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A STEP TOWARDS AGRICULTURE

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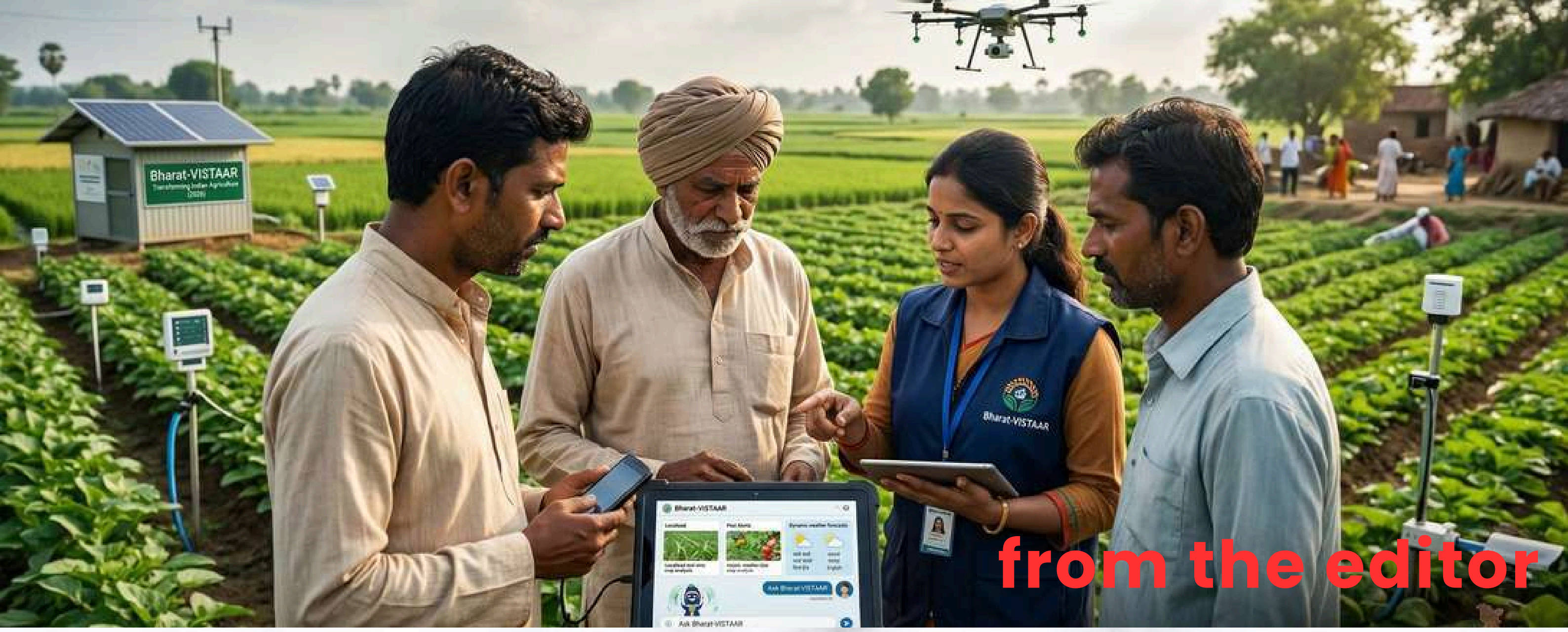

from the editor

Agricultural extension plays a vital role in bridging the gap between scientific research and farmers' fields. However, the traditional extension system often faces challenges in effectively reaching millions of smallholder farmers across diverse agro-ecological regions of India. In this context, the integration of artificial intelligence (AI) into agricultural advisory systems represents a major step toward strengthening the efficiency and accessibility of extension services.

The introduction of Bharat-VISTAAR (Virtually Integrated System to Access Agricultural Resources) in 2026 marks a significant advancement in India's digital agriculture initiatives. This AI-enabled platform integrates digital agricultural infrastructure, expert knowledge, and real-time data to deliver location-specific and personalized advisories to farmers. By utilizing information on weather, soil conditions, crop health, and market trends, the system aims to support farmers in making informed decisions regarding crop management, pest control, and resource utilization.

A key feature of Bharat-VISTAAR is its multilingual and user-friendly interface, which enhances accessibility for farmers from different linguistic and educational backgrounds. By combining AI-driven insights with established agricultural knowledge systems, the platform has the potential to modernize extension delivery and promote climate-resilient and sustainable agricultural practices.

As India advances toward a digitally empowered agricultural sector, initiatives such as Bharat-VISTAAR highlight the growing role of technology in strengthening farmer support systems and improving the overall efficiency of agricultural extension.

Dr. Deepak Kumar
FOUNDER & EDITOR

EXPLORING KNOWLEDGE & DISCOVERING AGRICULTURE

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Bharat-VISTAAR: Transforming Agricultural Extension through Artificial Intelligence in India (2026)

ARTICLE ID: 0338

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In 2026, the Government of India officially launched Bharat-VISTAAR (Virtually Integrated System to Access Agricultural Resources), a multilingual AI-powered advisory platform designed to provide real-time, personalized, and location-specific agricultural guidance to farmers (The Times of India, 2026; The Indian Express, 2026). Announced in the Union Budget 2026–27 and inaugurated on 17 February 2026 by the Union Minister of Agriculture and Farmers' Welfare, the platform aims to bring scientific advisories, weather alerts, market data, and government schemes into a single digital interface for farmers (The Times of India, 2026; The Indian Express, 2026).

The Need for Digital Transformation in Agricultural Extension

India's agricultural extension services—traditionally delivered through Krishi Vigyan Kendras (KVKs), field extension officers, and state agriculture departments—have struggled to meet the growing information demands of over 140 million farmers. Challenges such as delayed advisories, climate risks, pest outbreaks, and limited outreach to remote villages have constrained the impact of traditional extension systems (The Times of India, 2026).

Bharat-VISTAAR was introduced to overcome these constraints by leveraging artificial intelligence and integrated data sources, thereby strengthening the efficiency and reach of agricultural extension services.

What is Bharat-VISTAAR?

Bharat-VISTAAR is an AI-driven digital agriculture platform that integrates multiple government agricultural databases, scientific practice packages, and machine-learning models to provide tailored and actionable advice to farmers. It functions as a unified digital gateway for agricultural information, simplifying access to key resources that farmers previously had to obtain from multiple systems (The Indian Express, 2026).

Key Components Integrated

- AgriStack portals: Core digital ecosystem for farmer records, credit, inputs, and services (Moneycontrol, 2026).
- ICAR practices: Verified crop-specific guidance from the Indian Council of Agricultural Research.
- Weather data: Real-time forecasts from IMD APIs for sowing, irrigation, and climate-risk management (Skymet Weather, 2026).
- Market intelligence: Live mandi prices and advisories for better marketing decisions.
- Government schemes: Eligibility checks, applications, tracking, and grievance redressal integrated into a single platform (Mint, 2026).

Voice-Based AI Assistant “Bharati”

A key innovation of Bharat-VISTAAR is its voice-enabled AI assistant named “Bharati”, which allows farmers to interact with the platform using simple language through phone calls or digital interfaces (The Indian Express, 2026).

This feature is particularly beneficial for farmers with limited literacy and limited experience using smartphone applications (The Times of India, 2026).

Features and Innovations of Bharat-VISTAAR

AI Advisory Capabilities

The platform uses machine learning to analyze soil health, crop stages, climate data, and real-time inputs to generate personalized recommendations for sowing, pest control, fertilization, and irrigation. This approach goes beyond generic advisories and supports precision farming across diverse agro-climatic zones (Global Agriculture, 2026).

Multilingual Voice Access

Voice-based interactions in Hindi, English, and several regional languages allow farmers with low literacy levels to access advisories through toll-free calls (155261) or mobile applications using natural speech. This feature improves inclusivity by removing internet and smartphone barriers (ET Now Hindi, 2026).

Unified Services Hub

Farmers can access eligibility checks, applications, and tracking for government schemes such as PM-KISAN and crop insurance through a single interface. The system also provides grievance redressal and subsidy guidance.

Real-Time Intelligence

Integrated IMD weather APIs provide hyper-local forecasts, extreme weather alerts, and mandi price updates. These insights help farmers optimize planting, harvesting, and marketing decisions.

Open Innovation Platform

Designed as a plug-and-play digital public infrastructure, Bharat-VISTAAR provides APIs that allow agritech companies to build customized tools such as drone analytics, farm monitoring systems, and blockchain-based traceability solutions. The platform was piloted in Rajasthan for scalable implementation.

Integrated Agricultural Knowledge Base

By combining data from AgriStack, ICAR recommendations, soil health databases, and weather information, the platform ensures that advisory content remains scientifically validated and context-specific (Mint, 2026).

Implications for Agricultural Extension

Bharat-VISTAAR has the potential to revolutionize agricultural extension by digitizing and personalizing advisory services while supporting both farmers and extension workers.

Enhanced Decision-Making

Personalized advisories on sowing, irrigation, nutrient management, and crop protection help farmers make timely and science-based decisions, reducing dependency on intermediaries.

Improved Risk Management

Real-time alerts on weather fluctuations, pest outbreaks, and climate risks promote proactive adoption of climate-smart agricultural practices, minimizing crop losses.

Reduced Fragmentation

The platform consolidates weather data, market intelligence, government schemes, and ICAR recommendations in one place, simplifying access to information that was previously scattered across multiple portals.

Focus on Women Farmers

Bharat-VISTAAR has significant potential to support women farmers, who constitute nearly 75% of India's agricultural labor force but often face barriers in accessing extension services.

Addressing Access Barriers

Voice-enabled interactions allow women farmers to seek agricultural advice, market updates, and scheme information from home, overcoming literacy and mobility constraints (The Times of India, 2026).

Empowering Daily Operations

Real-time diagnostics, pest alerts, and price information enable women to manage crop production, livestock activities, and small enterprises more effectively.

Extension Impact

By expanding access to personalized information, the platform promotes climate-smart practices, financial inclusion, and economic empowerment among rural women.

Challenges and Considerations

Connectivity Gaps

Many rural areas still experience unreliable internet connectivity, which may limit access to real-time digital services. Strengthening initiatives such as BharatNet is essential for effective implementation.

Literacy and Digital Awareness

Limited familiarity with digital technologies, especially among elderly farmers and women, requires training programs and demonstrations through extension agencies.

Building Farmer Trust

Adoption may initially be slow due to skepticism toward AI-based recommendations. Demonstrations, field trials, and integration with Krishi Vigyan Kendras (KVKs) can help build credibility.

Data Privacy Concerns

Protection of farmer data stored within AgriStack requires strong governance frameworks, consent mechanisms, and transparent data policies.

Conclusion

Bharat-VISTAAR represents a significant step toward modernizing India's agricultural extension system through the integration of artificial intelligence and national agricultural databases. By delivering personalized, real-time, and data-driven advisories, the platform enhances farmers' decision-making capacity, productivity, and climate resilience.

Its multilingual and voice-enabled interface improves accessibility for smallholder and women farmers, fostering greater inclusion in the digital agricultural ecosystem. When effectively implemented and widely adopted, Bharat-VISTAAR has the potential to become a foundational pillar of India's digitally empowered and knowledge-driven agricultural sector.

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Bio-Herbicides: A Sustainable Pathway for Eco-Friendly Weed Management

ARTICLE ID: 0339

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Weeds are a persistent challenge in agriculture, competing fiercely with crops for sunlight, water, nutrients, and space. Traditional weed control has heavily relied on synthetic herbicides—chemicals designed to kill or suppress unwanted plants. While these products have contributed enormously to crop productivity, their long-term use has led to serious environmental, health, and ecological concerns. Problems such as herbicide-resistant weed populations, chemical residues in soil and water, and disruption of beneficial organisms have highlighted the need for greener alternatives. This is where bio-herbicides are emerging as an important tool for sustainable agriculture.

What are Bio-Herbicides?

Bio-herbicides are weed-control products derived from living organisms or natural compounds produced by plants, microbes, or their metabolites. Unlike synthetic herbicides, which are chemically manufactured, bio-herbicides work through natural biological processes to suppress weed growth.

They include:

- **Microbial Agents (Mycoherbicides and Bacterioherbicides)**: fungi or bacteria that infect or inhibit weeds, sometimes causing disease or growth suppression.
- **Plant-Based Products**: extracts, essential oils, or allelochemicals (natural biochemicals produced by plants to affect other plants).
- **Metabolite-Based Bio-Herbicides**: specific compounds produced by microbes or plants that are toxic to weeds.

Why Bio-Herbicides Matter for Sustainability

1. Reduced Environmental Impact

A key advantage of bio-herbicides is that they often leave little to no harmful residue in the environment, as they degrade relatively quickly and do not persist in soil or water like many synthetic chemicals. Their biological origin and limited environmental longevity help protect soil, waterways, and non-target organisms such as pollinators and soil microbes. In addition, plant extracts and allelochemicals derived from natural sources tend to be environmentally benign and less toxic to wildlife and humans. These traits make bio-herbicides attractive for use in organic and conservation-oriented farming systems.

2. Lower Risk of Resistance

One of the biggest challenges with synthetic herbicides is the rapid development of herbicide-resistant weed species. Repeated use of chemicals with the same mode of action selects for weeds that survive and proliferate despite treatment. Bio-herbicides often work through multiple physiological pathways, lowering the likelihood that weeds quickly adapt or develop resistance.

3. Integration with Integrated Weed Management (IWM)

Bio-herbicides are not a silver bullet but can play a valuable role within Integrated Weed Management (IWM) strategies—programs that combine cultural, mechanical, biological, and chemical methods to manage weeds sustainably. For example, using bio-herbicides alongside crop rotation, cover cropping, and selective synthetic herbicides can enhance overall weed control and reduce chemical dependency.

Types and Examples of Bio-Herbicides

Microbial Bio-Herbicides

Microbes such as fungi and bacteria can infect weeds or release phytotoxic substances that hinder weed growth. For example:

- ***Fusarium spp.*** : Certain fungal strains have been developed as bio-herbicides against specific weeds.
- ***Pseudomonas fluorescens***: Some strains have been tested for pre-emergent weed control by reducing weed seed emergence.

These agents act through mechanisms ranging from direct infection to toxin production, disrupting weed physiology without leaving harmful chemical residues.

Plant Extracts and Allelochemicals

Many plants naturally produce chemicals that inhibit the germination or growth of other plants—a phenomenon known as allelopathy**.** For instance:

- Sorghum extracts (Sorgoleone) have shown weed-suppressing effects when applied to soil.
- Essential oils from species such as Cistus ladanifer can inhibit weed seed germination.

These plant-derived bio-herbicides can be particularly useful in organic systems where synthetic chemicals are restricted or prohibited.

Challenges and Limitations

1. Efficacy and Consistency

Bio-herbicides often degrade quickly under natural conditions, reducing their persistence and efficacy compared with synthetic alternatives. Variations in environmental conditions such as temperature, humidity, and soil moisture can also affect their performance.

2. Formulation and Delivery

Producing stable and effective formulations that retain biological activity and can be applied easily remains a technical challenge. Advances in micro- and nano-encapsulation are being explored to improve stability and controlled release, but these approaches may increase complexity and cost.

3. Commercial Adoption

Only a limited number of bio-herbicide products are commercially available, and regulatory approval processes can be lengthy and costly. Scaling up production while ensuring quality and shelf life requires substantial investment and rigorous testing.

Looking Forward: The Future of Eco-Friendly Weed Control

Research on bio-herbicides continues to grow as scientists seek more sustainable weed management solutions that align with ecological and human health goals. Combining bio-herbicides with precision agriculture tools, improved formulation technologies, and integrated weed management strategies can enhance their role in modern farming. As global agriculture grapples with environmental challenges and rising food demands, bio-herbicides offer a viable complement to conventional herbicides—not as replacements but as part of a balanced, eco-friendly weed management toolkit.

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Determining Plant Pathogen Virulence Factors

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Plant pathogens such as fungi, bacteria, and oomycetes reduce host immunity, degrade plant cell walls, and alter plant physiology through various virulence factors, including effectors, toxins, and enzymes. Cell wall–degrading enzymes in fungi such as *Fusarium* spp. and type III secretion system effectors in bacteria such as *Pseudomonas syringae* are common examples. Understanding the function of these virulence factors facilitates the development of targeted biocontrol strategies and the breeding of resistant crop varieties.

Molecular approaches such as RNA sequencing (RNA-seq), proteomics, genomics, and metabolomics help identify potential virulence candidates by monitoring host responses during infection. Functional validation techniques, including CRISPR-Cas9 gene knockout and yeast two-hybrid assays, are commonly used to verify host targets and determine the role of virulence genes.

Understanding virulence factors in plant pathogens involves identifying molecular components such as effectors, toxins, enzymes, and adhesion proteins that enable pathogens to evade host defenses, colonize tissues, and cause disease symptoms. These virulence factors influence plant cellular processes including gene silencing, mitogen-activated protein kinase (MAPK) signaling, vesicle trafficking, and hormone regulation pathways. For example, bacterial type III effectors such as HopM1 from *Pseudomonas syringae* target ARF-GEF proteins like AtMIN7, interfering with immunity-related vesicle trafficking (Speth et al., 2007).

Virulence factors, which are often delivered through type III or type IV secretion systems in bacteria or through direct fungal hyphal invasion, allow pathogen attachment, penetration, nutrient acquisition, and suppression of basal plant defenses such as pathogen-associated molecular pattern (PAMP)-triggered immunity (PTI).

Quantitative real-time PCR (qRT-PCR) is one of the molecular tools used to identify virulence factors in plant pathogens. It amplifies and quantifies potential virulence genes, such as effector or toxin biosynthesis genes, from pathogen isolates during host–pathogen interactions (Van Doorn et al., 2007).

Gene knockout techniques such as CRISPR-Cas9 gene editing and RNA interference (RNAi) are used in model plants like *Arabidopsis* or *Nicotiana benthamiana* to disrupt virulence genes and evaluate their function in pathogenicity through reduced lesion formation or failure of host colonization.

Polymerase chain reaction (PCR) also enables direct detection of virulence genes such as hrp**,** pth**,** and vir genes from bacterial pathogens or effector genes in fungi without the need for culturing. Advanced variants including multiplex PCR, nested PCR, and real-time PCR allow simultaneous detection and quantification of multiple virulence factors from infected plant tissues. These approaches facilitate high-throughput screening for pathogens possessing specific virulence profiles using primers designed from known pathogenicity genes (Haas et al., 1995).

Bacterial Virulence Genes

The hrp (hypersensitive response and pathogenicity) gene cluster in bacteria such as *Xanthomonas oryzae* pv. *oryzae* can be amplified using specific primers such as DXoo_hrp1F and DXoo_hrp1R, producing a 384 bp product for sensitive detection down to 2.6×10^2 CFU ml^{-1} in rice seeds and leaves. Similarly, pathovar-specific primers are used to target pth genes in *Xanthomonas axonopodis* pv. *citri* and **vir** genes (e.g., *virD2*) in *Agrobacterium* spp. using quantitative real-time PCR to identify pathogenic strains and quantify infection levels.

Fungal Effector Genes

Fungal effector genes that enhance virulence by suppressing plant immunity can be detected even at low pathogen loads (1–100 cells) through PCR amplification of internal transcribed spacer (ITS) regions or specific effector gene sequences, often directly from infected tissue samples without culturing. In necrotrophic fungi, transcription factors such as PnPf2 regulate these effector genes, and PCR analysis confirms their expression during infection (Jones et al., 2019).

By systematically deleting genes in pathogens or host plants, CRISPR-Cas9 enables high-throughput genetic screening to identify genes essential for virulence by monitoring changes in infection outcomes.

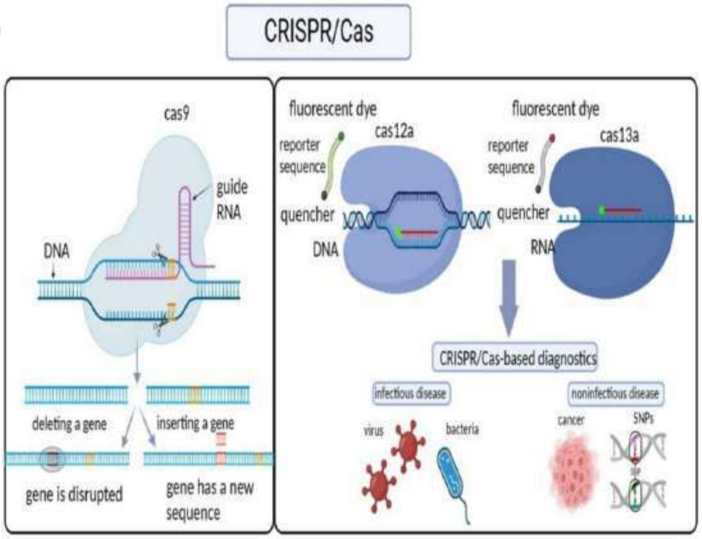

Figure 1: Illustration of CRISPR-Cas sensing mechanisms and their diagnostic applications (Source: Zeng et al., 2024).

Under the guidance of single-guide RNA (sgRNA), CRISPR-Cas9 generates double-strand breaks at specific genomic locations, resulting in insertions or deletions through non-homologous end joining. Editing virulence genes—such as those encoding effectors, toxins, or cell wall-degrading enzymes—produces mutants with reduced pathogenicity in plant pathogens including fungi and oomycetes. Phenotypic assays (e.g., lesion size on host plants) help determine gene function, while sequencing confirms successful genome editing (Dort et al., 2020).

RNA interference (RNAi) can also be applied through host-induced gene silencing (HIGS), where plants express hairpin RNA (hpRNA) that generates small interfering RNAs (siRNAs) targeting pathogen mRNAs. During haustorial invasion, these siRNAs enter the pathogen and degrade transcripts of virulence genes such as PtMAPK1 or PtCYC1 in *Puccinia triticina*, reducing their expression by 40–65%. This suppression results in slower fungal growth, fewer or smaller uredinia (lesions), and up to 79% reduction in fungal biomass in model systems (Panwar et al., 2018).

Importance of Determining Plant Pathogen Virulence Factors

Identifying virulence factors of plant pathogens is essential for understanding disease mechanisms and developing effective control strategies. These factors enable pathogens to infect, colonize, and damage host plants, ultimately affecting crop productivity and global food security.

Virulence factors such as effectors, toxins, and enzymes secreted by bacteria or fungi weaken plant defenses and facilitate disease development. Identifying these factors helps in targeted resistance breeding by revealing how pathogens manipulate host pathways such as vesicle trafficking or gene transcription.

Knowledge of these mechanisms also supports the development of targeted fungicides and genetically engineered resistant crop varieties, thereby reducing dependence on broad-spectrum pesticides that can harm ecosystems. Furthermore, studying virulence factors contributes to evolutionary research by helping predict changes in pathogen virulence and adaptation.

Conclusion

Identification of virulence factors in plant pathogens plays a crucial role in advancing disease management strategies in agriculture. Modern techniques such as genomics, metabolomics, and in-planta expression analysis have greatly enhanced the ability to detect and characterize these factors.

Understanding the complex interactions between pathogens and host plants enables the development of resistant crop varieties and innovative biocontrol strategies. Integration of CRISPR-Cas9 technology with multi-omics approaches will further help identify strain-specific virulence mechanisms and support the development of durable disease resistance. Applying this knowledge will be essential for combating emerging pathogen threats and promoting sustainable agriculture.

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From Photosynthesis to Phytochemicals: The Biochemical Machinery of Plants

ARTICLE ID: 0341

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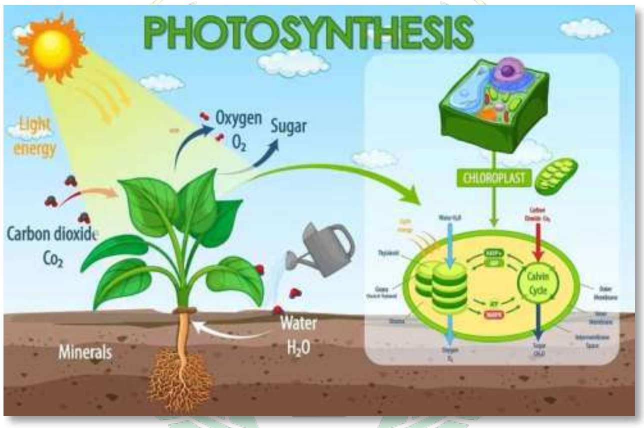
Plants are extraordinary biochemical factories. Unlike animals, they can harness light energy from the sun and convert it into chemical energy stored in organic compounds. This remarkable ability underpins life on Earth and forms the foundation of ecosystems, agriculture, and human nutrition. At the heart of this process lies plant biochemistry—the study of chemical processes within plants, covering everything from primary metabolism, such as photosynthesis, to the synthesis of complex secondary compounds known as phytochemicals.



These biochemical pathways not only sustain plant growth and survival but also yield compounds valuable to humans in medicine, nutrition, and industry.

Photosynthesis: The Core of Plant Biochemistry

Photosynthesis is the primary biochemical process through which plants convert light energy into chemical energy. This process occurs mainly in chloroplasts, specialized organelles containing light-absorbing pigments such as chlorophyll.

At its core, photosynthesis involves two major stages:

1. **Light-Dependent Reactions**: In this stage, light energy splits water molecules, releasing oxygen and generating energy-rich molecules (ATP and NADPH).
2. **Light-Independent Reactions (Calvin–Benson Cycle)**: ATP and NADPH power the fixation of carbon dioxide to produce sugars such as glucose.

A key enzyme in the carbon fixation step is RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase), which catalyzes the incorporation of CO_2 into organic molecules. RuBisCO is considered the most abundant enzyme on Earth, reflecting its central role in plant biochemistry.

Pathways of Carbon Fixation

Plants have evolved different biochemical strategies to optimize photosynthesis under varying environmental conditions:

- **C_3 Photosynthesis**: The most common pathway, where CO_2 is fixed directly into three-carbon compounds.
- **C_4 Photosynthesis**: Involves an additional biochemical step that concentrates CO_2 around RuBisCO, reducing energy loss through photorespiration. This pathway is common in grasses such as maize and sugarcane.
- **Crassulacean Acid Metabolism (CAM)**: Plants fix CO_2 at night to conserve water in dry environments, storing carbon as organic acids for daytime photosynthesis.

Together, these pathways demonstrate the biochemical flexibility of plants in response to environmental pressures.

Primary Metabolites: Building Blocks of Life

While photosynthesis produces sugars, these compounds are not an end in themselves. They serve as primary metabolites—molecules directly involved in growth, development, and reproduction.

Sugars enter metabolic pathways such as glycolysis and the citric acid cycle, generating ATP required for cellular activities. Glucose also provides carbon skeletons for synthesizing:

- Amino acids (building blocks of proteins)
- Fatty acids (components of cell membranes)
- Nucleotides (required for DNA and RNA)

The dynamic network of reactions involving these metabolites forms the backbone of plant energy metabolism and cellular function.

Phytochemicals: Diversity Beyond Growth

Beyond primary metabolism, plants synthesize a vast array of secondary metabolites, often referred to as phytochemicals. Although these compounds are not essential for basic life processes, they are crucial for adaptation, defense, and ecological interactions.

Common classes include:

- **Phenolics** (e.g., flavonoids)
- **Terpenoids** (essential oils and carotenoids)
- **Alkaloids** (many with potent biological activities)
- **Steroids and glycosides**

Secondary metabolites often originate from intermediates of primary metabolic pathways. For example, the shikimate pathway, linked to carbohydrate metabolism, produces aromatic amino acids that serve as precursors for many phenolics and alkaloids.

Functions of Phytochemicals

Contrary to earlier beliefs that secondary metabolites were merely “waste products,” modern biochemical research has revealed their multiple biological roles:

- Defense against herbivores, pathogens, and pests, such as alkaloids and terpenes acting as toxins or repellents.
- UV protection and antioxidant activity, for example flavonoid accumulation under light stress.
- Attraction of pollinators through pigments and scents.
- Plant–microbe communication in the rhizosphere, influencing root health and nutrient uptake.

Phytochemicals often accumulate in specialized tissues or structures (e.g., trichomes and vacuoles), enabling targeted defense or signaling.

Interconnected Biochemistry: From Primary to Secondary Metabolism

Photosynthesis and secondary metabolism are closely interconnected. Sugars produced during photosynthesis also serve as precursors for secondary metabolite pathways. For example:

- The phenylpropanoid pathway, branching from phenylalanine, leads to the synthesis of flavonoids and lignin.
- The mevalonate (MVA) and methylerythritol phosphate (MEP) pathways produce terpenoids using intermediates from central carbon metabolism.

These interconnected biochemical networks demonstrate how plants allocate resources to balance growth, defense, and adaptation under changing environmental conditions.

Applications and Human Relevance

Plant phytochemicals have significant importance for human society:

- **Medicinal Applications:** Many alkaloids and phenolic compounds serve as pharmaceutical agents (e.g., morphine and taxol).
- **Nutritional Benefits:** Flavonoids and carotenoids function as antioxidants beneficial to human health.
- **Industrial And Agricultural Uses:** Essential oils and bioactive compounds are utilized in flavorings, cosmetics, and natural pesticides.

Understanding the biochemical pathways underlying these compounds supports innovations in plant breeding, metabolic engineering, and biotechnology, enabling the enhancement of desirable traits and the large-scale production of valuable metabolites.

Conclusion

Plant biochemistry connects fundamental life processes with ecological adaptation. Beginning with photosynthesis—the conversion of light energy into life-sustaining compounds—plants channel carbon through a complex network of pathways that produce both essential nutrients and diverse phytochemicals.

These biochemical processes sustain plant life and contribute significantly to human nutrition, medicine, and industrial development. Advances in molecular biology, metabolomics, and genetic engineering continue to deepen our understanding of plant biochemical systems and offer new opportunities to harness their potential sustainably.

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Neural Seeds: The "AI + Plants" Concept: Educating Plants to Grow and Adapt

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The idea of neural seeds highlights plants' ability to exhibit adaptive activity through intricate networks of biochemical, hormonal, & electrical signals, challenging the conventional perception of plants as passive, reactive animals. Despite having no neurons, plants can learn through long-term memory, associative conditioning, and habituation. Although repeatability is still a problem, experimental data from research on *Pisum sativum* and *Mimosa pudica* indicates that plants can alter responses based on experience. Growth dynamics, environmental data, and plant electrophysiology may now be interpreted in real time thanks to developments in artificial intelligence (AI), especially convolutional as well as recurrent neural networks. Combining these systems with wearable sensors, biohybrid robots, and nanobionic devices can improve precision farming, environmental monitoring, and innovative computing applications. Potential applications for closed-loop AI systems and multimodal data fusion include adaptive plant-machine interactions and resource optimization. There are still issues, though, such as sensor invasiveness, experimental validity, and moral concerns about plant agency. The Neural Seeds framework has the potential to transform the role of plants in cross-disciplinary research and sustainable technologies by fusing responsible innovation with rigorous science.

The conventional wisdom that plants are static, reactive entities is called into question by the idea of neural seeds. Plants' complex biochemical, hormonal, and electrical signaling networks allow them to perceive, analyze, and react to their surroundings in adaptive ways, despite the fact that they lack neurons and a central nervous system (Calvo et al., 2020). Recent studies have demonstrated that plants may change their behavior in response to experience, a phenomena similar to animal learning (Gagliano et al., 2014). Complementary developments in AI have made it possible to decode intricate, non-linear biological signals. These consist of growth dynamics, gene expression patterns, & electrical impulses in plants (Vodeneev et al., 2023). When paired with biohybrid devices, such nanobionic systems and wearable plant sensors, artificial intelligence (AI) can instantly analyze and respond to data provided by plants. This opens up the possibility of new bio-computational models and adaptive, self-optimizing agricultural systems. This study looks at the interaction of AI with plant systems, experimental findings, prospective applications, ethical considerations, and the biological underpinnings of plant learning.

1. The Mechanisms of Plant Memory and Acquisition of Knowledge

1.1. Plant learning: A definition

Learning in animals is a long-lasting behavioral shift brought on by experience, backed by systems for storing and retrieving memories. Similar modifications are made by plants through changes in ion-channel regulation, hormone signaling, and epigenetic modifications (Trewavas, 2016). Despite the absence of neurons, these processes satisfy operational criteria of learning, including long-term memory, associative conditioning, and habituation (Calvo et al., 2020).

1.2. The "Nervous System" of Plants is Electrical Signalling

Plants generate systemic electrical responses, action potentials, and variation potentials that can pass into vascular tissues and affect defense and photosynthesis (Vodeneev et al., 2023). Together, these electrical patterns are referred to as the "plant electrome," and they may function as systems for information storage and communication.

2. Proof of Plant Learning through Experiments

2.1. Getting used to *Mimosa pudica*

The experiment conducted by Gagliano et al. (2014) with the "sensitive plant," *Mimosa pudica*, is among the most often cited research on plant learning. The plants first closed their leaves in response to the innocuous stimulus of being dropped repeatedly from a modest height, but they gradually ceased reacting. Even after being tested in various environmental settings, this behavioral shift lasted for weeks. According to the research, plants are able to "remember" past events and modify their reactions accordingly (Gagliano et al., 2014).

2.2. Pea Plants That Use Associative Learning

According to a contentious 2016 study, pea plants (*Pisum sativum*) seemed to link light and wind direction, changing their growth pattern to face the wind when light was absent (Gagliano et al., 2016). Although intriguing, this assertion was contested by attempts at replication that were unable to validate the findings (Markel, 2020). The discussion emphasizes the necessity of exacting, unbiased, and repeatable procedures in studies on plant cognition.

3. Plant Biohybrid Systems With AI

3.1. Plants That Are Nanobionic

In nanobionics, nanoparticles are inserted into plants to improve their sensory capacities. Carbon nanotube-based nanosensors, for instance, were created by Wong et al. (2017) to identify nitroaromatic contaminants and send signals via near-infrared fluorescence. These sensors provide living, self-sufficient detecting systems by integrating directly into plant tissues.

3.2. Plant Sensors That Can Be Worn

Leaves or stems can have flexible, lightweight sensors affixed to them to track electrical activity, water content, and sap flow. When connected to AI models, these gadgets enable automated decision-making and ongoing monitoring in precision farming (Zhang et al., 2024).

3.3. Combining Biohybrid Robots With Planetoids

"Plantoid" robots, which are modeled after plant root systems, combine mechanical systems and biological plant tissue to react adaptively to environmental stimuli (DeMarse et al., 2001). Space exploration and ecological monitoring may benefit from these hybrid systems.

4. AI to Interpret and Improve Plant Reactions

4.1. Processing And Classifying Signals

Signals from plants' electrophysiology are frequently complex and loud. In order to find patterns connected to stress, dietary deficits, or insect infestations, machine learning techniques, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), can process raw time-series data.

4.2. Fusion of Multimodal Data

AI can create a comprehensive model of plant health by combining electrical data from plants with hyperspectral imagery, thermal measurements, as well as environmental factors. These multimodal systems can function in field settings and increase accuracy (Zhang et al., 2024).

4.3. Systems With Closed-Loop Adaptation

AI may "experiment" with light, water, and fertilizer supply using reinforcement learning to find the best growing circumstances. These technologies create a feedback loop in which resource allocation is determined by the plant's real-time responses.

5. AI and Plant Systems Applications

- **A Precision Approach To Farming:** Farmers can optimize fertilizer and irrigation use when stress is detected early, which lowers waste and increases yield.
- **Observation of The Environment:** Nanobionic plants are able to identify poisons or other contaminants in the air and soil (Wong et al., 2017).
- **Green Infrastructure In Urban Areas:** Sensor-enabled trees and plants could offer real-time information on temperature, humidity, and urban air quality.
- **Non-traditional computing:** Neuromorphic computer systems could make advantage of plant tissues having memristive qualities (Volkov et al., 2014).

6. Restrictions and Ethical Issues

6.1. Issues With Reproducibility

It has been challenging to duplicate well-known plant learning experiments, which raises concerns regarding experimental controls and methods (Markel, 2020).

6.2. Invasiveness of sensors

The physiology of plants may change if sensors or nanomaterials are included into them. Ethical frameworks ought to address the permissible level of intervention.

6.3. Implications for philosophy

The ability of plants to learn and adapt could change how people view their moral standing (Calvo et al., 2020). However, assertions of plant sentience are still up for debate in philosophy and science.

7. Research Agenda

- Electrome datasets that are standardized for training AI models.

- Replicable methods for plant learning to settle disputes.
- Low-cost, scalable sensors for agricultural deployment.
- AI models that are explainable and relate patterns to physiological functions.
- Partnerships across disciplines between ethicists, AI engineers, and plant scientists.

Conclusion

The idea of Neural Seeds, which uses artificial intelligence to train plants to learn and adapt, lies at the nexus of biology, technology, and ethics. Although there is conflicting evidence about plant cognition, it is well known that artificial intelligence can monitor and decipher plant signals. Future developments in wearable sensors, nanobionics, and AI modeling suggest that plants will be active contributors to adaptive systems rather than merely passive crops. If such advances are explored with scientific rigor and ethical responsibility, they have the potential to transform fields such as agriculture, environmental monitoring, and even computers.

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Organic Farming as a Resilient Response to Agricultural Climate Change in India

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The world's food security is seriously threatened by climate change, especially in India, where unpredictable rainfall and rising heat interrupt important crop growth stages. According to this research, organic farming is an essential mitigation and adaptation tactic. Organic systems provide a higher priority on ecological balance and soil health than industrial agriculture, which uses synthetic inputs to worsen global warming. According to the study, organic farming substantially lowers emissions of methane (CH_4) and nitrous oxide (N_2O) through biomass recycling and improves the sequestration of soil organic carbon (SOC), hence mitigating climate change. Additionally, because organic livestock techniques lessen the need for concentrated feeds, they reduce carbon emissions. In conclusion, switching to organic farming methods provides a scientifically validated means of reestablishing agricultural ecosystems and guaranteeing long-term environmental sustainability.

Introduction to Organic Farming and Climate Change

Organic farming is a system of agricultural production that prioritizes ecological balance, biodiversity, and soil fertility. It prioritizes natural processes over artificial inputs like chemical insecticides and fertilizers. In reaction to the industrialization of agriculture, organic farming emerged in the early 20th century, highlighting the interdependence of soil, plants, animals, and people. In order to address global issues including environmental degradation, climate change, and food security concerns, organic farming has emerged as a crucial tactic in the pursuit of sustainable agriculture. Organic farming, which has its roots in traditional farming methods but is supported by contemporary scientific findings, prioritizes soil health, biodiversity, and the health of agricultural ecosystems in an effort to establish a system that is sustainable on all levels economically, socially, and environmentally.

Global agriculture is facing serious and expanding issues as a result of climate change. Its numerous effects, including frequent flooding, hurricanes, global warming, sea level rise, and the melting of polar ice, have been present since the turn of the twenty-first century and have become more noticeable in different parts of the globe. The scientific community agrees that in addition to reducing agricultural output, climate change would jeopardize the security of food and livelihood, have an impact on global trade, and undermine the stability of human civilization. Given that it both contributes to and is a victim of climate change, the agricultural sector is especially sensitive. Anthropogenic activities, such as burning fossil fuels and engaging in unsustainable agricultural practices like intensive livestock rearing and excessive use of synthetic inputs, have contributed significantly to the global warming of the past century, which has increased by about 0.7°C.

To secure future food security, it is imperative to boost agricultural yields in a sustainable way while also making crops more resilient to climate change. Extreme heat and unpredictable rainfall brought on by climate change will make it more difficult for agriculture to supply the world's growing population with food. Rapid knowledge and applied crop design advancements could offer answers based on cutting-edge techniques, such as gene editing, genomics, soil microbiome modification, and crop management techniques. Given the scope of the climate change problem, it is necessary to evaluate what is already known and think about how agri-food system targets may need to be met through cooperative activities that stimulate and promote better interactions between disciplines.

Impacts of Climate Change on Plant Production in Indian Agriculture

Climate change affects plant production in complex ways. While increased temperatures may enhance organic matter decomposition and biological nitrogen fixation, they also exacerbate evapotranspiration and reduce soil moisture retention. Variability in rainfall and shifts in seasonal patterns disrupt water availability, influencing crop growth and productivity. Critical crop stages such as flowering, pollination, and grain filling are highly susceptible to moisture stress, often resulting in yield losses.

The Role of Organic Farming in Mitigating Climate Change

1. Soil Organic Carbon's Mitigation Function in Agricultural Systems

Preserving and increasing soil organic carbon in agricultural systems is the best way to reduce the environmental impact of agriculture.

2. Lower Emissions of CH_4 and N_2O in Organic Farming

Reusing residual biomass as nutrients in organic farming increases soil fertility and lowers the demand for outside inputs. This procedure lowers emissions of nitrous oxide (N_2O) and methane (CH_4) because organic matter is sustainably repurposed.

3. Effects of Lower Concentrate Feed Consumption in Organic Animal Husbandry and Less Direct Land Use Change

By lowering the need for concentrated feed, organic livestock husbandry lessens the need to remove forests for feed production. As a result, CO_2 emissions from soil carbon loss due to changes in land use are reduced.

4. Farmers Profit Financially When Greenhouse Gas Emissions in Agricultural Systems Are Reduced

According to research, mixing organic fertilizer and following the right tillage procedures can greatly increase soil carbon storage and reduce greenhouse gas emissions.

Conclusion

By improving soil health and increasing carbon sequestration, organic farming provides a crucial approach to tackling the climate catastrophe. It successfully slows down global warming and increases agricultural tolerance to unpredictable weather by lowering greenhouse gas emissions and synthetic inputs. Making the switch to these sustainable practices is crucial for maintaining environmental stability, economic viability, and long-term food security in a warming planet.

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Packaging and Labelling of Milk and Milk Products: Ensuring Safety, Quality and Consumer Confidence

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Milk is a highly perishable and sensitive food commodity that can deteriorate rapidly if not handled properly. Effective packaging and appropriate labelling play a vital role in maintaining milk quality, ensuring safety, and delivering accurate product information to consumers. This article explains the objectives, materials, and types of packaging used for milk and dairy products, along with essential labelling requirements under Indian food safety regulations. It also outlines the regulatory framework for establishing dairy processing plants in India. Proper compliance with packaging and labelling standards not only safeguards public health but also enhances market trust and product value.

Milk is one of the most nutritious and widely consumed foods across the world. However, due to its high moisture content and rich nutrient composition, it is extremely prone to microbial contamination and spoilage. Without suitable protection, milk can lose its freshness, quality, and nutritional value within a short time.

Packaging and labelling, therefore, become essential components of the dairy supply chain. While packaging protects milk from contamination and environmental damage, labelling provides consumers with critical information regarding the product's identity, quality, safety, and usage instructions. Together, these processes ensure that milk and dairy products reach consumers in safe and marketable condition.

Meaning and Purpose of Packaging

Packaging refers to the process of filling and sealing milk in food-grade containers in such a way that it remains protected from contamination and maintains its quality during storage, transportation, and distribution.

Objectives of Packaging

The primary goals of dairy packaging include:

1. Protection from contamination: Shielding the product from dust, dirt, insects, microorganisms, and other external hazards.
2. Preservation of quality: Maintaining flavour, colour, aroma, texture, and nutritional value.
3. Extended shelf life: Allowing safe storage for a longer duration.
4. Safe transportation: Preventing leakage, breakage, or damage during handling and transport.
5. Consumer safety: Delivering hygienic and standardised products.
6. Information display: Providing essential product details through labelling.
7. Market appeal: Attracting consumers through neat and appealing packaging.
8. Regulatory compliance: Meeting food safety standards and legal requirements.

Essential Characteristics of Packaging Materials

Materials used for packaging milk and dairy products must possess the following qualities:

- Food-grade and safe for direct contact with food
- Non-toxic and chemically inert
- Neutral in taste, odour, and colour
- Strong and durable
- Resistant to moisture, oxygen, and light
- Hygienic and easy to clean or sterilise
- Capable of airtight sealing
- Economical and commercially viable
- Preferably recyclable or environmentally friendly

Types of Packaging

Based on function and level of protection, dairy packaging is generally classified into three categories:

1. Primary Packaging

This is the layer that directly contacts the product and ensures its immediate protection.

- Examples: Poly pouches for milk
- Plastic cups for curd
- Tin cans for milk powder

2. Secondary Packaging

This packaging surrounds primary packages to provide additional protection and grouping convenience.

- Examples: Carton boxes for milk pouches
- Trays for curd cups

3. Tertiary Packaging

Used for bulk handling, storage, and long-distance transportation.

Examples:

- Plastic crates
- Pallets
- Stretch wrapping films

Common Packaging Materials for Dairy Products

Liquid Milk

- LDPE/LLDPE poly pouches (most widely used)
- Tetra packs (for UHT milk)
- HDPE or PET bottles (flavoured milk)
- Glass bottles (limited or institutional use)

Milk Powder

- Tin containers
- Multi-layer laminated pouches
- HDPE jars

Curd and Buttermilk

- Plastic cups (PP/PS)
- Poly pouches
- Traditional earthen pots (limited use)

Ghee

- Tin containers
- Glass jars
- Food-grade plastic containers
- **Butter**
- Aluminium foil wrappers
- Parchment paper with foil
- Plastic tubs

Condensed or Evaporated Milk

- Tin cans
- Laminated pouches

Paneer and Cheese

- Wax paper
- Laminated films
- Vacuum-sealed pouches

Special Packaging Requirements for Milk

Milk packaging must meet specific standards to ensure safety and quality:

- Use of approved food-grade materials
- Proper sealing to prevent leakage
- Hygienic automated or semi-automated packing systems
- No reuse without proper cleaning and sterilisation
- Compatibility with cold chain storage
- Clear mention of processing type (Pasteurised, UHT, Sterilised)
- Standardised pack sizes (e.g., 200 ml, 500 ml, 1 L)
- Mandatory regulatory markings

Labelling Requirements for Milk and Milk Products

Labelling is the display of essential product information on the package to inform and protect consumers.

Under Indian food safety regulations, the following details must be clearly printed on all pre-packaged milk and dairy products:

1. Product Identification

- Name of the product (e.g., Cow Milk, Toned Milk, Ghee)
- Category or class of milk (Full cream, Double toned, Skimmed)
- Declaration of raw milk

2. Processing Information

- Type of heat treatment (Pasteurised, UHT, Sterilised)

3. Net Quantity

- Declared in metric units (ml, L, g, kg)

4. Date Marking

- Manufacturing/packing date
- Use-by or best-before date
- Batch or lot number

5. Nutritional Information

Per 100 ml or per serving:

- Energy
- Fat
- Protein
- Carbohydrates
- Sugars (if applicable)

6. Ingredient List

All ingredients are listed in descending order of quantity.

7. Allergen Declaration

- Clear statement indicating the presence of milk and other allergens.

8. Manufacturer Details

- Name and address of manufacturer/packer

- Food safety license number

9. Storage Instructions

Examples:

- “Keep refrigerated.”
- “Boil before use.”
- “Consume soon after opening.”

10. Language Requirement

Information must appear in Hindi or English (additional languages optional).

Special Declarations

Certain products, such as milk powder, require additional warnings regarding usage restrictions, especially for infant feeding.

Regulatory Requirements for Setting Up a Dairy Processing Plant

Licensing Categories

- Small businesses (up to 500 litres/day): Basic registration
- Medium capacity units: State license
- Large units or interstate operations: Central license

Hygiene and Sanitation

- Personal hygiene of workers
- Use of non-corrosive equipment
- Rapid cooling of milk to 4°C or below
- Regular cleaning and sanitation
- Proper waste disposal system

Quality Control

- Testing of raw milk
- Microbiological examination of finished products
- Internal quality assurance or approved external laboratory testing
- Calibration and documentation of equipment

Production Standards

- Compliance with fat and SNF standards
- Microbial limits
- Approved processing specifications

Application Procedure

- Online application through the official portal
- Submission of plant layout, water analysis report, product list, and food safety management plan
- Inspection and approval process

Timely license renewal and regulatory compliance are mandatory to avoid penalties.

Conclusion

Packaging and labelling are not merely marketing tools; they are fundamental pillars of dairy safety and quality assurance. Proper packaging protects milk from contamination and spoilage, while accurate labelling empowers consumers to make informed choices. Compliance with food safety standards strengthens public trust and supports the sustainable growth of the dairy sector. As consumer awareness increases, maintaining high packaging and labelling standards will continue to play a crucial role in delivering safe and nutritious dairy products to society.

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Risks from Black Plastic Packaging: Toxic Chemicals and Their Migration into Food

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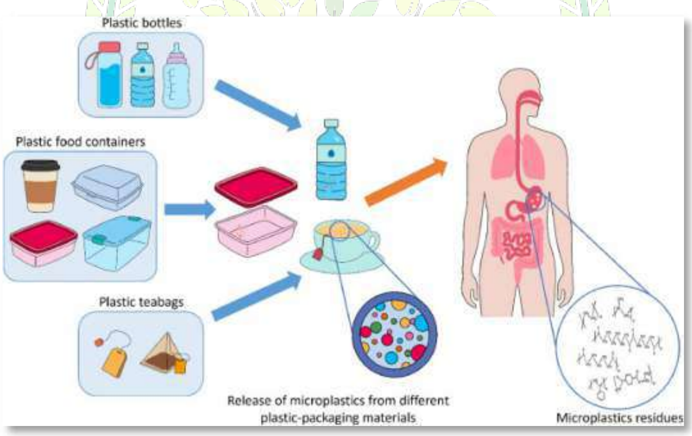
Black plastic has become ubiquitous in food service industries, takeaway containers, and household storage solutions across India and globally. However, mounting scientific evidence suggests that black plastic packaging poses significant health risks due to the migration of toxic chemicals into food products. This article examines the composition of black plastic, the mechanisms of chemical migration, associated health risks with detailed physiological effects, and the urgent need for enhanced consumer awareness regarding these potentially harmful materials. Understanding these risks is essential for informed consumer choices and public health protection.



Composition and Manufacturing of Black Plastic Food Packaging

Black plastic containers utilized in food packaging are predominantly manufactured from polypropylene (PP) or polystyrene (PS) polymers. The distinctive black coloration is achieved through the addition of carbon black pigment, a substance classified by the International Agency for Research on Cancer (IARC) as a Group 2B carcinogen, indicating it is possibly carcinogenic to humans (IARC, 2010). Perhaps more alarming is the origin of many black plastic food containers. Research has revealed that a substantial proportion of black plastic products are manufactured from recycled electronic waste, including discarded computers, keyboards, televisions, and other electronic equipment (Turner, 2018). This recycling practice introduces a complex cocktail of chemicals never intended for food contact applications, including flame retardants, heavy metals, and other toxic substances designed for electronics. When these materials are repurposed into food containers without adequate purification processes, these chemicals remain embedded in the polymer matrix, creating ongoing potential for migration into food products.

Chemical Migration Mechanisms and Heat Sensitivity

The transfer of chemicals from packaging materials into food is governed by complex physicochemical processes influenced by temperature, food composition, and contact duration. Polypropylene possesses a melting point ranging from 160°C to 170°C; however, chemical migration does not require complete polymer degradation. According to the Food Safety and Standards Authority of India (FSSAI), significant chemical leaching from plastic materials can commence at temperatures as low as 60°C to 70°C (FSSAI, 2018). This threshold is regularly exceeded in common food preparation and storage scenarios, including microwave heating, hot food service, and storage of freshly cooked meals. The migration process is substantially accelerated when plastic containers come into contact with hot, oily, or acidic foods. Research conducted at the Indian Institute of Toxicology Research (IITR), Lucknow, has documented that heated oils particularly enhance the extraction of chemicals from plastic container walls, creating a direct pathway for contamination of consumed foods (Sharma et al., 2020). Temperature elevation disrupts the polymer structure, increasing molecular mobility, and for every 10°C increase in temperature, the migration rate can approximately double, following established chemical kinetics principles.

Toxic Chemical Constituents and Their Physiological Effects

Brominated Flame Retardants (BFRs)

Brominated flame retardants, including polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA), are deliberately added to electronic equipment to reduce fire hazards. When electronics are recycled into food contact materials, these flame retardants persist and become potential contaminants. BFRs are structurally similar to thyroid hormones (T3 and T4), allowing them to bind to thyroid hormone receptors and interfere with normal thyroid function.

In the thyroid gland, BFRs compete with iodine for incorporation into thyroid hormones, reducing the production of active T3 and T4 and leading to hypothyroidism characterized by fatigue, weight gain, cold intolerance, and depression. Studies in Indian populations have shown that individuals with higher BFR exposure exhibit elevated TSH (thyroid-stimulating hormone) levels, indicating compensatory mechanisms attempting to restore normal thyroid function (Gascon et al., 2011).

In the developing brain, thyroid hormones are essential for neuronal migration, myelination, and synapse formation. BFR exposure during pregnancy and early childhood disrupts these critical processes, leading to reduced IQ scores, attention deficit disorders, motor skill delays, and memory impairment.

Phthalates and Bisphenol Compounds

Phthalates such as DEHP, DBP, and BBP, along with bisphenol-A (BPA), are plasticizers and monomers commonly found in various plastic formulations. While many manufacturers produce “BPA-free” plastics, recycled black plastics often contain these chemicals from their source materials. These compounds function as endocrine disruptors by mimicking or blocking natural hormones, particularly estrogen and testosterone.

In males, phthalate exposure disrupts Leydig cells in the testes and inhibits steroidogenic enzymes such as 3β-HSD and 17β-HSD, reducing testosterone synthesis and causing reproductive issues including low sperm count and DNA damage.

In females, these chemicals disrupt ovarian function and hormonal balance, contributing to conditions such as Polycystic Ovary Syndrome (PCOS), premature puberty, endometriosis, and pregnancy complications.

Additionally, phthalates and bisphenols activate peroxisome proliferator-activated receptors (PPARγ), promoting adipogenesis, insulin resistance, visceral fat accumulation, and increased risk of Type 2 diabetes.

Heavy Metals: Concentration and Toxic Effects

Black plastic derived from recycled electronics frequently contains elevated concentrations of heavy metals such as lead, cadmium, and hexavalent chromium. Studies analysing black plastic food containers in Indian markets have reported concerning levels exceeding permissible safety limits (Kale et al., 2019).

Lead interferes with neurological, cardiovascular, and renal systems. It impairs neurotransmission, damages the myelin sheath around neurons, increases blood pressure, and causes kidney dysfunction.

Cadmium accumulates in kidney tubules over decades and leads to chronic kidney disease, bone demineralization, and increased fracture risk.

Hexavalent chromium causes oxidative DNA damage, increasing cancer risk and causing skin ulceration and liver toxicity.

Microplastic Contamination and Systemic Effects

Beyond chemical additives, black plastic packaging releases microplastic particles during heating and use. Studies indicate that heating food in black plastic containers may release between 11 million and 21 million microplastic particles per serving.

These particles can cross the intestinal barrier and enter systemic circulation through several biological mechanisms. Microplastics have been detected in blood, liver, lungs, placenta, and even brain tissue (Leslie et al., 2022).

Their presence triggers chronic inflammation, oxidative stress, gut microbiome disruption, and potential autoimmune responses.

Chronic Disease Associations and Public Health Impact

Long-term exposure to chemicals migrating from plastic packaging has been associated with chronic diseases including cancer, endocrine disorders, and metabolic conditions.

Endocrine-disrupting chemicals are linked to hormone-dependent cancers such as breast and prostate cancer (IARC, 2010). In India, breast cancer incidence is increasing annually, while prostate cancer affects approximately 1 in 68 men.

Plastic-derived chemicals are also associated with metabolic disorders. Population studies have shown that individuals with higher urinary phthalate levels have a significantly increased risk of developing Type 2 diabetes (ICMR, 2017).

Additionally, chronic exposure to plastic chemicals may contribute to liver disorders such as non-alcoholic fatty liver disease (NAFLD), which affects a large proportion of the Indian population.

Regulatory Framework and Consumer Awareness

The Food Safety and Standards Authority of India (FSSAI) established the Food Safety and Standards (Packaging) Regulations, 2018, which prohibit the use of recycled plastics for packaging food products intended for human consumption.

Despite these regulations, enforcement remains challenging, and many black plastic containers continue to be used in street food, restaurants, and food delivery services.

Consumer awareness remains low. Surveys across major Indian cities reveal that only a small proportion of consumers understand the potential health risks associated with black plastic containers.

Public health education should emphasize avoiding reheating food in plastic containers, using safer alternatives such as glass or stainless steel, and selecting certified food-grade packaging materials.

Alternative Packaging Solutions

Safer packaging alternatives are available and increasingly recommended.

Glass containers provide an inert and non-reactive storage option suitable for both hot and cold foods.

Stainless steel containers are durable, heat-resistant, and widely used in Indian households.

Traditional materials such as banana leaves, lotus leaves, and terracotta containers offer biodegradable and culturally appropriate alternatives that have been safely used for centuries.

Emerging bioplastics derived from renewable resources such as cornstarch and sugarcane bagasse also present promising sustainable packaging options.

Conclusion

The migration of toxic chemicals from black plastic food packaging into consumable products represents a significant public health concern. Recycled electronic waste used in manufacturing introduces carcinogenic, endocrine-disrupting, and neurotoxic substances into the food chain.

Heat, fatty foods, and acidic conditions accelerate chemical migration, increasing the risk of human exposure. The health consequences include thyroid disruption, reproductive disorders, metabolic diseases, heavy metal toxicity, and chronic inflammation caused by microplastic contamination.

Despite regulatory restrictions, limited awareness and weak enforcement continue to allow unsafe materials in food packaging. A comprehensive strategy involving stricter regulatory enforcement, consumer education, and promotion of safer packaging alternatives is essential.

Consumers can immediately reduce risk by avoiding heating food in plastic containers, choosing glass or stainless steel alternatives, and advocating for safer food packaging standards.

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Nutritional and Functional Attributes of Sourdough Bread: A Fermentation-Based Perspective

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Sourdough bread is a type of bread made through natural fermentation using a mixture of lactic acid bacteria (LAB) and wild yeasts rather than commercial baker's yeast. The metabolic activity of lactic acid bacteria (LAB) and wild yeasts produces sourdough bread, a historically fermented grain product that greatly enhances its nutritional, physiological, and sensory qualities compared to typically leavened bread.

The extended fermentation process produces organic acids, primarily lactic and acetic acids, which lower dough pH and improve mineral bioavailability by breaking down phytic acid, a significant antinutritional component found in cereals that restricts the absorption of vital minerals like iron, zinc, calcium, and magnesium. Sourdough fermentation also causes complex carbohydrates and gluten proteins to partially hydrolyze, improving digestibility and reducing gastrointestinal discomfort, especially in individuals with mild gluten sensitivity.

Sourdough bread is a healthier option for people with diabetes or metabolic disorders because the organic acids produced during fermentation can alter starch structure and prolong gastric emptying, resulting in a lower glycemic index (GI) and improved postprandial glucose and insulin responses. Additionally, sourdough bread supports intestinal function and microbial balance by acting as substrates for beneficial gut microbiota through fermentation metabolites and bioactive compounds.

The acidic environment produced during sourdough fermentation also suppresses spoilage microorganisms, extending shelf life and reducing the need for chemical preservatives. Collectively, these characteristics establish sourdough bread as a functional bakery product with improved digestibility, enhanced nutritional value, and potential health benefits.

Health Benefits of Sourdough Bread

1. **Easy to Digest**: Natural fermentation breaks down starch and gluten.
2. **Improves Gut Health**: Contains beneficial bacteria that support digestion.
3. **Low Glycemic Index**: Helps control blood sugar levels.
4. **Better Mineral Absorption**: Reduces phytic acid and increases absorption of iron, zinc, and magnesium.
5. **Rich in Nutrients**: Good source of protein, fiber, vitamins, and minerals.
6. **Supports Heart Health**: Helps manage cholesterol and blood sugar.
7. **May Reduce Gluten Sensitivity**: Partial gluten breakdown makes it easier to tolerate (not gluten-free).
8. **No Artificial Preservatives**: Natural acids increase shelf life.

Functional and Nutritional Impacts of Sourdough Fermentation on Food Quality

Recipes of Sourdough Bread

1. Sourdough Bread Pudding

Ingredients

- 3 cups sourdough bread cubes
- 2 cups milk
- 2 tbsp sugar
- 1 egg (optional)
- ½ tsp vanilla essence
- Dry fruits or nuts (optional)

Method

1. Mix milk, sugar, egg, and vanilla in a bowl.
2. Add sourdough bread pieces and soak for 10 minutes.
3. Transfer to a greased baking dish and add nuts.
4. Bake at 180°C for 30 minutes until set.
5. Serve warm.

2. Sourdough Bread Pizza

Ingredients

- 4 slices sourdough bread
- 4 tbsp pizza sauce
- ½ cup grated cheese
- Chopped vegetables (onion, capsicum, tomato, corn)
- Oregano or chili flakes (optional)

Method

1. Spread pizza sauce on sourdough bread slices.

2. Add vegetables and grated cheese on top.
3. Sprinkle oregano or chili flakes.
4. Bake at 180°C for 8–10 minutes or toast in a pan until cheese melts.
5. Serve hot.

Shelf Life and Storage Stability of Sourdough Bread

- **Longer Shelf Life**: Sourdough bread stays fresh longer than regular bread due to natural fermentation.
- **Presence of Organic Acids**: Lactic and acetic acids inhibit microbial growth and delay spoilage.
- **Better Moisture Retention**: Helps maintain softness and reduces staling.
- **Room Temperature Storage**: Remains fresh for about 3–5 days when stored in a paper bag, cloth, or bread box.
- **Avoid Plastic Packaging**: Plastic traps moisture and increases mold growth.
- **Refrigeration Not Preferred**: Slows microbial growth but causes faster staling.
- **Freezing For Long-Term Storage**: Can be stored for 2–3 months without major quality loss.
- **High Microbial Stability**: Low pH inhibits fungal and bacterial growth.
- **Factors Affecting Shelf Life**: Storage temperature, moisture content, packaging, and hygiene conditions.

Consumer Health Trends and Industrial Relevance

Growing consumer demand for functional, minimally processed, and clean-label foods has renewed interest in sourdough bread. Advances in starter culture standardization and controlled fermentation technologies have enabled industrial-scale production while preserving traditional benefits. Sourdough bread aligns with current dietary trends emphasizing gut health, low glycemic foods, and natural preservation, making it a commercially viable and nutritionally relevant bakery product.

Conclusion

Sourdough bread is a nutritious and health-promoting bakery product produced through natural fermentation. It offers several advantages such as improved digestibility, better mineral absorption, enhanced gut health, and a lower glycemic response compared to conventional bread. The presence of organic acids also increases its shelf life and microbial stability. Due to its nutritional benefits, storage stability, and wide culinary applications, sourdough bread can be considered a valuable component of a healthy and balanced diet.

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Role of Pangenomes in Unlocking Hidden Genetic Diversity of Crops

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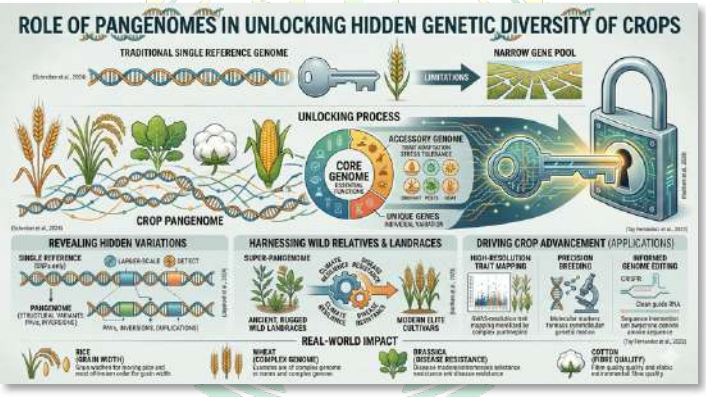
Global agriculture is now facing unprecedented challenges, including continuous climate change, population growth, and the consequent rise in food demand. These climatic changes affect weather patterns, irregular rainfall, temperature fluctuations, and an increased incidence of extreme climatic events, which lead to stress in crops and overall yield reduction.



An increase in population, along with the predicted impact of climate change, creates a pit in adequate supply, which needs to be filled. To fulfil this increasing food demand and urgency to develop resilient varieties of staple, emerging and orphan crops. Plant genomes are dynamic and environmentally responsive, serving as reservoirs of genetic diversity. However, domestication and intensive breeding have narrowed the genetic base of many cultivated crops, leading to the loss of valuable alleles. Traditionally, crop genomics has relied on a single reference genome (SRG), which represents only one individual and cannot capture the full spectrum of intraspecific variation.

In contrast, a pangenome encompasses the complete set of genes present across multiple individuals of a species. By classifying genes into core, dispensable (accessory), and unique categories, pangenomics provides a more comprehensive genomic framework. This expanded perspective enables the discovery of hidden alleles and structural variations that can enhance crop resilience, productivity, and nutritional quality in the face of climate uncertainty.

Concept of Pangenome

The term “pan-genome” was first used in 2000 in cancer genomics research, and in 2001, G.D. Ehrlich proposed the Distributed Genome Hypothesis, suggesting that not all members of a species share the same set of genes. In 2005, the word “pangenome” gained its modern meaning when used to describe genomic differences among multiple isolates of *Streptococcus agalactiae*. The concept was later extended to plants in 2007, where analysis of maize inbred lines Mo17 and B73 revealed significant genomic differences, highlighting intraspecific variation.

The core genome comprises genes present in all individuals and is essential for fundamental biological functions and species survival. The dispensable (accessory) genome includes genes present in some but not all individuals, contributing to adaptation, stress tolerance, and genetic diversity important for crop improvement.

During domestication and breeding, crops go through a bottleneck, meaning their genetic diversity becomes narrow due to selection and repeated use of a few genotypes. As a result, many useful genes are lost in modern cultivation. Although these dispensable genes are not necessary for the survival of the crop as core genes are, these genes help tolerate stress such as drought, salinity, and diseases. Wild crop relatives still contain this hidden genetic diversity, and pangenome studies help to identify these lost genes.

Presence–absence variation (PAV) represents a major component of genomic diversity captured by pangenomes, where certain genes are present in some individuals but completely absent in others. PAV analysis helps identify dispensable or variable genes that may contribute to important agronomic traits such as stress tolerance, disease resistance, and environmental adaptation. By comparing PAV patterns across wild relatives, landraces, and elite cultivars, researchers can detect genes lost during domestication and breeding. This information provides valuable targets for reintroduction through breeding or genome editing to enhance crop resilience and productivity.

Importance of Hidden Genetic Diversity in Crops

They can be gene-oriented, identifying the core genomes and dispensable/accessory genes. The sequence-oriented pangenome model includes genomic sequence variation, including single-nucleotide variants, insertions, deletions and structural variants. Compared to traditional linear references, pangenomes are less biased and improve mapping accuracy, variant identification, genotyping accuracy and the ability to link genes with phenotypes of interest.

Graph-based pangenomes overcome reference bias by integrating multiple genome assemblies into a non-linear structure where alternative alleles and structural variants are represented as branching paths. This improves the detection of presence–absence variation and complex structural rearrangements that are often missed in single-reference analyses. By enabling more accurate variant calling and allele mining across diverse germplasm, graph-based frameworks strengthen trait discovery and breeding applications, although they require advanced computational tools and resources.

Applications of Pangenomics in Crop Improvement

Pangenomics offers a powerful framework for crop improvement by capturing the full genomic diversity within a species rather than relying on a single reference genome. A major advantage is the identification of genes absent in modern elite cultivars but preserved in landraces and wild relatives, many of which are associated with stress tolerance, disease resistance, and environmental adaptation. Pangenomes can be created for many purposes, using a variety of genomic data formats and methods.

Pangenome analyses enable the detection of structural variations, including insertions, deletions, inversions, duplications, translocations, and copy-number variations. These large-scale genomic changes often influence key agronomic traits yet remain undetected in single-reference analyses. By uncovering such hidden variation, pangenomics broadens the genetic base of breeding populations and reduces genetic vulnerability.

The distinction between core and accessory genomes further clarifies the impact of domestication, as accessory genes are frequently enriched for adaptive and stress-responsive functions. Comparative analysis across diverse germplasm helps identify beneficial alleles that have been lost during crop improvement. Additionally, pangenomes enhance precision breeding by improving marker development, genomic selection accuracy, and candidate gene discovery. Integration with genome editing technologies enables targeted reintroduction of adaptive alleles. Overall, pangenomics reconnects modern cultivars with diverse gene pools, strengthening yield stability, climate resilience, and sustainable crop production.

Selected Case Studies

Pangenome studies across major crops have demonstrated the significance of hidden genetic diversity. To date, there are numerous case studies in the field of crop pangenomics, some involving staple crops and others involving orphan crops. *Brassica rapa*, *Glycine soja*, and *Oryza sativa* were the first three plant species to have their pangenome constructed in 2014. In the case of rice and wheat, a light-shotgun sampling metagenomic approach has been used to create pangenomes.

The rice pangenome was constructed using 1,483 rice lines by assembling only the sequences that did not match the reference genome, grouping them by subspecies. Although this method was cost-effective and allowed analysis of many lines, it could not trace genes back to individual plants and missed rare genes due to low sequencing depth. Even with these limitations, many new non-reference genes were identified. Importantly, a large proportion of metabolic and agronomic traits were linked to these variable, non-reference regions, highlighting the value of pangenomics in crop improvement.

The extensive hexaploid wheat genome faces difficulties for pan-genome development employing a metagenomic methodology. From 18 cultivars, researchers determined that the complete wheat pan-genome comprises 140,500 genes, of which roughly 81,070 are core genes.

Brassica pangenomes were developed using multiple accessions of *B. rapa*, *B. oleracea*, and *B. napus*, revealing thousands of genes beyond the reference genome, with a substantial proportion classified as core and several hundred unique to each species. Earlier iterative assembly approaches in *B. oleracea* also expanded the genome size and uncovered gene presence–absence variation, including flowering-time genes linked to early flowering. Later, a multi-species graph-based "super-pangenome" integrating 41 genomes further improved the representation of structural diversity across Brassica species and led to the development of the Brassica Panache web portal for data access and analysis.

Challenges and Future Perspectives

Despite their immense potential, crop pangenomes face several challenges. The assembly and integration of multiple high-quality genomes into graph-based structures require substantial computational resources and advanced bioinformatics expertise. Accurate detection and interpretation of structural variants and presence–absence variations remain technically demanding, particularly in large, repetitive plant genomes. Another major challenge lies in distinguishing functionally meaningful variation within the accessory genome from neutral diversity. Robust functional validation through transcriptomics, proteomics, and phenomics is essential to translate genomic discoveries into breeding applications.

Future advancements are expected through the integration of long-read sequencing technologies, improved graph-based frameworks, and multi-omics approaches. These developments will enhance allele discovery, functional annotation, and the implementation of precision breeding strategies.

Conclusion

Pangenomics represents a transformative shift in crop genomics by moving beyond single-reference genome models to capture the full spectrum of genetic and structural diversity within species. By uncovering hidden genes, presence–absence variations, and structural rearrangements, it reveals reservoirs of adaptive potential that were previously overlooked in conventional genomic analyses. This comprehensive view of genomic diversity not only deepens our understanding of domestication and evolutionary processes but also provides a powerful foundation for allele mining and precision breeding.

As agriculture faces mounting challenges from climate change, genetic erosion, and increasing global food demand, harnessing the diversity preserved within pangenomes—particularly from diverse germplasm and wild relatives—will be essential for developing resilient, high-yielding, and stress-tolerant crop varieties. With continued technological advancements and integration into breeding pipelines, pangenomics is poised to become a central tool for sustainable crop improvement and long-term food security.

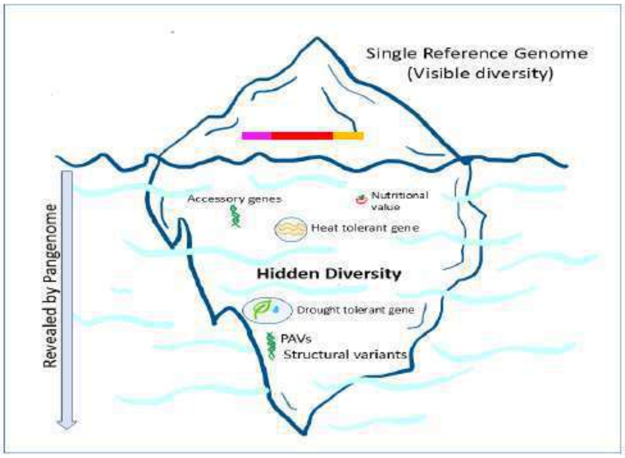


Figure 1. Conceptual representation of hidden genetic diversity revealed by pangenomics

The iceberg model illustrates the limitation of a single reference genome (visible portion above water), which captures only a fraction of the total genetic diversity within a crop species. The larger submerged portion represents hidden genetic variation, including accessory genes, presence–absence variations (PAVs), and structural variants. These hidden components often contain adaptive genes associated with drought tolerance, heat tolerance, disease resistance, and nutritional traits, which are uncovered through pangenome analysis.

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Next Generation Sequencing (NGS) for Identification of Disease Resistant Alleles in Plants

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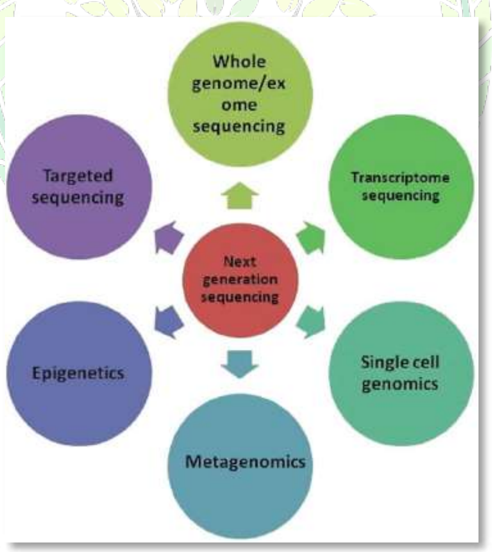
Development of disease resistant crop varieties plays a significant role in overcoming threats caused by plant pathogens. The advent of Next Generation Sequencing (NGS) plays a vital role in the identification of alleles responsible for disease resistance. This technology enables high-throughput, cost-effective, and rapid identification of novel alleles associated with disease resistance in plants. Integration of NGS with marker assisted selection (MAS) and multi-omics breeding programs can enhance the efficiency of breeding programs related to the development of disease resistant cultivars.



With increasing threats related to diseases in crops caused by fungi, bacteria, and viruses, development of disease resistant crop varieties has become increasingly important in the agricultural sector. In plant breeding, identification of disease resistant alleles that confer resistance against pathogens plays a pivotal role. The advent of Next Generation Sequencing (NGS) has revolutionized plant genomics by enabling rapid identification of novel alleles associated with disease resistance in crops.

NGS mainly works based on high-throughput DNA sequencing, which allows millions of DNA fragments to be sequenced simultaneously (Gupta et al., 2020). This technology utilizes several platforms such as Illumina, Thermo Fisher Scientific, and Pacific Biosciences. NGS allows rapid detection of genetic variations and helps in identifying rare and previously unknown alleles. This article explores the role of NGS in identifying novel alleles associated with plant disease resistance and highlights its workflow.

Next Generation Sequencing (NGS) in Identification of Novel Alleles Associated with Plant Disease Resistance

For the identification of disease resistant alleles in plants, NGS technology has played an important role by enabling high-throughput genotyping, whole genome sequencing, and target-based identification of resistance gene analogs. These approaches have played a central role in identifying novel alleles from diverse germplasm, including wild relatives, landraces, and cultivars (Smith, 2025).

The availability of whole genome sequencing (WGS) has shifted fragment-based polymorphism identification to sequence-based SNP identification, thereby improving marker discovery and increasing the number of informative markers. Earlier, WGS based on Sanger sequencing required more time and was limited in discovering specific genes. To overcome this limitation, NGS technologies have become powerful tools that have significantly reduced the cost of WGS and enabled discovery of thousands of markers in a single step (Ray and Satya, 2014).

Thus, NGS has become a powerful tool for identifying several disease resistant genes, as numerous DNA sequence polymorphisms can be detected within a short period of time.

Examples of NGS-Based Disease Resistant Gene Identification in Plants

Based on NGS, several studies have been conducted across the world to identify novel and candidate genes responsible for disease resistance in plants. Zhong et al. (2018) reported a novel gene, RpsHC18, on chromosome 3 that confers resistance against *Phytophthora sojae* in soybean. Two diagnostic markers were developed for RpsHC18 and two NBS-LRR candidate genes were identified.

Using NGS technology such as double-digest restriction site associated DNA sequencing (ddRAD-Seq), a total of 6,514 SNPs were genotyped in an F_2 population derived from wild relatives of tomato. Subsequent genotype-phenotype association studies revealed a 6.8 Mb genomic region on chromosome 6 as a candidate locus for resistance against tomato late blight (Arafa et al., 2017).

Recent advances in NGS have also enabled rapid identification of candidate genes responsible for blackleg resistance in *Brassica napus*. Genome sequencing of *B. rapa* (diploid progenitor of *B. napus*) revealed numerous disease resistance candidate genes, most of which were clustered around the major blackleg resistance locus Rlm4 on chromosome A7 (Tollenaere et al., 2012).

Sequencing-based bulked segregant analysis (Seq-BSA) has identified seven SNPs associated with resistance to Fusarium wilt (FW) and sterility mosaic disease (SMD) in pigeon pea. In silico protein analysis further identified two promising candidate genes, namely *C. cajan_01839* and *C. cajan_03203*, for SMD and FW resistance respectively (Singh et al., 2016).

Targeted NGS has also been used to identify mutations in resistance gene analogs (RGAs) in wild and cultivated beets. Using Ion Torrent sequencing technology, mutations were identified in 21 RGAs. The sequence CCCTCC was identified as a diagnostic marker to differentiate wild and domesticated beets and to assist marker-assisted breeding programs (Stevanato et al., 2017).

Thus, NGS technology has played an instrumental role in identifying resistance genes against several plant pathogens in diverse crops. The detailed findings of the above-mentioned studies are summarized in Table 1.

Table 1: Some of the Key Research Works Carried Out to Identify Disease Resistant Alleles/Markers in Crops Using NGS

Year	Author	Significant Findings
2012	Tollenaere et al.	Next-generation sequencing of *Brassica rapa* revealed numerous disease resistance candidate genes clustered around the blackleg resistance locus Rlm4 on chromosome A7 of *Brassica napus*.
2016	Singh et al.	Seq-BSA identified seven SNPs associated with resistance to Fusarium wilt and sterility mosaic disease in pigeon pea.
2017	Arafa et al.	ddRAD-Seq genotyped 6,514 SNPs in tomato and identified a 6.8 Mb candidate genomic region on chromosome 6 associated with late blight resistance.
2017	Stevanato et al.	Targeted NGS using Ion Torrent identified mutations in 21 resistance gene analogs in beet.
2018	Zhong et al.	Identified soybean resistance gene RpsHC18 on chromosome 3 against *Phytophthora sojae*.

Mechanism of NGS in Identification of Alleles Responsible for Disease Resistance in Plants

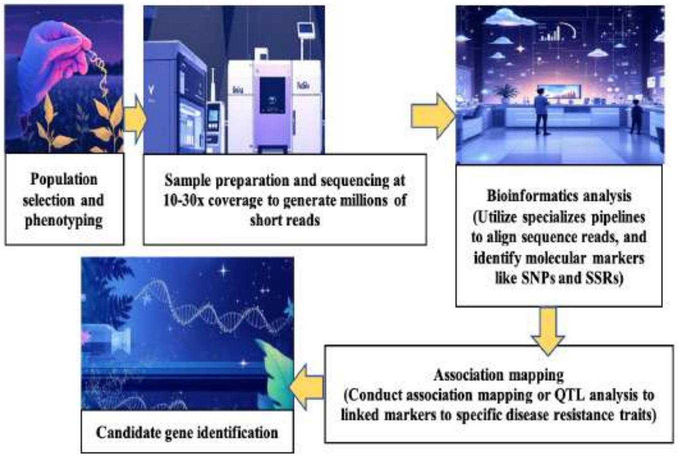


Fig 1: Workflow of NGS for identification of candidate genes responsible for disease resistance in plants.

Conclusion

NGS technology accelerates the discovery of resistant alleles responsible for disease resistance in plants. The combined use of NGS with other advanced genomic tools will further enhance the development of crop varieties resistant to plant diseases. Thus, this technology has great potential to contribute to global food security and sustainable agriculture.

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Sea Buckthorn (*Hippophae rhamnoides* L.) Juice: Nutritional Composition, Functional Properties, and Comparative Evaluation with Selected Berry Juices

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Sea buckthorn (*Hippophae rhamnoides* L.), belonging to the family Elaeagnaceae, has been traditionally utilized in Asian and European medicinal systems for centuries. Its berries are recognized for their therapeutic properties and nutritional richness. Historical records indicate its use in treating digestive, respiratory, and skin-related ailments.

The plant thrives in extreme environmental conditions, including high altitudes and poor soils. In India, it is predominantly found in Himalayan regions such as Ladakh and Himachal Pradesh. Due to its high nutritional value, it has been recommended as a dietary supplement, particularly for individuals exposed to harsh climates.

Recent scientific investigations have revealed that sea buckthorn berries contain more than 190 biologically active compounds, making them one of the most nutritionally complex plant sources available. The juice derived from these berries retains most of these compounds, making it an important functional beverage.

Nutritional Composition

The berries contain moderate levels of carbohydrates, proteins, and fats. A distinctive feature of sea buckthorn is its lipid composition, which includes all major omega fatty acids—omega-3, omega-6, omega-7, and omega-9.

Omega-7 (palmitoleic acid), rarely found in plant sources, is particularly significant due to its role in metabolic regulation and skin health. The presence of dietary fiber further enhances its nutritional profile.

Vitamin Content

Sea buckthorn juice is exceptionally rich in vitamin C, with concentrations significantly higher than most fruits. It also contains substantial amounts of vitamin E and provitamin A carotenoids. Additionally, several B-complex vitamins are present, contributing to metabolic and neurological functions.

Phytochemical Composition

Polyphenols and Flavonoids

Polyphenols represent the dominant antioxidant components present in sea buckthorn juice. Research indicates that the total polyphenol concentration ranges between 12.36 and 34.6 mg GAE/g (gallic acid equivalents), which is considerably higher than that found in commonly consumed fruits such as oranges, mandarins, blueberries, sour cherries, and strawberries.

Comprehensive studies have identified nearly 100 individual polyphenolic constituents in sea buckthorn, including approximately 17 phenolic acids. Among these, salicylic acid is the most abundant, accounting for nearly 55–74% of the total phenolic acid fraction in the fruit.

Flavonoids are present in substantial quantities in sea buckthorn juice and include important compounds such as quercetin, kaempferol, isorhamnetin, rutin, and myricetin. These bioactive molecules exhibit antioxidant, anti-inflammatory, antiviral, and anticancer effects.

Carotenoids

Sea buckthorn berries are recognized as one of the richest natural sources of carotenoids among plant-based foods. The major carotenoids present include beta-carotene, lycopene, zeaxanthin, lutein, cryptoxanthin, and canthaxanthin.

The overall carotenoid concentration in freshly extracted juice generally ranges between 30 and 60 mg per 100 mL. These compounds are responsible for the bright orange coloration characteristic of sea buckthorn berries and their juice.

Functionally, carotenoids possess strong anti-inflammatory and anticancer properties and play a protective role against certain types of skin cancers. Lutein and zeaxanthin are particularly important for eye health.

Organic Acids

Sea buckthorn juice contains a diverse range of organic acids, including quinic acid, L-malic acid, D-malic acid, succinic acid, pyruvic acid, tartaric acid, acetic acid, formic acid, and citric acid.

These acids contribute to the characteristic taste of the juice and have physiological importance, including potential roles in bone formation and improved skeletal health.

Minerals and Trace Elements

Sea buckthorn juice is a valuable source of essential minerals, containing at least 14 elements in biologically significant amounts. Potassium is the most predominant mineral. Other important minerals include phosphorus, copper, and calcium.

Selenium plays a key role in antioxidant defense and immune regulation. The high vitamin C content enhances iron absorption in the human body.

Comparative Nutritional Analysis

Nutrient Comparison (per 100 g fresh weight)

Nutrient	Sea Buckthorn	Blueberry	Raspberry	Strawberry	Cranberry	Black Currant
Calories (kcal)	82–120	57	52	33	46	63
Carbohydrates (g)	5–8	14.5	12.0	7.7	12.2	15.4
Fibre (g)	6.55	2.4	6.5	2.0	4.6	3.6
Protein (g)	3.12	0.74	1.2	0.67	0.39	1.4
Omega-7 (mg)	High*	None	Trace	Trace	None	None
Vitamin C (mg)	360–2500	9.7	26.2	58.8	13.3	181
Vitamin E (mg)	~15	0.57	1.07	0.29	1.2	1.0
Carotenoids (mg)	30–60	0.08	0.06	0.01	0.05	0.27
Polyphenols (mg GAE/g)	12–35	2.19	1.8	1.12	3.2	6.4
Potassium (mg)	~200	77	151	153	85	322
Selenium	Significant	Low	Low	Low	Low	Low

Key Differentiating Factors

The comparative evaluation clearly demonstrates the superior nutritional profile of sea buckthorn juice in relation to commonly consumed berry juices.

It has exceptionally high vitamin C content, significantly higher vitamin E levels, and dramatically greater carotenoid concentration compared to other berries. These attributes make it a highly valuable functional food.

Health Benefits of Sea Buckthorn Juice

Cardiovascular Health: Consumption of sea buckthorn juice has been associated with improved lipid profiles.

Immune System Support: High levels of vitamin C and antioxidants strengthen immune defense mechanisms.

Anti-Cancer Potential: Bioactive compounds such as flavonoids and carotenoids inhibit cancer cell growth.

Skin and Dermatological Benefits: Sea buckthorn promotes collagen synthesis, improves skin elasticity, and protects against UV damage.

Discussion

The analysis indicates that sea buckthorn juice is one of the most nutritionally superior plant-based beverages. Its unique combination of vitamins, antioxidants, and fatty acids provides multiple health benefits.

Variability in nutrient composition due to geographic and environmental factors remains a challenge, and standardization is necessary.

Safety and Consumption

Sea buckthorn juice is generally safe when consumed in moderate quantities (50–100 mL per day).

Individuals on medication should consult healthcare professionals before regular consumption.

Conclusion

Sea buckthorn juice is a highly valuable functional food with exceptional nutritional and therapeutic properties. Its superiority in vitamin C content, antioxidant capacity, and omega fatty acid profile makes it a promising dietary component.

References

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