Type**	**Institution**	**Bt/Non-Bt**	**Suitable Regions & Soil Types**	**Remarks**
F 2383	2016	State	PAU, Faridkot	Non-Bt	Punjab; suitable for medium to deep loamy soils under irrigated conditions.	Compact plant type; suitable for HDPS.
CSH 3075	2017	Central	CICR, Sirsa	Not specified	North Zone (Punjab, Haryana, Rajasthan); adaptable to sandy loam to loamy soils under irrigated conditions.	Tolerant to major biotic stresses; suitable for HDPS with a yield potential of 25 q/ha.
Cotton CO 15 (TCH 1705)	2018	Central	TNAU, Coimbatore	Not specified	Tamil Nadu; thrives in black cotton soils under both rainfed and irrigated conditions.	Developed for high-density systems; semi-compact growth habit.
F 2381	2016	Central	PAU, Faridkot	Not specified	Punjab; suitable for medium to deep loamy soils under irrigated conditions.	Early maturing variety; potential for HDPS.
ARBC 19	2016	Central	UAS, Dharwad	Not specified	Karnataka; adaptable to red loamy soils under rainfed conditions.	Compact plant type; suitable for HDPS.
CO 17	2020	State	TNAU, Coimbatore	Not specified	Tamil Nadu (Perambalur, Ariyalur districts); performs well in black cotton soils	Short duration (125-130 days); high yielding; suitable for HDPS and mechanical harvesting.

					under rainfed conditions.	
RS 2818	2020	Central	SKRAU, Sriganganagar	Not specified	North-West Rajasthan; thrives in sandy loam soils under irrigated conditions.	Suitable for HDPS; consistent yield performance.
ARBC 1601	2020	Central	UAS, Dharwad	Not specified	Karnataka; adaptable to red loamy soils under rainfed conditions.	Compact growth habit; suitable for HDPS.
ARBC 1651	2020	Central	UAS, Dharwad	Not specified	Karnataka; suitable for red loamy soils under rainfed conditions.	Compact plant type; suitable for HDPS.
DSC 1651	2020	Central	UAS, Dharwad	Not specified	Karnataka; adaptable to red loamy soils under rainfed conditions.	Possibly similar to ARBC 1651; suitable for HDPS.
PKV 081-Bt	-	-	ICAR-CICR	Bt	Maharashtra; performs well in shallow to medium black soils under rainfed conditions.	Compact Bt variety; suitable for HDPS.
Suraj Bt	-	-	ICAR-CICR	Bt	Maharashtra; adaptable to shallow to medium black soils under rainfed conditions.	Compact Bt variety; suitable for HDPS.
Rajat Bt	-	-	ICAR-CICR	Bt	Maharashtra; thrives in shallow to medium black	Compact Bt variety; suitable for HDPS.

					soils under rainfed conditions.	
GJHV 374 Bt	-	-	ICAR-CICR	Bt	Maharashtra; suitable for shallow to medium black soils under rainfed conditions.	Compact Bt variety; suitable for HDPS.
CICR- H Bt Cotton 63 (Samrat Bt / CICR-183059-2)	2022	-	ICAR-CICR	Bt	Rainfed conditions of South Zone (Karnataka, Tamil Nadu, Andhra Pradesh and Telangana)	Early maturing, medium staple Bt cotton variety amenable for HDPS (Average Yield – 13.73 q/ha; Potential yield -24.14 q/ha)
CICR- H Bt Cotton 62 (Namami Bt / CICR 19-32 Bt)	2022	-	ICAR-CICR	Bt	Rainfed conditions of Central Zone (Maharashtra, Madhya Pradesh and Gujarat)	Early maturing, medium staple Bt cotton variety amenable for HDPS (Average Yield – 11.49 q/ha; Potential yield – 20.72 q/ha)
CICR- H Bt Cotton 61 (Tejas Bt / Bt - 183059-4)	2022		ICAR-CICR	Bt	Rainfed conditions of Central Zone (Maharashtra, Madhya Pradesh and Gujarat)	Early maturing, medium staple *Bt* cotton variety amenable for HDPS (Average Yield- 11.63 q/ha; Potential yield – 20.5 q/ha)
CICR- H Bt Cotton 60 (Yugank Bt / CICR-183059- 5)	2022		ICAR-CICR	Bt	Rainfed conditions of Central Zone (Maharashtra, Madhya Pradesh and Gujarat)	Early maturing, medium staple *Bt* cotton variety amenable for high density planting (Average Yield – 12.65 q/ha; Potential yield – 22.1 q/ha)

LAND PREPARATION, SOWING, AND NUTRIENT MANAGEMENT

Proper land preparation is essential for successful HDPS cultivation. Deep ploughing is recommended periodically to improve soil structure, followed by harrowing and incorporation of organic manures such as farmyard manure. A well-prepared seedbed ensures uniform germination and crop establishment.

Timely sowing is critical, with the optimal window in central and southern India generally falling between mid and late June. Precision sowing using manual methods or pneumatic planters ensures accurate spacing and depth, which are crucial for maintaining the desired plant population.

Nutrient management in HDPS requires a balanced and split application approach. A recommended fertilizer dose of nitrogen, phosphorus, and potassium is applied in stages to match crop demand at different growth phases. Micronutrients such as zinc and boron are also included to support plant growth and boll development. Foliar nutrition may be used under stress conditions or high yield potential situations to enhance productivity.

A field view of cotton crop

CANOPY AND WATER MANAGEMENT

Canopy management plays a vital role in HDPS due to the increased plant density. The use of plant growth regulators, particularly mepiquat chloride, helps control plant height, reduce internodal length, and improve boll retention. Proper canopy architecture ensures better light penetration and reduces the risk of pest and disease incidence.

Water management is equally important, especially under rainfed conditions. Practices such as earthing up, furrow opening, and moisture conservation techniques help maintain soil moisture and improve water-use efficiency. In irrigated systems, controlled irrigation can further enhance crop performance and support higher yields.

WEED MANAGEMENT

Weed control is critical during the early stages of crop growth in HDPS. The rapid canopy closure associated with high plant density helps suppress weed growth at later stages. Pre-emergence application of herbicides such as pendimethalin effectively controls weeds during the initial growth period.

Subsequent weed management includes mechanical methods such as hoeing and hand weeding, along with post-emergence herbicides targeting specific weed types. Integrated weed management ensures minimal competition for nutrients, water, and light, thereby supporting optimal crop growth.

INSECT PEST MANAGEMENT

Pest management is a key component of HDPS due to the dense canopy, which can favour pest multiplication. An integrated pest management approach is essential for maintaining crop health and productivity.

Monitoring tools such as pheromone traps are used to detect pest populations, particularly pink bollworm. Biological control measures, including the release of beneficial insects, complement chemical control strategies. Neem-based products and selective insecticides are applied based on economic threshold levels to minimize damage while reducing environmental impact.

Timely management of sucking pests, bollworms, and whiteflies is crucial to prevent yield losses. The adoption of IPM practices ensures sustainable pest control and reduces reliance on chemical pesticides.

ADVANTAGES OF HDPS

The High-Density Planting System offers several advantages over conventional cotton cultivation. It significantly increases productivity, with yield gains of 20–40% reported in various regions, particularly under rainfed conditions (CICR, 2025). The system also enables early crop maturity, reducing exposure to late-season pest infestations such as pink bollworm.

HDPS supports mechanization, including machine harvesting, which addresses labour shortages and reduces production costs. Improved resource-use efficiency, including better utilization of nutrients and water, contributes to sustainability. Additionally, the system allows for crop diversification, as early harvest enables the cultivation of subsequent crops in the same field.

The incorporation of crop residues into the soil further enhances soil health, improves organic matter content, and supports long-term productivity.

ADOPTION AND IMPACT IN INDIA

The adoption of HDPS in India has gained momentum in recent years, particularly in states such as Maharashtra, Andhra Pradesh, Gujarat, Karnataka, Telangana, and Tamil Nadu. Collaborative efforts involving research institutions, extension agencies, and private sector organizations have played a crucial role in promoting this technology.

Initiatives such as farmer demonstrations and training programs have helped build awareness and confidence among farmers. Reports indicate substantial improvements in yield and profitability, making HDPS an attractive option for cotton growers. The system aligns with national goals of enhancing agricultural productivity and strengthening the textile sector.

CONCLUSION

The High-Density Planting System represents a transformative approach to cotton cultivation in India, addressing key challenges of low productivity, labour scarcity, and resource inefficiency. By increasing plant density and adopting improved agronomic practices, HDPS enables farmers to achieve higher yields and better economic returns. Its compatibility with mechanization, suitability for rainfed conditions, and contribution to sustainable farming make it a promising strategy for the future. As adoption expands and technological innovations continue, HDPS has the potential to significantly enhance India’s position in the global cotton market. Ultimately, this system not only improves farm-level productivity but also supports the broader goals of agricultural sustainability and economic development.

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NON-CODING RNA BASED GENE REGULATION IN PLANT ABIOTIC STRESS TOLERANCE

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ABSTRACT

Plants are continuously exposed to abiotic stresses such as drought, salinity, heat, and nutrient deficiency, which significantly affect growth and productivity. Unlike mobile organisms, plants rely on intricate molecular regulatory systems to adapt and survive. Recent advances in plant genomics have revealed that non-coding RNAs (ncRNAs), which do not encode proteins, play a crucial role in regulating gene expression under stress conditions. These molecules, including microRNAs, small interfering RNAs, long non-coding RNAs, and circular RNAs, act at transcriptional and post-transcriptional levels to fine-tune stress-responsive pathways. Understanding ncRNA-mediated regulation provides new opportunities for developing climate-resilient crops through advanced biotechnological interventions.

KEYWORDS: Abiotic stress, Gene regulation, lncRNA, miRNA, Non-coding RNA

INTRODUCTION

Agricultural productivity is increasingly threatened by abiotic stresses such as drought, salinity, extreme temperatures, and nutrient limitations. These stresses disrupt physiological and biochemical processes, ultimately reducing crop yield and quality. Since plants are sessile organisms, they have evolved highly sophisticated molecular mechanisms to perceive stress signals and initiate adaptive responses.

Traditionally, research in plant stress biology has focused on protein-coding genes; however, recent discoveries have highlighted the importance of non-coding regions of the genome. A substantial proportion of plant transcripts do not encode proteins but instead function as regulatory molecules. Among these, non-coding RNAs (ncRNAs) have emerged as key regulators of gene expression, modulating stress responses at multiple levels. Their ability to control complex gene networks makes them central players in plant adaptation to adverse environmental conditions.

NON-CODING RNAS: DEFINITION AND TYPES

Non-coding RNAs are RNA molecules that are transcribed from DNA but are not translated into proteins. Despite lacking coding potential, they regulate gene expression at transcriptional, post-transcriptional, and epigenetic levels. Based on their size and function, ncRNAs are broadly classified into several categories, including microRNAs (miRNAs), small interfering RNAs (siRNAs), long non-coding RNAs (lncRNAs), and circular RNAs (circRNAs).

These molecules act as molecular regulators that control when and how genes are expressed, enabling plants to respond rapidly and efficiently to environmental changes. Their regulatory roles are particularly critical under stress conditions, where precise modulation of gene expression determines plant survival and productivity.

CLASSES OF NON-CODING RNAS AND THEIR FUNCTIONS

MICRO RNAS (MIRNAS)

MicroRNAs are short RNA molecules, typically 21–24 nucleotides in length, that regulate gene expression by binding to complementary sequences in messenger RNAs (mRNAs). This interaction leads to mRNA degradation or inhibition of translation, thereby reducing protein synthesis.

In plants, miRNAs are among the most extensively studied ncRNAs and are known to play critical roles in abiotic stress responses. Under conditions such as drought or salinity, specific miRNAs are either upregulated or downregulated, leading to the modulation of stress-responsive genes. Many miRNAs interact with hormone signaling pathways, particularly abscisic acid (ABA), which regulates stomatal closure and water balance. Additionally, miRNAs target transcription factors that control large gene networks, enabling coordinated stress responses at the cellular and whole-plant levels.

SMALL INTERFERING RNAS (SIRNAS)

Small interfering RNAs are another important class of regulatory RNAs that primarily function in gene silencing through RNA interference (RNAi). They are involved in RNA-directed DNA methylation and chromatin modification, leading to transcriptional gene silencing.

siRNAs play a significant role in epigenetic regulation, allowing plants to switch stress-related genes on or off depending on environmental conditions. This mechanism can also contribute to stress memory, where prior exposure to stress enhances the plant’s ability to respond to subsequent stress events. Such epigenetic modifications provide an additional layer of regulation that complements transcriptional and post-transcriptional control mechanisms.

LONG NON-CODING RNAS (LNCRNAS)

Long non-coding RNAs are transcripts longer than 200 nucleotides that exhibit diverse regulatory functions. Unlike miRNAs and siRNAs, lncRNAs act through multiple mechanisms, including serving as molecular scaffolds, guides, or decoys for proteins and other RNA molecules.

Recent studies have demonstrated that lncRNAs are actively involved in plant responses to abiotic stress by regulating gene expression, chromatin structure, and hormone signaling pathways. They can modulate antioxidant defense systems, transcriptional activity, and metabolic processes, thereby enhancing stress tolerance. The functional diversity of lncRNAs makes them key components of complex regulatory networks in plants (Huang et al., 2023; Yang et al., 2023).

Furthermore, lncRNAs have been implicated in chromatin remodeling and three-dimensional genome organization, influencing gene accessibility and expression patterns under stress conditions (Feuerstein et al., 2025; Chanwala et al., 2026).

CIRCULAR RNAS (CIRCRNAS)

Circular RNAs are a relatively recent addition to the family of ncRNAs and are characterized by their covalently closed loop structure, which confers high stability. One of their primary functions is to act as “miRNA sponges,” binding to miRNAs and preventing them from interacting with their target mRNAs.

Through this mechanism, circRNAs indirectly regulate gene expression and contribute to the formation of complex regulatory networks. Their stability and regulatory potential make them important players in stress adaptation, although their roles in plants are still being actively explored.

ROLE OF NCRNAS IN ABIOTIC STRESS TOLERANCE

Abiotic stresses negatively affect plant growth by disrupting water relations, nutrient uptake, photosynthesis, and cellular homeostasis. Non-coding RNAs play a central role in mitigating these effects by regulating key physiological and biochemical processes.

For instance, ncRNAs influence root architecture, enabling plants to explore soil more efficiently for water and nutrients under stress conditions. They also regulate stomatal behavior, helping to control water loss during drought. Additionally, ncRNAs modulate osmotic adjustment and antioxidant defense systems, which protect cells from oxidative damage caused by stress.

Another important aspect of ncRNA function is their involvement in coordinating large gene networks. By targeting transcription factors and signaling pathways, ncRNAs enable plants to mount a rapid and integrated response to environmental challenges. This coordinated regulation is essential for maintaining growth and productivity under stress conditions.

TECHNOLOGICAL ADVANCES AND APPLICATIONS

The study of ncRNAs has been greatly facilitated by advances in high-throughput sequencing technologies such as RNA sequencing (RNA-seq), small RNA profiling, and degradome analysis. These tools allow researchers to identify stress-responsive ncRNAs and map their target interactions with high precision.

The integration of multi-omics approaches, including genomics, transcriptomics, and epigenomics, has further enhanced our understanding of ncRNA-mediated regulatory networks. These insights are now being translated into practical applications in crop improvement.

Biotechnological tools such as CRISPR/Cas systems enable precise editing of ncRNA genes, their regulatory elements, or target sites in mRNAs. Additionally, artificial miRNAs and RNA interference strategies can be designed to modulate specific stress-response pathways. These approaches offer significant advantages, as targeting a single ncRNA can influence multiple downstream genes, resulting in more robust and coordinated stress tolerance.

FUTURE PROSPECTS

As climate change continues to intensify environmental stresses, the importance of developing resilient crop varieties cannot be overstated. Non-coding RNA–based regulatory mechanisms provide a promising avenue for achieving this goal.

Future research should focus on integrating ncRNA studies with systems biology approaches to better understand their roles in complex stress responses. The development of advanced bioinformatics tools and databases will further facilitate the identification and functional characterization of ncRNAs.

Moreover, translating laboratory findings into field applications remains a critical challenge. Efforts should be directed toward developing ncRNA-based technologies that are cost-effective, scalable, and suitable for diverse agricultural systems. Harnessing the regulatory potential of ncRNAs will play a pivotal role in ensuring sustainable agriculture and global food security in the face of climate change.

CONCLUSION

Non-coding RNAs have emerged as key regulators of gene expression in plants, particularly under abiotic stress conditions. Through their diverse mechanisms of action, including post-transcriptional regulation, epigenetic modification, and interaction with other regulatory molecules, ncRNAs enable plants to adapt to challenging environments. Their ability to control complex gene networks makes them valuable targets for crop improvement strategies aimed at enhancing stress tolerance and productivity. With ongoing advancements in molecular biology and biotechnology, ncRNA-based approaches are expected to play a central role in the development of climate-resilient crops, contributing to sustainable agricultural systems and long-term food security.

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SOIL ORGANIC CARBON, NITROGEN DYNAMICS AND GREENHOUSE GAS EMISSIONS

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ABSTRACT

Soil organic carbon (SOC) and nitrogen (N) are key components of soil fertility and play a central role in regulating greenhouse gas (GHG) emissions. Their interaction controls microbial activity, nutrient availability, and the release of gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). This article explains the relationship between SOC and nitrogen in simple yet scientific terms, highlighting how soil processes influence climate change. It also discusses practical management strategies that help improve soil health while reducing emissions, making agriculture more sustainable and climate-resilient.

KEYWORDS: C:N ratio, Climate-smart agriculture, Greenhouse gases, Nitrogen cycle, Soil organic carbon

INTRODUCTION

Soil is not just a medium for plant growth; it is a living system where carbon and nitrogen continuously interact. These two elements are essential for plant nutrition and also play a major role in environmental sustainability. Soil organic carbon (SOC) comes mainly from plant residues, roots, and microbial biomass, while nitrogen is a key nutrient required for plant growth.

The interaction between SOC and nitrogen determines how nutrients are released, how efficiently plants grow, and how much greenhouse gases are emitted from the soil. Poor management of these elements—such as excessive fertilizer use or intensive tillage—can lead to increased emissions of greenhouse gases, contributing to climate change. Therefore, understanding this relationship is important not only for farmers but also for environmental protection.

UNDERSTANDING SOIL ORGANIC CARBON

SOC represents the carbon stored in soil organic matter. It plays multiple roles in improving soil health:

- Enhances soil structure and aggregation
- Improves water holding capacity
- Supports beneficial microorganisms
- Acts as a reservoir of nutrients

When organic materials such as crop residues or manure are added to soil, microorganisms decompose them. During this process, some carbon is released as carbon dioxide (CO_2), while some is stored in the soil for longer periods.

If soils are disturbed frequently (e.g., through excessive tillage), decomposition increases, leading to higher CO_2 emissions. On the other hand, conservation practices help retain carbon in soil, reducing emissions and improving fertility.

NITROGEN DYNAMICS IN SOIL

Nitrogen exists in both organic and inorganic forms in soil. Plants mainly absorb nitrogen as nitrate (NO_3^-) or ammonium (NH_4^+). However, nitrogen is constantly transformed through microbial processes:

- **Mineralization**: Conversion of organic N into plant-available forms
- **Immobilization**: Temporary locking of nitrogen in microbial biomass
- **Nitrification**: Conversion of ammonium to nitrate
- **Denitrification**: Conversion of nitrate to gases like N_2O

These processes are strongly influenced by the availability of SOC, as microorganisms require carbon as an energy source to carry out these transformations.

CARBON–NITROGEN RELATIONSHIP (C: N RATIO)

The relationship between carbon and nitrogen is commonly expressed as the C:N ratio, which determines how quickly organic matter decomposes and how nutrients are released.

- **High C:N ratio (e.g., straw):**
  - ✓ Slow decomposition
  - ✓ Nitrogen is temporarily unavailable (immobilization)
- **Low C:N ratio (e.g., legumes, manure):**
  - ✓ Fast decomposition
  - ✓ Nitrogen is released quickly (mineralization)

An ideal soil C:N ratio (around 10–12:1) ensures balanced nutrient cycling, efficient microbial activity, and better plant growth.

LINK BETWEEN SOC, NITROGEN AND GREENHOUSE GASES

1. Carbon Dioxide (CO_2) Emissions

CO_2 is released during the decomposition of organic matter. When SOC levels are high and soils are frequently disturbed, microbial activity increases, leading to higher CO_2 emissions.

However, practices like reduced tillage and organic amendments help store carbon in soil, reducing CO_2 release.

2. Nitrous Oxide (N_2O) Emissions

Nitrous oxide is one of the most potent greenhouse gases. It is mainly produced during nitrification and denitrification processes.

- Excess nitrogen fertilizer → higher N_2O emissions
- Wet or poorly aerated soils → increased denitrification

SOC plays an indirect role by supplying energy to microbes that produce N_2O. Thus, both carbon and nitrogen together control N_2O emissions.

3. Methane (CH_4) Emissions and Soil Conditions

Methane (CH_4) is mainly produced in waterlogged soils such as rice fields, where oxygen is limited. Under such conditions, special microorganisms called methanogens break down organic matter and release methane.

Higher SOC levels provide more food for these microbes, increasing methane production. At the same time, certain nitrogen fertilizers can reduce methane consumption by soil microbes, allowing more methane to escape into the atmosphere.

Farmers can reduce methane emissions through simple practices such as:

- Alternate wetting and drying (AWD) in rice fields
- Avoiding excess fresh organic residues under flooded conditions
- Improving drainage to increase soil aeration

ROLE OF MICROORGANISMS

Microorganisms are the key link between SOC, nitrogen, and greenhouse gas emissions. They use carbon as an energy source and nitrogen for growth.

- If carbon is high but nitrogen is low → microbes compete with plants for nitrogen
- If nitrogen is high → faster decomposition and more emissions

Efficient microbial activity helps:

- Store more carbon in soil
- Reduce nitrogen losses
- Improve soil fertility

Table 1: Relationship Between Soil Processes and Greenhouse Gas Emissions

Soil Process	**Role of SOC**	**Role of Nitrogen**	**Main Gas Emitted**
Decomposition	Provides energy to microbes	Releases N during breakdown	CO_2
Nitrification	Indirect support	Converts NH_4^+ to NO_3^-	N_2O
Denitrification	Provides carbon for microbes	Uses NO_3^- in low oxygen	N_2O
Methanogenesis	Substrate for microbes	Influences oxidation	CH_4

MANAGEMENT PRACTICES FOR REDUCING EMISSIONS

To maintain a balance between productivity and environmental sustainability, the following practices are recommended:

- ***Conservation tillage:*** Reduces CO_2 emissions and preserves SOC
- ***Balanced fertilization:*** Prevents excess nitrogen and lowers N_2O emissions
- ***Organic amendments:*** Improve SOC and nutrient retention
- ***Crop rotation with legumes:*** Enhances natural nitrogen supply
- ***Water management (AWD):*** Reduces methane emissions in rice systems

CONCLUSION

The relationship between soil organic carbon and nitrogen is fundamental to maintaining soil health and regulating climate, as their interaction governs microbial processes that influence nutrient availability and the emission of greenhouse gases. Effective management of these components can shift soils from being sources of greenhouse gases to functioning as carbon sinks. By implementing sustainable practices such as balanced fertilization, residue management, and conservation agriculture, farmers can enhance soil fertility while minimizing environmental impacts. Therefore, a clear understanding of this relationship is crucial for developing climate-smart agricultural systems that support food security and environmental sustainability.

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