

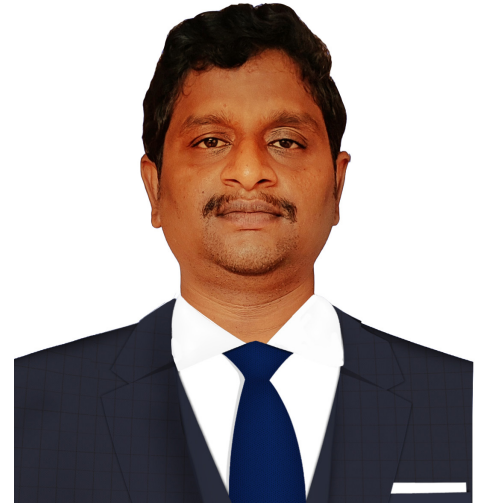
INDEX

S.No	Title	Page No
1.	A Public Disconnected from Agriculture	04
2.	Embracing the Future of AI Shaping a Better Tomorrow	11
3.	Fisheries Science in the UPSC Civil Services Examination: Rationale, Scope and Policy Perspectives	15
4.	India's Careful Bet on Gene-Edited Crops	22
5.	Halim Seeds: An Underutilised Nutraceutical Food	25
6.	Edible Flowers: From Cultivation to Nutritious Food and Value Addition	29
7.	Digital Agricultural Extension: Transforming Farmer Advisory Services in the Digital Era	31
8.	Plant Pangenomics: Concepts, Classification and Construction Approaches	36
9.	Pangenomics: Applications in Plant Genetics and Breeding	43
10	Soil-Borne Diseases of Pigeonpea: A Hidden Threat to Crop Productivity	53
11	Pumpkin Seeds- Power House Of Nutrition With Healthpromoting Properties And Food Applications	58

From the Desk of Editor-in-Chief

With immense humbleness and anticipation, I seek it's my pleasure to launch the September 2026 issue of the **“Krishi Netra”** a monthly e-Magazine subtitled “Invisible Vision on Farming” published by **GRN Creatives**. On behalf of the Krishi Netra Editorial Team, I would like to take this opportunity to thank our authors, editors, reviewers and all of them who have volunteered to contribute to the successful release of the first (December) issue of the e-Magazine.

The magazine aims to provide a common platform for the scientific community, research scholars and other readers to publish their ideas, new inventions, research findings etc., to provide the invisible insights for betterment of the farming community. Krishi Netra magazine is primarily focused on the areas of Agriculture, Horticulture, Precision Farming, Fisheries & Animal Sciences, Agriculture Engineering, Agribusiness Management, Food & Dairy Technology, Bio-Sciences/ Life-Sciences, Biotechnology & Biochemistry, Environmental Science & Forestry, Organic Farming, Sericulture and Home Science.



As we turn the pages of Krishi Netra, let us celebrate the unsung heroes, the farmers, the agri-entrepreneurs, the scientists, and the agri scholars. Together, we delve into the realms of sustainable practices, agro ecology, and the transformative power of technology, ensuring that the seeds we sow today yield a bountiful harvest for generations to come.

May this magazine be a source of inspiration, knowledge, and appreciation for the remarkable journey from seed to harvest. Join us on this exploration of the fields that bind us all, as we cultivate a deeper understanding and appreciation for the intricate dance of life on the farm.

I warmly welcome the authors with their contributions that can meet the practical appliances with an integrated/ convergent approach. I wish, with all your support I could see a very bright prospects for Krishi Netra magazine as an eye opener in serving the needs of the farming community.

We look forward for your valuable feedback!

For any questions/ suggestions/ concerns, please contact us: krishinetra@gmail.com

Thank you.

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Gangisetty Srikanth Kumar

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Gangisetty Srikanth Kumar
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A Public Disconnected from Agriculture

Dr.T.Bharath

Senior Scientist& head, Krishi Vigyan Kendra, Bhadradi Kothagudem

Corresponding Author: kvkkothagudem@pjtau.edu.in

Agriculture is one of the oldest and most fundamental activities of human civilization. Every meal we eat, every grain of rice we cook, every vegetable we consume and every cotton garment we wear has a connection with agriculture. Yet, in today's rapidly urbanizing world, a growing section of society is becoming increasingly disconnected from farming and from the people who produce our food. This disconnect is not simply a physical distance between cities and villages. It is also a **social, economic, cultural and psychological disconnect**. Many people, particularly younger generations living in towns and cities, know little about where their food comes from, how it is produced, what challenges farmers face, or how much effort is required to produce a crop.

Agriculture: The Invisible Foundation of Everyday Life

For most consumers, food appears on supermarket shelves, in restaurants or through online delivery platforms. The long journey from soil to plate is largely invisible. A packet of rice may appear as a simple commodity, but behind it lies land preparation, seed selection, nursery management, transplanting or sowing, irrigation, nutrient management, weed control, pest and disease management, harvesting, drying, processing, transportation and marketing.

Similarly, vegetables reaching an urban household may have passed through the hands of farmers, agricultural labourers, traders, transporters, wholesalers and retailers before reaching the consumer. The consumer generally sees only the **final product**, while the farmer experiences the entire production process. This creates a dangerous misconception that food production is easy, automatic and always available.

Why Is Society Becoming Disconnected from Agriculture?

1. Rapid Urbanization

Urbanization has transformed the relationship between people and agriculture. As villages expand into towns and cities, agricultural land is converted for housing, roads, industries and commercial establishments. Children growing up in cities may have very limited exposure to farms. They may know the names of agricultural products but not understand how those products are produced. A child may recognize a tomato in a supermarket but may never have seen a tomato plant.

2. Changing Occupational Patterns

Agriculture once provided employment and livelihood to a large proportion of rural families. Today, many rural youth are moving towards education, government employment, business, construction, manufacturing and service-sector jobs. This transformation provides new opportunities, but it can also weaken the transfer of traditional agricultural knowledge from one generation to another. As young people leave

farming, agriculture may gradually become associated with older generations rather than being viewed as a modern and knowledge-intensive profession.

3. Food Has Become a Consumer Product

Modern food systems have made food increasingly convenient. People purchase packaged foods, processed products and ready-to-eat meals without necessarily knowing their agricultural origins. A consumer may know the brand name of a product but not the crop, farmer or farming system behind it. This creates what can be called the “**farm-to-plate awareness gap.**”

4. Perception of Farming as a Low-Status Occupation

In some communities, farming is still perceived as less prestigious than urban employment.

Such attitudes can discourage educated rural youth from entering agriculture.

However, modern agriculture requires knowledge of:

- Soil science
- Plant breeding
- Agronomy
- Agricultural engineering
- Weather and climate
- Digital technologies
- Farm economics
- Marketing
- Post-harvest management
- Data analysis
- Natural resource management

The farmer of the future will not simply be a cultivator. He or she will increasingly be an **entrepreneur, environmental manager, technology user and business decision-maker.**

The Hidden Challenges Faced by Farmers

The public often sees agricultural commodities but rarely sees agricultural risks. Farmers operate under uncertainties that consumers may not fully appreciate.

Weather Risk

Rainfall may arrive late, early or excessively. Drought, floods, heat waves and unseasonal rains can severely affect production.

Pest and Disease Risk

Crops are vulnerable to insects, diseases, weeds and other biological stresses. A pest outbreak can significantly reduce both yield and income.

Market Risk

Even when a farmer produces a good crop, the selling price may fluctuate. Production costs, transportation expenses, market demand and supply conditions all influence farm profitability.

Rising Input Costs

Seeds, fertilizers, pesticides, machinery, labour, irrigation and fuel contribute to production costs. Farmers must make decisions before knowing the final market price of their produce.

Climate Change

Changing temperature and rainfall patterns are creating additional challenges for agriculture. Farmers increasingly need climate-resilient varieties, efficient water management, diversified farming systems and improved weather-based decision-making. Thus, when consumers complain about food prices, it is important to understand that the price paid by the consumer and the income received by the farmer are not necessarily the same.

The Farmer–Consumer Relationship Needs to Be Rebuilt

Agriculture should not be viewed merely as a sector that produces food. It is a **shared social system connecting farmers and consumers**. Consumers depend on farmers for food, while farmers depend on consumers and markets for income. This relationship can be strengthened through greater transparency, direct marketing, farmer-producer organizations, local markets, community-supported agriculture and awareness programmes. When consumers understand the effort involved in food production, they are more likely to appreciate the value of food and reduce unnecessary food waste.

Reconnecting Children with Agriculture : One of the most effective ways to address agricultural disconnect is to introduce children to farming at an early age.

School Nutrition Gardens : Students can grow vegetables, herbs and fruit plants and learn about soil, seeds, water and nutrition.

Farm Visits : Educational visits to farms can allow students to observe sowing, crop growth, harvesting and livestock management.

Farmer Interaction Programmes : Farmers can be invited to schools to explain their experiences and challenges.

Agricultural Science Activities : Students can conduct simple experiments involving seed germination, composting, soil types, water conservation and plant growth.

Such activities can transform agriculture from a textbook subject into a **living experience**.

Technology Can Help Reconnect Society with Agriculture

Interestingly, technology that sometimes contributes to the disconnect can also help overcome it.

Digital platforms can bring consumers closer to farmers through:

- Farmer stories
- Farm videos
- Digital marketplaces
- Traceability systems
- Crop information
- Weather advisories
- Agricultural podcasts
- Social media awareness campaigns
- Virtual farm tours

A consumer can potentially learn where a product was grown, which farming practices were used and how it travelled to the market. Digital agriculture therefore has the potential to create a more transparent relationship between **producer and consumer**.

Agriculture Is More Than Food

Another important reason for reconnecting society with agriculture is that farming provides numerous environmental services.

Well-managed agricultural landscapes can contribute to:

- Soil conservation
- Water conservation
- Carbon sequestration
- Biodiversity conservation
- Nutrient cycling
- Landscape management
- Rural employment
- Preservation of traditional knowledge

Systems such as **agroforestry, integrated farming, organic and natural farming approaches, conservation agriculture, crop diversification and integrated crop-livestock systems** can improve

resource-use efficiency while supporting farm livelihoods when appropriately designed for local conditions. Therefore, agriculture should not be evaluated only by the quantity of food produced. Its contribution to **environmental sustainability and rural society** must also be recognized.

Food Waste: A Major Consequence of Disconnection

When people do not understand the effort required to produce food, food may be treated as disposable. Food wasted at homes, restaurants, institutions and markets represents wasted:

Seed + Soil + Water + Labour + Energy + Money + Time

Reducing food waste is therefore one of the simplest ways for consumers to show respect for farmers and natural resources. Consumers can help by purchasing appropriate quantities, storing food properly, using leftovers creatively and avoiding unnecessary disposal.

Supporting Farmers Does Not Mean Rejecting Modernization

Reconnecting with agriculture does not mean returning society to the past. Agriculture itself must continue to modernize.

The goal should be to combine:

Traditional agricultural wisdom + Scientific knowledge + Modern technology + Sustainable resource management

Precision agriculture, drones, remote sensing, artificial intelligence, improved crop varieties, farm mechanization, protected cultivation, micro-irrigation and digital marketing can create new opportunities. At the same time, traditional knowledge regarding local crops, seed conservation, mixed farming and natural resource management can provide valuable lessons. The future of agriculture lies not in choosing between tradition and technology, but in **combining the strengths of both**.

The Role of Krishi Vigyan Kendra's and Extension Institutions

Agricultural extension institutions have an important role in reconnecting society with farming. Krishi Vigyan Kendras (KVKs), agricultural universities, research institutions, NGOs and farmer organizations can organize:

- Farmers' training programmes
- School agricultural awareness programmes
- Farm and field demonstrations
- Exposure visits
- Agricultural exhibitions
- Farmer–consumer meetings
- Nutrition garden programmes

- Youth-oriented agricultural entrepreneurship programmes
- Skill development programmes
- Awareness campaigns on sustainable agriculture

Extension should not communicate only with farmers. **Consumers, students, teachers, entrepreneurs and urban communities also need agricultural awareness.**

Rural Youth Can Become the Bridge

Rural youth have a unique opportunity to reconnect agriculture with modern society.

They can create enterprises in:

- Seed production
- Nursery management
- Custom hiring of farm machinery
- Food processing
- Digital agriculture
- Agri-tourism
- Dairy and livestock enterprises
- Mushroom cultivation
- Beekeeping
- Organic input production
- Farm advisory services
- Direct marketing

Agriculture can become attractive to young people when it is presented not merely as traditional cultivation but as a **diverse and innovative economic sector**.

Urban Consumers Also Have a Role

Reconnecting with agriculture does not require everyone to become a farmer.

Urban citizens can contribute in simple ways:

- Learn where their food comes from.
- Visit farms when opportunities arise.
- Support local farmers and farmer organizations.

- Avoid unnecessary food waste.
- Grow a small kitchen or terrace garden.
- Encourage children to learn about agriculture.
- Understand seasonal availability of crops.
- Respect the labour involved in food production.
- Prefer informed and responsible consumption.
- Recognize agriculture as an essential part of society.

Even a small balcony garden can change the way a person looks at food. When someone grows a tomato plant and waits weeks for a few fruits, the effort involved in farming becomes much more understandable.

Building a Farm-to-Plate Culture

A healthier society needs a stronger **farm-to-plate connection**. Imagine a system in which a child understands that rice comes from a paddy field, cotton comes from a cotton plant, pulses come from legume crops and edible oils originate from oilseed crops. Imagine consumers understanding seasonal production and farmers receiving greater recognition for their contribution. Imagine schools where students grow food, communities where farmers and consumers interact, and markets where the origin of agricultural products is transparent.

Such a system would create not only better-informed consumers but also a more respectful relationship between rural and urban communities.

Agriculture and the Future of Civilization

Human civilization has always depended on the ability to produce food sustainably. As population, urbanization, climate pressures and resource constraints increase, society cannot afford to remain disconnected from agriculture.

“How can society and agriculture understand and support each other?”

Farmers need access to knowledge, technology, markets, infrastructure and fair economic opportunities. Consumers need safe, nutritious and affordable food. The environment needs responsible management of soil, water and biodiversity.

Conclusion: From Disconnection to Appreciation

The growing distance between society and agriculture is one of the less visible challenges of modern development. When people become disconnected from farming, they can lose sight of the labour, risks, natural resources and knowledge involved in producing food.

Embracing the Future of AI Shaping a Better Tomorrow

Dr. Roshni Sahu and Dr. Rakesh Sahu
College of Agriculture, JNKVV Jabalpur
Corresponding Author: roshnisahujbp@gmail.com

The creation of Artificial Intelligence, mostly known as AI, has raised important questions regarding ethical and humane practices in fast growing society. While some of its applications propose new practices and perspectives, there's also a profound danger that comes with the potential harm that can be caused with such a tool at the tip of anyone's fingers. Ultimately, what I find most interesting about AI is the ability for it to offer global evidence for vast issues that many people are uneducated on. I feel like one thing that can be eye opening and incredibly hopeful is developing many solutions to environmental issues and supporting global challenges.

Imagine AI as a supercharged tool—a kind of Swiss Army knife for solving humanity's biggest problems. Here's how it can change our lives:

How AI Can Help Society

1. Better Healthcare:

Think of AI as a super-doctor. It can spot diseases early, create personalized treatments, and help manage chronic conditions. This means people could live longer, healthier lives, and hospitals could work more efficiently.

2. Saving the Planet:

AI is like a climate scientist on steroids. It can predict weather patterns, model climate change, and help us make smarter decisions about how to protect the environment. This could mean fewer natural disasters and a healthier planet for future generations.

3. Boosting the Economy:

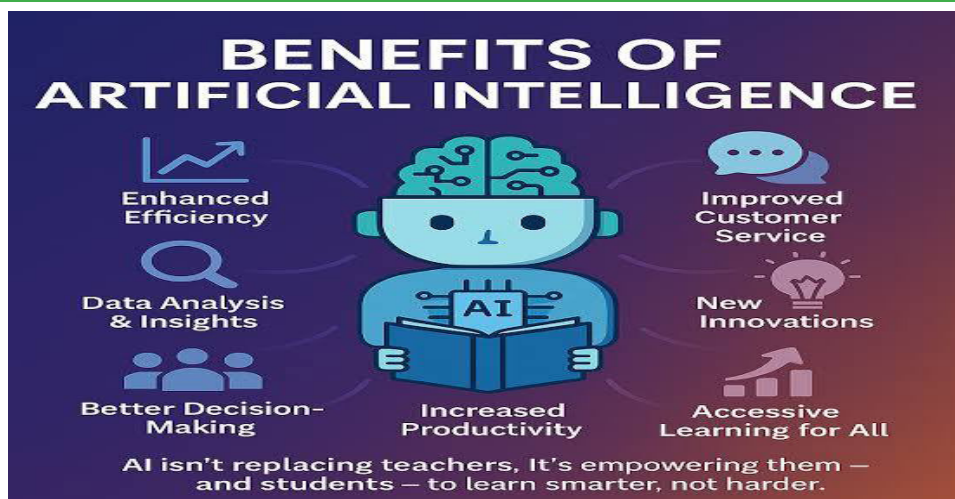
AI is a turbocharger for innovation. It can speed up scientific discoveries, create new industries, and make businesses more productive. This means more jobs, better products, and a stronger economy.

4. Fighting Inequality:

AI can be a tool for fairness. It can help distribute resources more evenly, improve access to healthcare and education, and support policies that lift up marginalized communities. In short, it can help level the playing field.

5. Global Teamwork:

AI brings people together. It encourages scientists, governments, and businesses to collaborate across borders, sharing knowledge to solve big problems like pandemics, hunger, and energy shortages.



How AI Will Change Industries

1. Faster Innovation:

AI can discover new materials, design better products, and make manufacturing cleaner and more efficient. Imagine lighter, stronger materials for cars or buildings, all designed by AI.

2. Smarter Decisions:

AI can analyze mountains of data to help businesses make better choices. For example, it can predict market trends, manage risks, or even help doctors diagnose diseases faster.

3. Teamwork Between Sectors:

AI encourages collaboration. Universities, companies, and governments can work together more effectively, sharing ideas and turning them into real-world solutions.

4. New Jobs and Skills:

As AI changes industries, workers will need new skills. This means schools and training programs will have to adapt, teaching people how to work with AI instead of being replaced by it.

5. Rules for AI:

With great power comes great responsibility. As AI becomes more common, we'll need new laws and guidelines to make sure it's used ethically and safely.

Real-World Examples of AI in Action

1. Healthcare:

- AI can help doctors detect diseases like cancer earlier and create personalized treatment plans.
- It can also speed up drug development by analyzing data from clinical trials.

2. Environment:

- AI can predict hurricanes, droughts, and other climate-related events, helping us prepare and adapt.

- It can also optimize energy use, reduce waste, and design eco-friendly technologies.

3. Manufacturing:

- AI can invent new materials, like stronger metals or biodegradable plastics.
- It can also make supply chains more efficient, reducing delays and costs.

4. Education:

- AI can create personalized learning plans for students, helping them learn at their own pace.
- It can also identify skills gaps in the workforce and design training programs to fill them.

5. Business:

- AI can analyze customer behavior, predict trends, and help companies make smarter decisions.
- It can also improve customer service by offering personalized recommendations and instant support.

The Bottom Line

AI isn't just a fancy gadget—it's a game-changer. By integrating AI into healthcare, the environment, education, and business, we can solve problems faster, work smarter, and create a better future for everyone. But to make this happen, we need to invest in research, teach people how to use AI, and make sure it's used responsibly. The future is in our hands—let's make it a good one.

Making the world a better place

The third pillar of responsible AI, sustainability, is about tackling the environmental implications of AI development. Training a state-of-the-art machine learning model requires significant energy — [in some cases](#), this process can emit as much carbon dioxide as five vehicles across their lifespans. One of the solutions that partners of the Center for Responsible AI will be collaborating on is the development of a “green score” for rating AI models on their energy efficiency. Similar to Energy Star certified appliances, we want to have a seal of approval that designates when an AI model has achieved a certain level of sustainable energy performance.

Summary of the Article on Artificial Intelligence and Society



Artificial Intelligence (AI) has rapidly evolved and raised important ethical questions about how it should be used responsibly. While AI holds risks, especially when misused, it also offers enormous potential to help solve global problems. One of its most promising strengths is its ability to analyze massive amounts of information and create solutions to issues that many people may not fully understand, particularly environmental and societal challenges.

AI can transform society in several positive ways. In healthcare, it can detect diseases early and personalize treatment, helping people live healthier lives. For the environment, AI can predict climate events, improve

resource management, and support climate change solutions. Economically, AI boosts innovation, productivity, and job creation. It can also help reduce inequality by improving access to education, healthcare, and resources. AI further encourages global collaboration by helping scientists and governments work together on issues like pandemics, hunger, and energy shortages.

Industries are also being reshaped by AI. It accelerates innovation by designing new materials and improving manufacturing. Businesses use AI for smarter decision-making and risk management. Education systems will need to adapt as new skills become necessary for the AI-driven workforce. At the same time, ethical rules and regulations will be essential to ensure safe and responsible AI use.

Real-world applications already show AI's impact in healthcare, environmental protection, manufacturing, education, and business. However, AI development also has environmental costs. Training advanced models consumes large amounts of energy—sometimes producing as much carbon dioxide as multiple cars over their lifetimes. To address this, researchers are developing a “green score” to evaluate and certify AI models based on their energy efficiency, similar to Energy Star ratings for appliances.

Overall, AI is a powerful tool that can make the world better—if developed responsibly, used ethically, and designed with sustainability in mind.

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Fisheries Science in the UPSC Civil Services Examination: Rationale, Scope and Policy Perspectives

A Case for Recognising Fisheries Science as a Dedicated Academic Subject in Civil Services Education and Examination

Dr. Vinay Maruti Hatte
Assistant Fisheries Development Officer, Jalgaon
Corresponding Author: hatte.vinay@gmail.com

Abstract

Fisheries and aquaculture are strategically important to India's food and nutritional security, employment, rural livelihoods, coastal and inland economies, exports and blue-economy development. The sector is also closely linked with biodiversity conservation, aquatic ecosystem management, climate resilience, rural development, technology, public administration and inclusive growth. Despite this broad significance, Fisheries Science is not currently offered as a dedicated optional subject in the Union Public Service Commission (UPSC) Civil Services Main Examination. The present article examines the rationale for considering Fisheries Science as a dedicated optional subject and, more broadly, for strengthening fisheries content within civil-services education and capacity building. It reviews the multidisciplinary character of Fisheries Science, its relevance to governance and public policy, the existing position of fisheries-related topics within the Civil Services Examination, possible academic scope, institutional requirements and challenges. The article argues that any consideration of a new subject should be based on transparent syllabus development, availability of qualified academic expertise, adequate question-setting and evaluation capacity, and consistency with UPSC's examination framework.

Keywords: Fisheries Science, UPSC, Civil Services Examination, aquaculture, fisheries governance, blue economy, public administration, optional subject, human resource development

1. Introduction

The fisheries sector is a multidimensional component of India's economy and natural-resource governance. It includes marine and inland capture fisheries, aquaculture, ornamental fisheries, fish seed production, fish nutrition, aquatic animal health, processing, cold-chain, marketing, fisheries economics, extension and aquatic environmental management. Consequently, effective governance of fisheries requires administrative officers to understand biological resources as well as socioeconomic, technological, environmental and regulatory dimensions.

The Union Public Service Commission (UPSC) conducts the Civil Services Examination (CSE) for recruitment to services and posts of the Government of India. The examination includes General Studies papers and an optional-subject component in the Main Examination. The UPSC's current examination material lists Agriculture and Animal Husbandry & Veterinary Science among the optional subjects, but Fisheries Science is not listed as a separate optional subject.

This situation provides a basis for a policy and academic discussion: whether Fisheries Science, as a distinct multidisciplinary professional field, merits recognition as a dedicated optional subject in the Civil Services

Main Examination and whether fisheries-related content should receive greater systematic attention in civil-service training.

2. Current Position of Fisheries in the Civil Services Examination

Fisheries-related issues can be relevant to several areas of the Civil Services syllabus, including agriculture and allied activities, environmental conservation, biodiversity, food security, rural development, science and technology, economics, disaster management and governance. However, the absence of a dedicated Fisheries Science optional means that candidates with specialized academic training in fisheries do not have an optional subject directly aligned with their professional discipline.

The current UPSC examination framework demonstrates that specialized scientific and professional subjects are already accommodated as optional disciplines. The official UPSC previous-question-paper repository for 2026, for example, includes Agriculture and Animal Husbandry & Veterinary Science among the optional subjects.

The proposal to consider Fisheries Science therefore needs to be examined not as a preference for one profession over another, but as a question of academic representation, administrative relevance, syllabus feasibility and examination integrity.

3. Why Fisheries Science is Important for Public Administration

3.1 Food and Nutritional Security

Fish is an important source of high-quality animal protein and micronutrients. Public administrators working in agriculture, rural development, food systems and social-sector programmes benefit from understanding fisheries production, distribution, food safety and access.

3.2 Livelihoods and Rural Development

Millions of people participate directly or indirectly in fisheries and allied activities. Fisheries governance therefore involves livelihood support, infrastructure, market access, social protection, cooperative development and community institutions.

3.3 Blue Economy

Fisheries are a major component of the blue economy. Governance of marine resources increasingly requires integration of economic development with ecosystem conservation, maritime interests, coastal livelihoods and sustainable resource use.

3.4 Environmental Governance

Aquatic ecosystems face pressures from pollution, habitat alteration, overexploitation, invasive species, climate change and other factors. Fisheries Science provides scientific foundations for resource assessment, ecosystem management and biodiversity conservation.

3.5 Aquaculture Development

India's aquaculture sector involves hatcheries, nursery systems, ponds, reservoirs, cages, feed, aquatic

health, processing and marketing. Administrators involved in agricultural and rural development require an understanding of these interconnected systems.

3.6 Climate Change and Disaster Resilience

Cyclones, floods, droughts, heat stress, changing rainfall and other climate-related risks can affect fishers, aquaculture farms and aquatic ecosystems. Fisheries knowledge can strengthen planning for adaptation, disaster preparedness and resilient livelihoods.

4. Multidisciplinary Nature of Fisheries Science

Fisheries Science is not limited to fish biology. It integrates multiple scientific and social disciplines, making it relevant to the broad analytical requirements of civil services:

Fisheries biology, taxonomy and ecology

Aquaculture and hatchery management

Fish genetics, breeding and biotechnology

Fish nutrition and feed technology

Aquatic animal health and disease management

Fisheries oceanography and limnology

Fishing technology and fisheries engineering

Fish processing, preservation and food safety

Fisheries economics and marketing

Fisheries extension and rural development

Fisheries resource management and conservation

Climate change, aquatic environment and sustainability

5. Rationale for a Dedicated Fisheries Science Optional Subject

5.1 Academic Recognition

Fisheries Science has developed into a specialized professional discipline with undergraduate, postgraduate and doctoral education, research institutions, universities and a specialized workforce. Recognition as an optional subject could provide a formal examination pathway for candidates trained in this field.

5.2 Administrative Relevance

Civil servants may work in departments and programmes concerned with agriculture, fisheries, rural development, environment, food processing, coastal development and blue economy initiatives. A structured fisheries syllabus could test knowledge directly relevant to these administrative responsibilities.

5.3 Balanced Representation of Allied Sectors

The present optional-subject framework includes several specialized scientific disciplines. Consideration of Fisheries Science could be examined within the broader principle of whether important professional disciplines with substantial academic infrastructure and public-policy relevance are adequately represented.

5.4 Strengthening Fisheries Governance

A dedicated academic subject could encourage deeper understanding of fisheries policies, resource management, aquaculture development, community institutions, technology adoption and sustainability among aspirants who choose the discipline.

6. Proposed Scope of a Fisheries Science Syllabus

If UPSC were to consider Fisheries Science as an optional subject, a balanced syllabus could be developed around the following broad areas:

Fisheries biology, biodiversity and aquatic ecology.

Marine and inland fisheries resources, stock assessment and sustainable management.

Aquaculture systems, hatchery management, seed production and farm management.

Fish genetics, selective breeding, biotechnology and emerging technologies.

Fish nutrition, feed formulation and feed management.

Aquatic animal health, fish pathology, biosecurity and disease prevention.

Fishing craft, gear technology and responsible fishing practices.

Fish processing, preservation, value addition, food safety and quality assurance.

Fisheries economics, marketing, entrepreneurship and value-chain management.

Fisheries extension, fisher institutions, cooperatives and livelihood development.

Fisheries policies, legislation, governance and institutional framework.

Climate change, aquatic pollution, conservation and ecosystem-based fisheries management.

Blue economy, marine spatial planning and emerging opportunities.

Case studies involving Indian fisheries and aquaculture development.

7. Relationship with General Studies

Recognition of Fisheries Science as an optional subject would not eliminate the need for fisheries-related issues in General Studies. Fisheries intersects with several general-policy themes and can be incorporated through current affairs, agriculture and allied sectors, environment, biodiversity, science and technology, economy, rural development and disaster management.

A dedicated optional subject and appropriate General Studies coverage would serve different purposes. General Studies could assess broad awareness and policy understanding, while an optional subject could assess deeper scientific, technical and analytical knowledge.

8. Potential Benefits for Civil Services and Governance

Improved availability of candidates with specialized fisheries knowledge for public-sector administration.

Greater scientific understanding of fisheries and aquaculture policy issues.

Improved capacity to interpret technical reports, research findings and fisheries statistics.

Better appreciation of the livelihood dimensions of fisheries-dependent communities.

Stronger understanding of aquatic environmental management and conservation.

Greater integration of fisheries with agriculture, rural development and blue-economy planning.

Encouragement of fisheries graduates to consider civil services as a career pathway.

Potential strengthening of interdisciplinary policymaking involving fisheries, environment, food systems and rural development.

9. Academic and Institutional Requirements

The introduction of any new UPSC optional subject requires careful institutional preparation. A Fisheries Science syllabus should be developed through consultation with experienced fisheries academics, researchers, administrators and subject experts.

1. Constitute an expert committee representing major fisheries disciplines.
2. Develop a comprehensive but manageable syllabus with clearly defined learning outcomes.
3. Ensure adequate academic depth while avoiding excessive specialization.
4. Establish transparent standards for question-paper setting and evaluation.
5. Prepare model question papers and examiner guidelines.
6. Ensure availability of qualified evaluators across the major sub-disciplines.
7. Review the syllabus periodically to incorporate advances in fisheries science and policy.
8. Maintain parity in examination standards, analytical demand and workload with existing optional subjects.
10. Challenges and Considerations

10.1 Institutional Capacity

A new optional subject requires sustained capacity for question setting, moderation, evaluation and syllabus review. Adequate availability of qualified subject experts would therefore be essential.

10.2 Syllabus Breadth

Fisheries Science covers a large number of disciplines. A syllabus that is too broad could become difficult to prepare, while excessive specialization could reduce accessibility and create an imbalance between sub-disciplines.

10.3 Candidate Base

The likely number of candidates choosing a new subject would need to be considered as part of the Commission's assessment. However, the size of a discipline alone should not determine its academic value; examination feasibility and administrative relevance are also important considerations.

10.4 Maintaining Examination Neutrality

Any new subject should be designed and evaluated according to the same principles of fairness, comparability and academic rigor applied to other optional subjects.

10.5 Periodic Review

Fisheries technologies and policy priorities change rapidly. Areas such as precision aquaculture, genomics, artificial intelligence, climate-resilient aquaculture and blue-economy governance may require periodic syllabus revision.

11. Fisheries Education and Civil-Service Capacity Building

Even if Fisheries Science is not immediately introduced as a dedicated optional subject, fisheries education can be strengthened within civil-service capacity building. Foundation and professional training programmes can provide administrators with introductory knowledge of fisheries policy, aquaculture, aquatic conservation, fisheries economics and livelihood development.

Universities, ICAR fisheries institutes, State fisheries departments and civil-service training institutions can collaborate to develop short courses, policy modules, case studies and field-based learning programmes. Such collaboration can improve the ability of administrators to translate fisheries science into effective public policy.

12. Way Forward

1. Undertake an academic and administrative feasibility study on Fisheries Science as a potential UPSC optional subject.
2. Map existing fisheries content across the Civil Services syllabus and identify areas requiring stronger representation.
3. Consult ICAR institutes, fisheries universities, subject experts, administrators and professional bodies.
4. Develop a draft syllabus covering fundamental science, applied fisheries, economics, governance, environment and contemporary issues.
5. Assess the availability of qualified question setters, moderators and evaluators.
6. Prepare sample papers and conduct an academic review before any formal introduction.

7. Strengthen fisheries-related modules in civil-service foundation and in-service training regardless of the decision on an optional subject.
8. Promote interdisciplinary understanding of fisheries within agriculture, environment, rural development and blue-economy policy.

13. Conclusion

Fisheries Science has developed into a comprehensive professional discipline with direct relevance to food security, livelihoods, environmental conservation, aquaculture, rural development, exports and the blue economy. The current UPSC Civil Services Examination offers several specialized optional subjects, including Agriculture and Animal Husbandry & Veterinary Science, while Fisheries Science is not presently available as a separate optional subject.

The proposal to consider Fisheries Science as a dedicated optional subject can therefore be examined on the basis of academic maturity, multidisciplinary scope, administrative relevance, availability of expertise and examination feasibility. Such consideration should be undertaken through an objective and transparent process rather than through sectoral preference alone.

Whether or not a dedicated optional subject is ultimately introduced, greater fisheries literacy among civil servants would be valuable. Strengthening fisheries content in General Studies, civil-service training and public-policy education can help administrators understand aquatic resources, fisher livelihoods, aquaculture, environmental sustainability and the emerging blue economy. A systematic interface between fisheries education and civil-service capacity building could consequently contribute to more scientifically informed and context-sensitive fisheries governance in India.

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India's Careful Bet on Gene-Edited Crops

Pranita Thakur*, Srushti Gunjal, Suhani Singh.

D. Y. Patil school of Biotechnology and Bioinformatics, Navi-Mumbai, India

Corresponding Author: pranita.thakur@dypatil.edu

INTRODUCTION

In laboratories across India, researchers are using genome-editing technologies to make targeted changes to crop genomes in the hope of developing plants with improved productivity, drought tolerance, salinity tolerance and climate resilience. Unlike conventional genetic modification, some genome-editing approaches can produce plants without foreign DNA remaining in the final product. This distinction has become central to India's regulatory approach to genome-edited plants (Department of Biotechnology [DBT], 2022; Press Information Bureau [PIB], 2022). India's regulatory framework distinguishes genome-edited plants according to different categories of site-directed nuclease (SDN) technology, making the nature of the genetic change important in determining the appropriate regulatory pathway (DBT, 2022).

Three Letters That Matter: SDN

SDN-1 generally involves targeted genetic changes without the use of a repair template, whereas SDN-2 uses a template to guide a specific modification. SDN-3 involves more substantial genetic alterations, including the insertion of genetic material, and is subject to more extensive regulatory requirements under India's genome-editing framework (DBT, 2022). In March 2022, India's Ministry of Environment, Forest and Climate Change provided an exemption from certain provisions of the 1989 Rules for qualifying SDN-1 and SDN-2 genome-edited plants that are free from exogenous introduced DNA. The Department of Biotechnology subsequently issued the Guidelines for the Safety Assessment of Genome Edited Plants, 2022, followed by Standard Operating Procedures for the regulatory review of SDN-1 and SDN-2 plants (PIB, 2022; DBT, 2022).

This does not mean that all genome-edited plants are completely unregulated. Developers must provide evidence demonstrating that the plant falls within the relevant SDN category and does not contain exogenous introduced DNA, while other stages of varietal development and evaluation remain subject to applicable laws and procedures (DBT, 2022; Government of India, 2025).

The underlying regulatory question is therefore whether a plant carrying a targeted genetic alteration, particularly one without foreign DNA, should automatically be treated in the same way as a conventionally transgenic genetically modified organism. India's current framework distinguishes qualifying SDN-1 and SDN-2 plants from other forms of genetic engineering while maintaining biosafety oversight (PIB, 2022).

Why India Is Betting on This at All

Indian agriculture faces major environmental and climatic pressures, including drought, salinity and other climate-related stresses. Genome editing has attracted attention because it can enable precise modifications to existing crop varieties, potentially improving specific traits while retaining characteristics already valued by farmers (ICAR, 2025). Rice has become an important area of genome-editing research in India. In 2025,

the Indian Council of Agricultural Research announced two genome-edited rice varieties, DRR Rice 100 (Kamala) and Pusa DST Rice 1, developed using CRISPR-based genome-editing technology without the introduction of foreign DNA. According to ICAR, these varieties were developed to improve productivity and tolerance to drought, salinity and other climate stresses (ICAR, 2025).

The potential appeal of genome editing is therefore not necessarily the creation of entirely unfamiliar crops, but the targeted improvement of varieties that already have agricultural importance and farmer acceptance. This approach is illustrated by India's genome-edited rice research, which modified established rice varieties through targeted genetic changes (ICAR, 2025; ICAR Genome Editing Project, n.d.).

Old Arguments, New Technology

Genome editing has emerged against the background of India's long-running debates over genetically modified crops. These earlier debates have shaped public discussions concerning agricultural biotechnology, regulation and public acceptance.

A central policy disagreement concerns whether regulation should focus primarily on the product or the process. Under a product-oriented approach, regulatory attention focuses on the characteristics of the final plant and whether it contains foreign genetic material. A process-oriented approach, by contrast, gives greater significance to the method used to create the genetic change. India's current framework gives particular regulatory importance to whether SDN-1 and SDN-2 plants are free from exogenous introduced DNA, thereby distinguishing these plants from conventional transgenic products for certain regulatory purposes (DBT, 2022; PIB, 2022).

The potential advantages of genome editing include targeted modification, potentially faster crop improvement and the development of traits associated with productivity and climate resilience. India's genome-edited rice programme, for example, has focused on improving yield, water use and tolerance to environmental stresses (ICAR, 2025).

At the same time, regulatory questions remain concerning biosafety assessment, the detection of unintended genetic alterations, transparency, intellectual property and public confidence. India's regulatory framework continues to require specified evidence and regulatory review even for genome-edited plants seeking exemption under the SDN-1 and SDN-2 pathway (DBT, 2022).

The Part Money and Science Can't Fix Alone: Trust

A scientifically developed regulatory system may still face difficulties if farmers and consumers do not trust how decisions are made. Public confidence can therefore depend not only on scientific evidence but also on the transparency and credibility of regulatory institutions. Important questions include how the absence of exogenous DNA is verified, what regulatory information is publicly available, how environmental performance is monitored and how intellectual-property arrangements affect access to the technology. India's regulatory process requires developers of qualifying SDN-1 and SDN-2 plants to provide evidence regarding their genome-edited products and their absence of exogenous introduced DNA (DBT, 2022).

India's substantial public agricultural research system may also play an important role in directing genome-editing research towards crops and agricultural challenges of national importance. ICAR's development of

genome-edited rice varieties demonstrates the significant role of public research institutions in this field (ICAR, 2025). Nevertheless, questions concerning patents, ownership, licensing and farmer access remain important policy considerations as genome-editing technologies move towards wider agricultural use.

Approval Is the Easy Part

Biosafety review is only one stage in the pathway from scientific research to widespread agricultural adoption. Genome-edited plants must also undergo relevant varietal development, evaluation and release procedures in accordance with applicable laws and regulations (Government of India, 2025). The development and release of India's genome-edited rice varieties illustrate how scientific innovation must move beyond laboratory research towards field evaluation and agricultural adoption (ICAR, 2025). Further policy questions may concern how farmers are informed about crop development methods, whether and how consumers receive information, and how differences between national regulatory systems may affect international trade.

Neither Too Fast Nor Too Slow

India faces the challenge of encouraging scientific innovation while maintaining credible biosafety oversight. Its current regulatory approach attempts to distinguish among different forms of genome editing while providing a defined pathway for qualifying SDN-1 and SDN-2 plants that are free from exogenous introduced DNA (DBT, 2022; PIB, 2022).

The policy challenge is not simply a choice between innovation and regulation. Effective regulation can provide researchers with clearer expectations while maintaining safeguards designed to address legitimate biosafety concerns. India's Guidelines and Standard Operating Procedures were specifically developed to provide a regulatory framework and clarify requirements for genome-edited plants (PIB, 2022). Transparency, proportionate risk assessment and clearly defined regulatory processes may therefore be important for balancing scientific development with public confidence.

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Halim Seeds: An Underutilised Nutraceutical Food

Dr. Jessie Suneetha. W^{1*}, Dr. D. Sravanthi¹, Dr. R. Neela Rani¹, Dr. G. Swarupa Rani¹, and
Ms. K. B. Nirmala²

¹ AICRP on Women in Agriculture, PJTAU, Rajendranagar, Hyderabad 500030

² Post Graduate and Research Center, PJTAU, Rajendranagar, Hyderabad 500030

Corresponding Author: wjsuneetha@yahoo.com

Introduction: Halim seeds commonly known as garden cress, aliv, asaliyo or chandrasura are the seeds of *Lepidium sativum* L., an annual herb belonging to the family Brassicaceae. Although the plant is widely distributed and traditionally consumed in several parts of India, its seeds remain comparatively underutilised in the modern food system. Recent studies have highlighted garden cress as a nutritionally dense seed containing appreciable amounts of protein, lipid, dietary fibre, minerals, essential fatty acids and diverse phytochemicals. Its traditional food use combined with its nutritional composition and functional properties places halim among the promising underutilised foods for further nutraceutical and functional-food development.

Cultivation and availability: Garden cress is a fast-growing herb adapted to a range of climatic conditions and is cultivated in parts of Asia, Africa and other regions. In India, it is traditionally grown for its seeds which are used as a food ingredient and in traditional health practices. The plant has a relatively short crop duration and can be cultivated with comparatively modest agricultural inputs making it relevant among underutilised crops suitable for diversification.

The seeds are small, reddish-brown to brown and contain a characteristic mucilaginous seed coat. On soaking, they develop a transparent mucilage, a property that contributes to their traditional culinary applications and also provides opportunities for food-ingredient development. Garden cress is currently cultivated on a relatively limited scale compared with major oilseed and cereal crops despite its nutritional potential.

Nutritional profile of halim seeds: The nutritional importance of halim seeds is particularly relevant in the context of dietary diversification. Unlike many commonly consumed cereal-based foods, the seed provides substantial protein and lipid along with minerals and bioactive compounds. It contains 21.0-25.0% protein, 23.0-25.0% fat and 30.0-34.0% carbohydrates, 11.9% fibre, 7.1% ash and 2.9% moisture. The seeds contained approximately 266.35 mg calcium, 8.31 mg iron, 339.23 mg magnesium, 608.63 mg phosphorus, 1236.51 mg potassium and 6.99 mg zinc per 100 g with variation in nutritional values based on cultivars, soil conditions and cultivation methods.

The protein fraction is also nutritionally relevant. Reported amino-acid values include leucine (8.21% protein), valine (8.04 % protein), lysine (6.26 % protein) and isoleucine (5.11% protein) indicating the presence of several nutritionally important essential amino acids. Halim is also notable for its lipid profile with approximately 34.0% α -linolenic acid in the seed lipid fraction together with linoleic acid and other fatty acids.

Bioactive components and nutraceutical potential: The nutritional value of garden cress seeds is complemented by a diverse phytochemical profile. Phytochemicals like phenolic acids, flavonoids, glucosinolates, terpenes, tocopherols and alkaloids, gallic acid, protocatechuic acid, caffeic acid, p-coumaric

acid and kaempferol derivatives. These compounds provide a biochemical basis for the antioxidant and other biological activities reported for garden cress. Glucosinolates are particularly important because they are characteristic secondary metabolites of Brassicaceae plants. The interaction between glucosinolates and their hydrolysis products together with phenolic and flavonoid compounds, contributes to the functional significance of the seed.

The seed mucilage is another important functional component. Hydration causes considerable swelling of the seed coat producing a viscous mucilaginous layer. This property has potential applications in food formulations where natural hydrocolloids are required for water binding, viscosity and texture modification. Garden cress seed oil, protein and fibre fractions have also been investigated as potential functional ingredients.

Halim seeds drink and food applications: Halim seeds are traditionally consumed as a cooling food, particularly after soaking in water or preparing them with milk. The hydrated mucilage absorbs water and produces a soft, gelatinous texture, which makes halim seeds suitable for refreshing summer beverages. A simple halim seeds drink can be prepared by soaking the seeds and combining them with milk, buttermilk or fruit-based beverages, along with jaggery or dates for sweetness. While the traditional “cooling” effect is widely recognised, studies specifically demonstrating a physiological cooling effect are limited.

Beyond beverages, halim seeds can be incorporated into laddoo, kheer, porridges, bakery products, biscuits, nutrition bars, breakfast mixes and extruded foods. Their protein, fibre, minerals and bioactive compounds can improve the nutritional density of these products, while soaking, roasting and germination can be used to modify their texture, flavour and functional properties. Thus, halim seeds offered scope for both traditional preparations and modern functional-food applications.

Health benefits: Halim seeds contain several bioactive compounds that contribute to their nutraceutical value. *Lepidium sativum* include gallic acid, caffeic acid, p-coumaric acid and protocatechuic acid while flavonoids such as kaempferol derivatives have also been identified. These compounds work as anticancer potential by enhancing antioxidant activity by scavenging reactive oxygen species and reducing oxidative stress. The garden cress seeds work as anti-hyperglycaemic, hypolipidemic, anti-inflammatory due to presence of α -linolenic acid and dietary fibre that also improves gastrointestinal and hormonal regulation,

Conclusion: Halim seeds have considerable potential to transition from a traditional, underutilised seed to a scientifically validated functional food ingredient. Their significance lies in the combination of high-quality

nutrients and bioactive compounds within a single, easily incorporable food resource. Rather than promoting garden cress seeds solely for its traditional medicinal uses, future research should establish its nutritional bioavailability, effects of processing and germination, and efficacy in human diets. Development of acceptable, affordable garden cress seeds-based foods could help its established nutritional potential into practical dietary benefits and contribute to greater utilisation of an underexploited crop.




Halim seeds



Halim seeds drink

Edible Flowers: From Cultivation to Nutritious Food and Value Addition

B. Akshitha^{1*} and Nazneen Begum¹

¹ Postgraduate Students, College of Community Science, Professor Jayashankar Telangana Agricultural University (PJTU), Hyderabad, Telangana, India.

Corresponding Author: akshithaburra04@gmail.com

Abstract

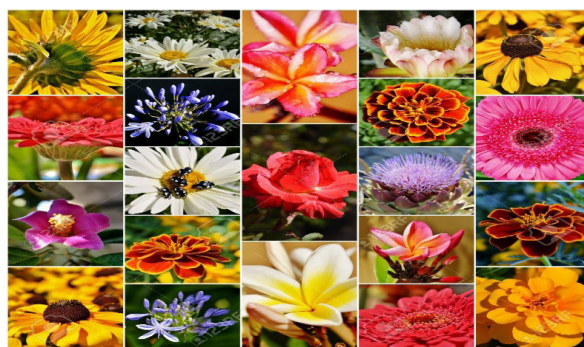
Edible flowers are gaining attention as an underutilized food resource, providing opportunities for crop diversification, value addition and direct marketing. Flowers like rose, hibiscus, butterfly pea, marigold, pumpkin, banana and moringa were used in different food preparations traditionally and explored for their nutritional and bioactive components. They are consumed fresh and also incorporated into teas, infusions, beverages, syrups, dried products, powders and bakery applications. For farmers, edible flowers can provide an opportunity to enter speciality markets, while food entrepreneurs can develop value-added products from fresh or dried flowers. Correct botanical identification, food-safe cultivation, hygienic handling and appropriate post-harvest management are essential because not all flowers are edible and flowers produced for ornamental purposes may have been exposed to unsuitable chemicals.

Keywords: Bioactive compounds, Food entrepreneurship, Food safety, Functional foods, Horticulture

Edible flowers are an underutilized plant resource that can be explored for both food and livelihood opportunities. Flowers are the plant tissues containing water, dietary fibre, pigments, minerals and a variety of bioactive compounds. Traditionally, Indians, Greeks, Romans, and Chinese have incorporated flowers into a wide range of foods, including flavourful drinks, vibrant salads, aromatic purees, delicate omelettes and indulgent desserts and they were also used as colouring agents. With appropriate production, handling and processing practices, these floral resources can be developed into fresh and value-added products, providing additional avenues for farm diversification and small-scale food enterprises.

Nutritional Composition of Edible Flowers

Nutritionally, edible flowers are predominantly water-rich, low-energy plant foods.



Their moisture content exceeds 80%, while protein and fat contents are relatively low. They provide carbohydrates, dietary fibre along with minerals like potassium, iron, zinc, manganese and copper. Their nutritional composition varies considerably with species. Along with the basic nutrients, edible flowers

contain bioactive compounds such as flavonols, anthocyanins and phenolic acids (Navarro-González *et al.*, 2014). Some edible flowers may contain antinutritional or potentially toxic compounds, emphasizing correct identification and safe preparation (Sotelo *et al.*, 2007).

Table 1. **Bioactive compounds in edible flowers**

Major group	Examples	Main visible/functional role
Phenolics	Gallic acid, caffeic acid, chlorogenic acid, ferulic acid	Antioxidant potential
Flavonoids	Quercetin, luteolin, rutin, catechin	Antioxidant potential; some contribute to colour
Anthocyanins	Cyanidin	Red, purple and blue colours; antioxidant potential
Carotenoids	β -carotene, β -cryptoxanthin, lutein	Yellow/orange colour; antioxidant potential
Tannins	Tannic acid	Polyphenolic plant compounds
Saponins	Various saponins	Naturally occurring plant bioactives
Terpenoids	Various terpenoids	Aroma and biological activity
Vitamin C	Ascorbic acid	Nutrient and antioxidant
Vitamin E	Tocopherol-related compounds	Antioxidant activity

Source: Compiled from Takahashi *et al.*, 2020; Suksathan *et al.*, 2021

Common Edible Flowers and Their Food Uses

Flowers are usually associated with gardens, decoration and fragrance but some flowers can also become interesting food ingredients.



Rose: Rose petals have a pleasant fragrance and are used to prepare rose water, syrups, jams, jellies and gulkand, desserts, ice creams, beverages and herbal infusions. Dried rose petals can be added to teas.

Hibiscus: Hibiscus is commonly used in beverages and infusions and can also be incorporated into syrups, jams, desserts, salads, sauces and other food products.

Butterfly pea: Its flowers are used in herbal drinks, infusions and foods such as bread, cakes, noodles and yoghurt. Their blue colour changes towards purple or pink when acidic ingredients such as lemon juice are added.

Marigold: Edible Tagetes species are used as colourful garnishes and in salads, soups, beverages and baked

foods; their pigments provide yellow to orange shades.

Pumpkin flowers: Flowers of *Cucurbita* species can be eaten fresh or cooked and are used in stuffed, fried, soup, salad and other preparations.

Banana flower: In different regions of India, it is prepared as curries, stir-fries, fritters, cutlets, chutneys and other traditional dishes. Examples include *Mochar Ghonto*, *Vazhaipoo Poriyal*, *Vazhaipoo Vadai* and banana flower chutney. In Assam, banana flower is also traditionally used in dishes such as *koldil bhaji* (Chowdary *et al.*, 2022).

Moringa or drumstick flowers: The flowers are traditionally incorporated into food preparations in some regions and are being explored as ingredients in food products and fortification.

Other edible flowers: Calendula, nasturtium, pansy, chrysanthemum, borage, lavender, violet and daylily have also been reported as edible and used in salads, desserts, beverages, garnishes and infusions.

Cultivation and Safe Production of Edible Flowers

Edible flowers are delicate and highly perishable. Therefore, harvesting and post-harvest handling are essential for maintaining quality. Flowers should be harvested at the appropriate stage, free from visible disease, insect damage and physical injury, and handled gently using clean food-contact containers while protecting them from excessive heat. For production, farmers should select species with an established history of food use that are suitable for the local environment, considering climate, flowering duration, planting material, labour, perishability and market access. A small-scale trial can help assess yield, harvesting requirements, consumer preference and market demand before expansion.

Edible Flowers and Food Entrepreneurship

Opportunities for Farmers: For small and marginal producers, marketing risk can be reduced by starting with limited-area cultivation and establishing a reliable buyer before expanding production. Fresh flowers can be supplied directly to restaurants, bakeries, caterers and speciality food outlets, flowers that cannot be marketed fresh may be dried and processed. **Opportunities for Food Entrepreneurs:** Food entrepreneurs can convert fresh edible flowers into a variety of value-added products. Flower teas and herbal infusions are among the simplest products because suitable flowers can be carefully dried and packed for sale (Chetia *et al.*, 2025). Flowers can also be processed into syrups, beverages and concentrates. Dried flowers may be further processed into powders that can be used in selected bakery and food products. **Food Safety and Market Potential:** The development of edible-flower enterprises should always be based on food safety and consumer acceptance. Flowers from ornamental nurseries or florists should not be assumed to be safe for eating because chemical treatments may have been used. Appropriate packaging, storage and clear labelling are also important. With safe production practices, suitable processing and reliable market linkages, edible flowers have potential to develop into a niche value-added food category. Good agricultural practices, hygienic handling and appropriate storage are important for reducing contamination and ensuring the safe consumption of edible flowers.

Value-added products: Value-added products provide an additional marketing pathway. Dried flowers can be processed into teas, infusions, syrups and powders, while suitable flower materials can also be incorporated

into jams, jellies, preserves, bakery products and confectionery products and can potentially reach consumers beyond the immediate production area. Farmers and entrepreneurs should assess local demand and production costs before investing in processing or large-scale cultivation.

Conclusion: Edible flowers can link horticultural production with traditional food culture and value-added food enterprises. Flowers such as rose, hibiscus, butterfly pea, marigold, pumpkin, banana and moringa offer opportunities for fresh marketing and products such as teas, syrups, beverages, powders and bakery foods. For farmers, they can support crop diversification and niche marketing. But commercialization requires correct identification, food-safe cultivation, hygienic handling, suitable packaging and reliable market linkages.

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Digital Agricultural Extension: Transforming Farmer Advisory Services in the Digital Era

H. Nagesh, V. Jyothi, K. Srinivasarao, V. Ramarao
Sri Kinjarapu Yerrannaidu College of Agriculture-ANGRAU, AP-532401.
Corresponding Author: nageshnani77@gmail.com

Introduction

Agriculture is rapidly changing with the advancement of digital technologies. Farmers today require not only inputs such as seed, fertilizer and machinery, but also timely and reliable information to make better decisions. Weather variability, emerging pests and diseases, changing market prices, water scarcity and increasing production costs have made timely agricultural advisories more important than ever. In this changing scenario, **digital agricultural extension** is emerging as a powerful approach for connecting farmers with knowledge, experts, markets and services.

Traditional agricultural extension has mainly depended on personal visits, demonstrations, farmer meetings, training programmes, field days and printed materials. These approaches continue to be important, particularly for hands-on learning. However, they may not always reach every farmer at the right time. Digital technologies can complement conventional extension by delivering information quickly, widely and in a farmer-friendly manner.

What is Digital Agricultural Extension?

Digital agricultural extension refers to the use of **information and communication technologies (ICTs), mobile phones, internet-based platforms, social media, artificial intelligence, digital applications, satellite technologies and other digital tools** to provide agricultural knowledge and advisory services to farmers.

It enables farmers to access information without always having to physically visit an extension office. A farmer can receive a weather alert on a mobile phone, watch a video on a crop management practice, identify a pest through a digital application, check market prices online or communicate with an agricultural expert through a digital platform.

Thus, digital extension is not simply the replacement of traditional extension with technology. It represents a transition towards a more accessible, timely, interactive and farmer-centred extension system.

Digital Tools Transforming Agricultural Extension

Several digital technologies are changing the way agricultural information is generated, communicated and used.

1. Mobile Phones

Mobile phones have become one of the most important tools for agricultural extension. SMS messages, voice calls, mobile applications and messaging platforms can provide farmers with information on crop

production, weather, pest management, government schemes and market opportunities.

Voice-based services are particularly useful for farmers who have limited literacy or prefer receiving information in their local language.

2. Social Media

Social media platforms have created new opportunities for farmer learning and interaction. Agricultural departments, universities, Krishi Vigyan Kendras, experts and farmer groups can share crop advisories, demonstration videos, success stories and alerts through social media.

Farmer-to-farmer communication can also become faster through digital communities.

3. Digital Videos

Agriculture is a practical field, and many farming operations are easier to understand through visual demonstrations. Digital videos can demonstrate seed treatment, nursery management, mechanization, integrated pest management, compost preparation, harvesting and post-harvest practices.

Local-language videos can make technical information easier for farmers to understand and apply.

4. Weather and Climate Advisory Services

Weather information is becoming increasingly important for farm-level decision-making. Digital platforms can provide information about rainfall, temperature, wind, dry spells and extreme weather events.

Such advisories can help farmers decide when to sow, irrigate, spray pesticides, apply fertilizers or harvest crops. Climate-related advisories can also support farmers in preparing for droughts, floods, heat waves and other risks.

5. Artificial Intelligence

Artificial Intelligence (AI) is creating new possibilities for agricultural advisory services. AI-based systems can analyse large amounts of agricultural, weather and market information and provide customized recommendations.

For example, AI-based applications may assist in identifying crop diseases from photographs, recommending suitable management practices or answering farmers' frequently asked questions through chatbots.

However, AI should complement—not replace—qualified agricultural experts and field-level extension personnel.

6. Remote Sensing, GIS and Drones

Satellite imagery, Geographic Information Systems (GIS) and drone technologies can provide valuable information about crop conditions, soil moisture, vegetation health, pest outbreaks and drought conditions.

These technologies can help extension agencies identify vulnerable areas and provide targeted advisories rather than applying the same recommendation to all farmers.

How Digital Extension Benefits Farmers

Digital agricultural extension can provide several benefits to farmers.

Timely information: Agricultural advisories can reach farmers quickly, particularly during critical crop-management periods.

Wider coverage: A single digital message, video or advisory can reach thousands of farmers across geographically dispersed areas.

Lower cost: Digital communication can reduce the cost associated with repeated physical meetings and travel.

Personalized advice: Digital systems can increasingly provide recommendations based on crop, location, weather and farmer needs.

Better decision-making: Access to weather, market, pest and production information can help farmers make informed decisions.

Continuous learning: Farmers can access agricultural information whenever required instead of depending only on scheduled extension programmes.

Improved connectivity: Digital platforms can connect farmers with scientists, extension officers, markets, financial institutions and other service providers.

Digital Extension and Climate-Resilient Agriculture

Digital agricultural extension has particular importance in the context of climate change. Rainfed farmers frequently face uncertainties associated with delayed monsoon, prolonged dry spells, excessive rainfall, high temperatures and changing pest and disease patterns.

Digital climate advisories can help farmers prepare for these risks. For example, farmers can receive early warnings about heavy rainfall and modify irrigation, fertilizer application or harvesting decisions accordingly. Short-duration crop varieties, contingency crop planning and drought-management practices can also be communicated through digital platforms.

Therefore, digital extension can become an important component of climate-risk management and resilient agricultural development.

Role of Extension Personnel in the Digital Era

The emergence of digital technology does not reduce the importance of extension personnel. Instead, their role is changing. The extension worker of the future needs to function as a knowledge facilitator, digital communicator, technology mediator and problem-solving expert. Extension personnel should be able to identify credible information, communicate it through appropriate digital channels and help farmers interpret and apply it under local conditions.

A strong extension system should therefore combine digital tools with personal interaction. Digital platforms can provide speed and scale, while extension personnel provide local understanding, practical guidance, trust and human interaction.

Challenges of Digital Agricultural Extension

Despite its potential, digital extension faces several challenges.

The **digital divide** remains an important concern. Small and marginal farmers, women farmers, elderly farmers and farmers in remote areas may have limited access to smartphones, internet connectivity or digital services.

Digital literacy is another challenge. Having a smartphone does not necessarily mean that a farmer can effectively search for, evaluate and use agricultural information.

Information overload can also create confusion. Farmers may receive contradictory recommendations from different sources. Therefore, the credibility and quality of digital agricultural information are extremely important.

Language is another major issue. Digital agricultural content should be available in local and easily understandable languages rather than relying mainly on technical terminology.

Poor internet connectivity, limited electricity supply, affordability of devices and concerns regarding data privacy are additional barriers.

Making Digital Extension More Farmer-Centred

The success of digital agricultural extension depends not simply on introducing new technologies but on designing services around farmers' actual needs.

Digital advisory systems should provide:

- Local-language information
- Simple and practical recommendations
- Location-specific advisories
- Weather-based recommendations
- Crop-specific information
- Audio and video content
- Interactive farmer–expert communication
- Reliable and scientifically validated information
- Accessible services for women and marginalized farmers

Farmers should also be involved in designing and evaluating digital extension services. Their feedback can help improve the relevance, usability and credibility of digital platforms.

The Future of Agricultural Extension

The future of agricultural extension is likely to be hybrid, combining the strengths of traditional and www.krishinetra.com

digital approaches. Digital technologies can provide information rapidly and reach large numbers of farmers, while face-to-face extension can provide practical demonstrations, build trust and address complex field-level problems.

The integration of Artificial Intelligence, Internet-based services, remote sensing, mobile applications, climate information and farmer databases may enable more personalized and predictive agricultural advisory systems in the future.

However, technology should remain a means rather than an end. The ultimate objective of digital extension should be to improve farmers' knowledge, decision-making capacity, productivity, income and resilience.

Conclusion:

Digital agricultural extension is transforming the way agricultural knowledge and advisory services reach farmers. Mobile phones, social media, digital videos, weather services, artificial intelligence, remote sensing and other technologies are creating new opportunities for faster and more accessible agricultural communication.

At the same time, technology alone cannot solve all agricultural problems. Bridging the digital divide, improving digital literacy, ensuring reliable information, promoting local-language content and strengthening the capacity of extension personnel are essential.

The future of agricultural extension lies in creating a farmer-centred, inclusive and technology-enabled extension ecosystem in which digital tools and human expertise work together. If used effectively, digital agricultural extension can help farmers make better decisions, respond to emerging challenges and move towards a more productive, sustainable and climate-resilient agriculture.

Plant Pangenomics: Concepts, Classification and Construction Approaches

JadalaSupraja^{1*}, TalariAkshay Kumar², KommulaUday³

^{1*} M.sc Scholar, Department of Genetics and Plant Breeding, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya, Raipur (C.G.) 492012

² PhD Scholar, Department of Genetics and Plant Breeding, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya, Raipur (C.G.) 492012

³ PhD Scholar, Department of Genetics and Plant Breeding, ICAR-Indian Agricultural Research Institute, New Delhi.

Corresponding Author: suprajajadala@gmail.com

Abstract

A single reference genome cannot capture the full genomic diversity of a crop species, as it omits presence/absence variations, structural variants and novel genes present in other individuals. Pangenomics addresses this limitation by integrating genomic information from multiple accessions to represent the complete gene and sequence repertoire of a species. This review provides the conceptual and methodological foundation of plant pangenomics. It describes the components of a pangenome, namely the core genome shared by all or nearly all individuals, the accessory or dispensable genome present in a subset of individuals, and the private genome restricted to single or very few genotypes, and discusses their importance for crop improvement. The historical development of the field is traced from its origin in microbial genomics, where the concept was first introduced, through its extension to plants with early evidence of extensive gene-content variation in maize, to recent advances driven by long-read sequencing, high-quality genome assembly and graph-based genome representations. Pangenomes are classified as open or closed according to whether the gene repertoire continues to expand or reaches a plateau as additional genomes are sampled, and the implications of this distinction for germplasm selection, including landraces and wild relatives, are considered. The major approaches to pangenome construction are then compared: de novo assembly and genome comparison, reference-based iterative assembly, and graph-based pangenomes. Each differs in comprehensiveness, cost, computational demand and susceptibility to reference bias, and the most suitable strategy depends on genome quality and number, sequencing technology, available resources and the intended application. Together, these concepts and approaches provide the basis for the applications of pangenomics in plant genetics and breeding discussed in the companion article.

Keywords: plant pangenome; core genome; accessory genome; open and closed pangenome; de novo assembly; graph-based pangenome; structural variation; crop wild relatives

1. Introduction

The rapid development of DNA sequencing and computational genomics has greatly improved the study of genetic diversity in crop plants. However, a single reference genome cannot fully represent the genomic variation present within a species, including presence/absence variations, structural variations and novel genes (Schreiber *et al.*, 2024; Hu *et al.*, 2024).

A pangenome represents the complete genomic diversity of a species by combining genome information from multiple individuals. It includes the core genome, shared among individuals, and the accessory or dispensable genome, present only in some individuals, along with private genomic sequences (Schreiber *et al.*, 2024; Hu *et al.*, 2025). Advances in long-read sequencing, high-quality genome assembly and graph-based genome analysis have accelerated the development of plant pangenomes and improved the detection of complex genetic variation (Hu *et al.*, 2024).

Plant pangenomics has important applications in genetics and breeding, including the discovery of novel genes and variants associated with yield, quality, stress tolerance, disease resistance and environmental adaptation (Schreiber *et al.*, 2024; Hu *et al.*, 2024). These applications are reviewed in the companion article, “Pangenomics: Applications in Plant Genetics and Breeding”. This article provides the foundation for that discussion by summarizing the concept and components of the plant pangenome, its historical development, the classification of pangenomes and the approaches used for their construction.

2. Concept and Components of the Plant Pangenome

A plant pangenome represents the complete set of genomic sequences found across multiple individuals of a species. It provides a broader view of species-level genetic diversity than a single reference genome and can include genes, regulatory regions and structural variations that differ among individuals (Schreiber *et al.*, 2024; Hu *et al.*, 2024).

2.1 Core genome

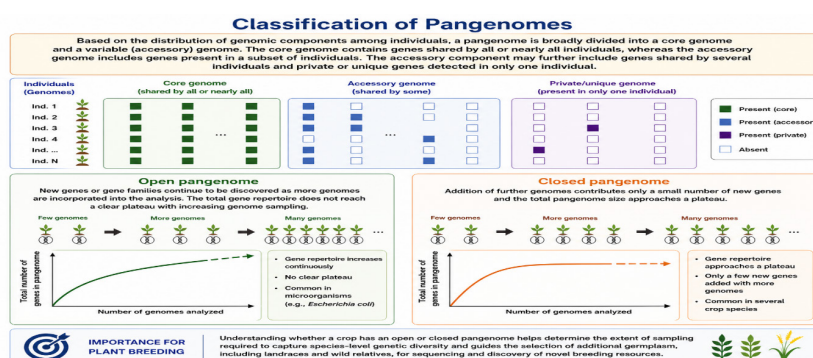
The core genome consists of genes or genomic sequences shared by all, or nearly all, individuals examined. These regions generally represent conserved components of the genome and are often associated with essential biological functions (Hu *et al.*, 2025; Schreiber *et al.*, 2024).

2.2 Accessory or dispensable genome

The accessory or dispensable genome contains genes or genomic regions present in only a subset of individuals. These variable regions can contribute to differences in adaptation, disease resistance and other phenotypic characteristics among genotypes (Hu *et al.*, 2025).

2.3 Private or genotype-specific genome

The private genome comprises genes or sequences detected in only one individual or a very small number of individuals. These sequences represent rare genetic variation and may provide valuable sources of novel alleles for crop improvement (Hu *et al.*, 2025).



2.4 Importance of pangenome components

The combined analysis of core, accessory and private genomic components provides a more complete understanding of genetic diversity within crop species. In breeding, variable genomic regions are particularly valuable because they may contain novel genes and structural variants that are absent from the conventional reference genome and could contribute to useful agronomic traits (Schreiber *et al.*, 2024; Hu *et al.*, 2024).

3. Historical Development of Pangenomics

The concept of the pangenome was first introduced in microbial genomics by Tettelin *et al.* (2005) through comparative analysis of eight isolates of *Streptococcus agalactiae*. Their study demonstrated that the genome of a species could be divided into a conserved core component shared among isolates and a variable component containing genes that were present in only some strains or were strain-specific. The researchers also showed that the gene repertoire of the species could continue to expand as additional genomes were analysed, highlighting the dynamic nature of a pangenome.

The pangenome concept was subsequently extended to plants to capture genomic variation that cannot be adequately represented by a single reference genome. Morgante *et al.* (2007) provided early evidence for extensive gene-content variation among maize lines, demonstrating the importance of considering multiple genomes when studying plant genetic diversity. Since then, advances in genome sequencing, de novo assembly and comparative genomics have facilitated the development of pangenomes for several crop species.

More recently, long-read sequencing, high-quality genome assemblies and graph-based genome representations have greatly improved the ability to characterize structural and sequence variation across plant genomes. These developments have transformed pangenomics from a primarily comparative-genomics concept into an important resource for studying evolution, domestication, adaptation and crop improvement (Schreiber *et al.*, 2024; Hu *et al.*, 2024).

4. Classification of Pangenomes

Based on the distribution of genomic components among individuals, a pangenome can be broadly divided into a core genome and a variable or accessory genome. The core genome contains genes shared by all or nearly all individuals, whereas the accessory genome includes genes present in only a subset of individuals. The accessory component may further include genes shared by several individuals and private or unique genes detected in only one individual (Tettelin *et al.*, 2005; Edwards *et al.*, 2018).

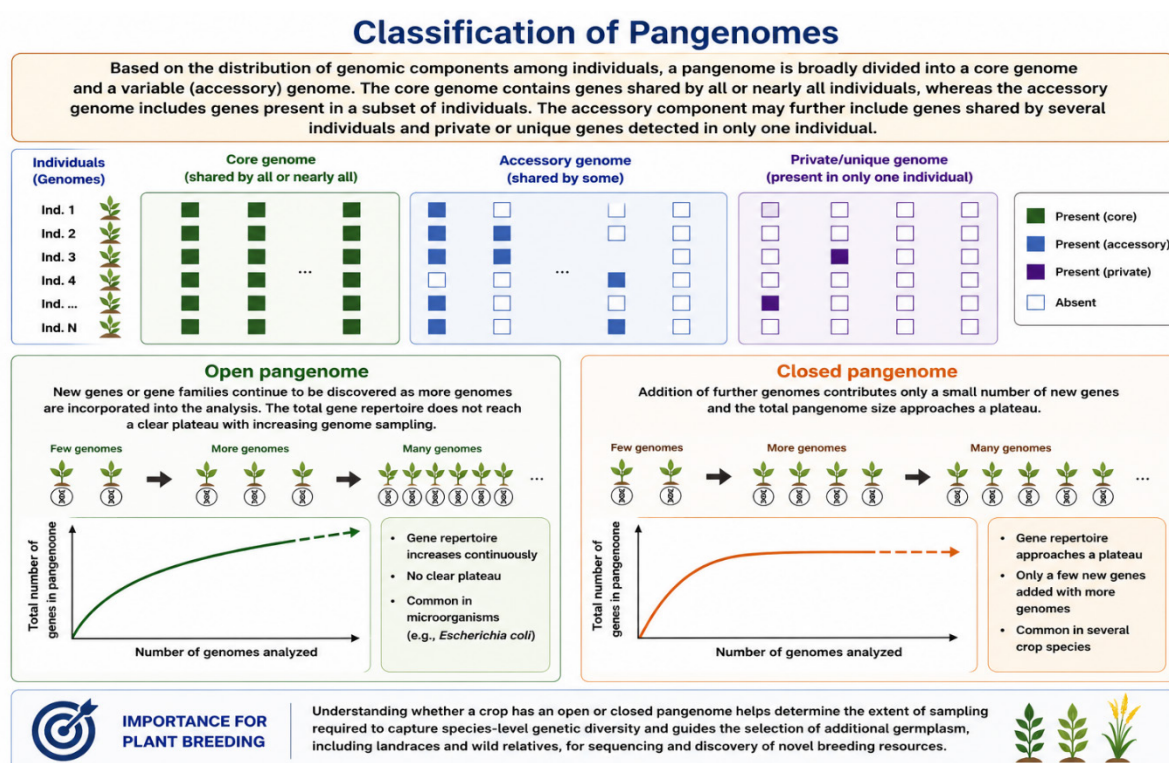
4.1 Open pangenome

An open pangenome is characterized by the continued addition of new genes or gene families as more genomes are incorporated into the analysis. In such a pangenome, the total gene repertoire does not reach a clear plateau with increasing genome sampling, indicating that additional individuals are likely to contribute previously unobserved genetic components (Medini *et al.*, 2005; Jayakodi *et al.*, 2025). Open pangenomes are particularly well documented in microorganisms such as *Escherichia coli*, where substantial genetic variation exists among strains (Tettelin *et al.*, 2008).

4.2 Closed pangenome

A closed pangenome occurs when the addition of further genomes contributes only a small number of new genes and the total pangenome size approaches a plateau. This indicates that most of the gene repertoire has already been captured with the available genome samples (Edwards *et al.*, 2018; Jayakodi *et al.*, 2025). Several crop species have been reported to show relatively closed pangenomes, although the classification can depend on the number and diversity of genomes sampled and the analytical method used (Tao *et al.*, 2019).

The distinction between open and closed pangenomes is useful for determining the extent of sampling required to capture species-level genetic diversity. In plant breeding, understanding whether a crop has a relatively open or closed pangenome can help guide the selection of additional germplasm, particularly landraces and wild relatives, for genome sequencing and discovery of novel breeding resources (Schreiber *et al.*, 2024; Jayakodi *et al.*, 2025).



5. Approaches for Plant Pangenome Construction

The construction of a plant pangenome involves integrating genomic information from multiple individuals to capture both conserved and variable genomic regions. Advances in sequencing technologies and genome assembly have led to the development of several approaches, which can broadly be grouped into de novo assembly and comparison, reference-based iterative assembly, and graph-based pangenome construction (Hu *et al.*, 2024; Schreiber *et al.*, 2024).

5.1 De novo assembly and genome comparison

In the de novo approach, genomes from multiple individuals are assembled independently without relying entirely on a single reference genome. The resulting assemblies are compared to identify shared sequences, novel sequences, structural variations and other genomic differences. This approach can provide a comprehensive representation of genetic diversity, particularly when high-quality long-read genome assemblies are available (Hu *et al.*, 2024). However, generating and comparing many high-quality assemblies requires substantial sequencing, computational resources and accurate genome annotation.

5.2 Reference-based iterative assembly

Reference-based iterative assembly begins by mapping sequencing reads from different individuals to an available reference genome. Reads that fail to align to the reference are subsequently assembled into contigs and incorporated into the pangenome. This strategy can be relatively cost-effective for analysing large populations because short-read sequencing data can be used for many individuals (Hu *et al.*, 2024; Hu *et al.*, 2025). However, sequences that are highly divergent from the reference may be difficult to detect or accurately position, which can introduce reference bias.

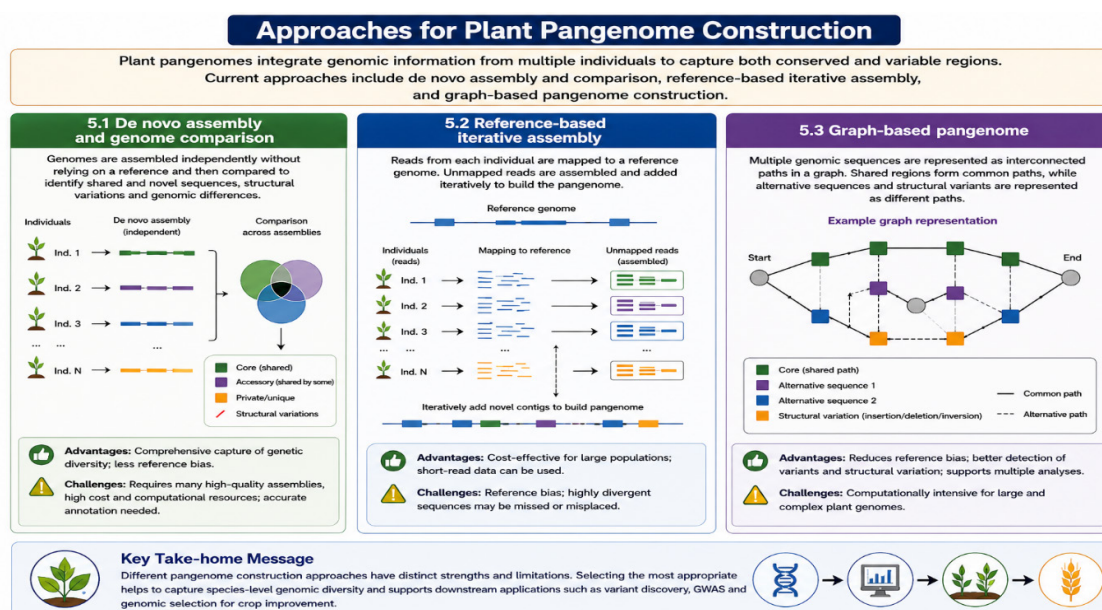
5.3 Graph-based pangenome

Graph-based pangenomes represent multiple genomic sequences as interconnected paths rather than as a single linear reference. Shared genomic regions form common paths, whereas alternative sequences and structural variants are represented as different paths within the graph. This representation can reduce the limitations associated with a single reference genome and improve the detection of genetic variation in divergent regions (Garrison *et al.*, 2024; Hu *et al.*, 2025).

Graph-based approaches are becoming increasingly important in plant genomics because they can integrate multiple high-quality assemblies and support downstream analyses such as read mapping, variant detection, genome-wide association studies and genomic selection. Nevertheless, graph construction and analysis can require substantial computational resources, particularly for large and complex plant genomes (Hu *et al.*, 2025).

5.4 Comparison of construction approaches

The choice of pangenome construction strategy depends on the quality and number of available genomes, sequencing technology, computational resources and the intended application. De novo assembly provides extensive information about genomic variation but is resource-intensive, whereas iterative assembly is more economical for large populations but may be affected by reference bias. Graph-based approaches provide a flexible representation of multiple genomes and are increasingly useful for comprehensive variant discovery and breeding applications (Hu *et al.*, 2024; Schreiber *et al.*, 2024).



6. Conclusion

A plant pangenome captures the genomic diversity of a species by combining information from multiple individuals, and is commonly described in terms of core, accessory and private components (Schreiber *et al.*, 2024; Hu *et al.*, 2025). Since the pangenome concept was first introduced in microbial genomics (Tettelin *et al.*, 2005) and extended to plants (Morgante *et al.*, 2007), advances in long-read sequencing, high-quality genome assemblies and graph-based representations have improved the characterization of structural and sequence variation (Schreiber *et al.*, 2024; Hu *et al.*, 2024). Whether a pangenome is open or closed helps determine how much sampling is needed to capture species-level genetic diversity, including landraces and wild relatives (Schreiber *et al.*, 2024; Jayakodi *et al.*, 2025).

The choice among de novo assembly, reference-based iterative assembly and graph-based construction depends on the quality and number of available genomes, sequencing technology, computational resources and the intended application (Hu *et al.*, 2024; Schreiber *et al.*, 2024). Together, these resources and approaches provide the basis for the applications of pangenomics in plant genetics and breeding discussed in the companion article.

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Pangenomics: Applications in Plant Genetics and Breeding

JadalaSupraja^{1*}, KommulaUday²

^{1*} M.sc Scholar, Department of Genetics and Plant Breeding, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya, Raipur (C.G.) 492012 ² PhD Scholar, Department of Genetics and Plant Breeding, ICAR-Indian Agricultural Research Institute, New Delhi.
Corresponding Author: suprajajadala@gmail.com

Abstract

Advances in long-read sequencing, genome assembly and graph-based computational approaches have enabled the development of plant pangenomes, which capture the genomic diversity of a species far more completely than a single reference genome. By integrating genomes from diverse cultivars, landraces and wild relatives, pangenomes reveal core and accessory genomic components, including presence/absence variations, structural variants and novel genes that are often missed by conventional reference-based analyses. This review summarizes the applications, challenges and future prospects of plant pangenomics in genetics, breeding, stress tolerance and crop improvement. In plant genetics, pangenomes support the discovery of genetic variation and genes, the study of hidden structural diversity, and the investigation of crop evolution, domestication and adaptation. In breeding, pangenomic resources improve germplasm characterization, identification of favourable alleles and haplotypes, GWAS and QTL analysis, genomic selection, and marker-assisted and precision breeding. Pangenomics also provides new opportunities for uncovering genetic variation underlying abiotic stress tolerance, such as drought, salinity and temperature stress, and biotic stress resistance, including pan-NLRome-based studies of disease resistance genes. Integration with multi-omics and machine learning further strengthens functional interpretation and trait prediction for improving yield, quality and resilience. Despite this potential, important challenges remain, including genome assembly and annotation in complex or polyploid species, computational demands of graph-based pangenomes, difficulties in repetitive regions, reference bias, methodological inconsistency, limited standardization, and the need to link variants to phenotypes through experimental validation. Future directions include super-pangenomes, pan-omics, artificial intelligence, genome editing, greater inclusion of underutilized and orphan crops, and the development of breeder-friendly tools and databases. Overall, pangenomics is poised to become a key component of modern plant genetics and precision breeding for developing productive, stress-resilient and climate-adapted crops.

Keywords: plant pangenomics; structural variation; presence/absence variation; GWAS; genomic selection; stress tolerance; disease resistance; crop improvement; precision breeding

1. Introduction

The rapid development of DNA sequencing and computational genomics has greatly improved the study of genetic diversity in crop plants. However, a single reference genome cannot fully represent the genomic variation present within a species, including presence/absence variations, structural variations and novel genes (Schreiber et al., 2024; Hu et al., 2024).

A pangenome represents the complete genomic diversity of a species by combining genome information from multiple individuals. It includes the core genome, shared among individuals, and the accessory or dispensable genome, present only in some individuals, along with private genomic sequences (Schreiber et al., 2024; Hu et al., 2025). Advances in long-read sequencing, high-quality genome assembly and graph-based genome analysis have accelerated the development of plant pangenomes and improved the detection of complex genetic variation (Hu et al., 2024).

Plant pangenomics has important applications in genetics and breeding because it enables the discovery of novel genes and variants associated with yield, quality, stress tolerance, disease resistance and environmental adaptation. Integration of pangenomic data with GWAS, multi-omics and genomic selection can further enhance the identification and utilization of useful genetic variation for crop improvement (Schreiber et al., 2024; Hu et al., 2024). This review summarizes the applications, challenges and future prospects of plant pangenomics in genetics, breeding, stress tolerance and crop improvement. The concept, historical development, classification and construction of plant pangenomes are covered in the companion article, “Plant Pangenomics: Concepts, Classification and Construction Approaches”.

2. Applications of Pangenomics in Plant Genetics

Plant pangenomics has expanded the study of genetic variation from single-reference comparisons to population-level analyses. By incorporating genomes from diverse accessions, landraces and wild relatives, pangenomes can reveal genetic sequences and variants that are absent from the commonly used reference genome (Schreiber et al., 2024; Hu et al., 2024).

2.1 Genetic diversity and variation discovery

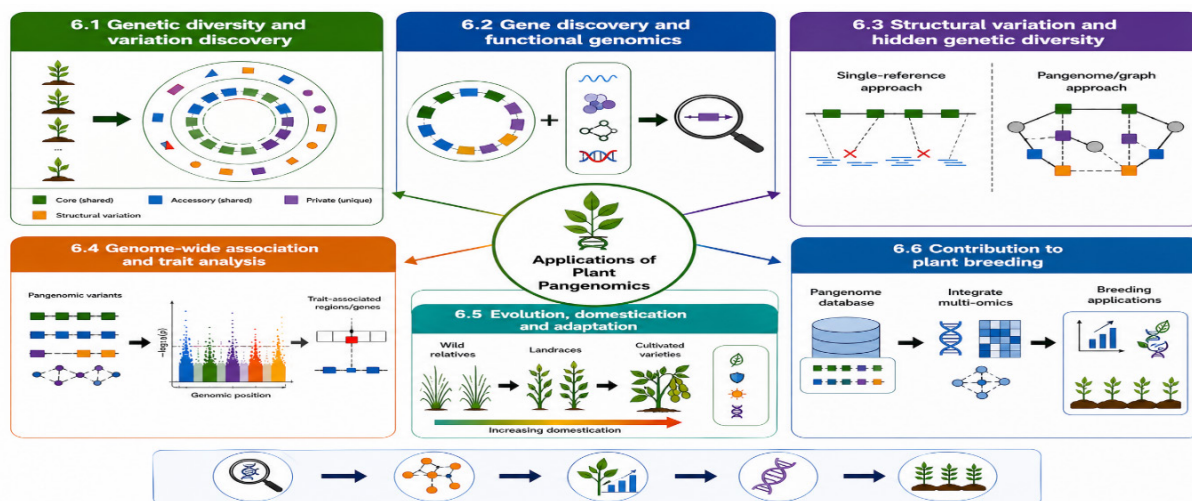
One of the major applications of pangenomics is the identification of genetic diversity within a species. Pangenomes allow researchers to characterize presence/absence variations (PAVs), structural variations (SVs), copy-number variations and other sequence differences among individuals. These variants provide a broader picture of genome organization and can help explain phenotypic differences that are not adequately captured by conventional single-reference analyses (Schreiber et al., 2024; Hu et al., 2024).

2.2 Gene discovery and functional genomics

Pangenomic analysis facilitates the discovery of genes and genomic regions that are absent from a reference genome but present in other individuals. Such variable genes may contribute to adaptation, disease resistance, stress responses and other biologically important traits. Integration of pangenomes with transcriptomic and other multi-omics datasets can further help prioritize genes and genomic regions for functional investigation (Hu et al., 2024; Schreiber et al., 2024).

2.3 Structural variation and hidden genetic diversity

Structural variants, including insertions, deletions, duplications and inversions, can represent an important source of genetic diversity in plants. Many of these variants are difficult to detect using conventional short-read, single-reference approaches. Pangenome and graph-based approaches provide improved opportunities to represent and analyse such variation, including genomic regions that may otherwise remain underrepresented or inaccessible (Hu et al., 2024; Hu et al., 2025).



2.4 Genome-wide association and trait analysis

Pangenomic resources can be integrated with genome-wide association studies (GWAS) to improve the identification of genomic regions associated with complex traits. Incorporating PAVs, structural variants and non-reference sequences into association analyses can provide additional markers or candidate regions beyond conventional single-nucleotide polymorphisms (SNPs). This approach can help improve the resolution of genotype–phenotype relationships and support the identification of candidate genes for further validation (Schreiber et al., 2024; Hu et al., 2024).

2.5 Evolution, domestication and adaptation

Pangenomes are also valuable for investigating crop evolution, domestication and adaptation. Comparisons among cultivated varieties, landraces and wild relatives can reveal genomic changes associated with domestication and subsequent breeding. The inclusion of wild relatives is particularly important because they may retain genetic diversity that has been reduced during domestication and intensive crop improvement (Schreiber et al., 2024; Hu et al., 2025).

2.6 Contribution to plant breeding

The genetic information generated through pangenomics provides a foundation for downstream breeding applications. Pangenome databases can be integrated with multi-omics information to identify trait-associated genes and variants, while the resulting genomic resources can support genomic selection, marker development and genome editing. Thus, pangenomics provides an important link between genetic diversity analysis and the targeted utilization of useful variation in crop improvement programmes (Hu et al., 2024; Schreiber et al., 2024).

3. Applications of Pangenomics in Plant Breeding

Pangenomics provides breeders with a broader representation of genetic diversity than a single reference genome and can therefore improve the identification and utilization of valuable variation. The integration of pangenomic resources with phenotypic, transcriptomic and other multi-omics datasets creates opportunities for more precise selection of breeding material and candidate genes (Schreiber et al., 2024; Hu et al., 2024).

3.1 Germplasm characterization and utilization

Pangenomes can be constructed using diverse cultivated varieties, landraces and crop wild relatives to capture a wider range of genomic variation. This information helps breeders identify rare or population-specific sequences and variants that may be useful for improving agronomic performance, adaptation and resilience. Crop wild relatives are particularly valuable because they can retain genetic diversity that has been reduced during domestication and modern breeding (Schreiber et al., 2024; Hu et al., 2025).

3.2 Identification of favourable alleles and haplotypes

Pangenomic analysis can reveal presence/absence variations, structural variants and alternative haplotypes that are not adequately represented in a single reference genome. When these variants are associated with phenotypic data, they can be used to identify candidate genes and favourable genomic regions for breeding. Such information can complement conventional SNP-based marker discovery and broaden the range of markers available for selection (Hu et al., 2025).

3.3 Pangenome-assisted GWAS and QTL analysis

Integration of pangenome-derived variants with genome-wide association studies and QTL analysis can improve the detection of genomic regions underlying complex traits. Inclusion of PAVs and structural variants may help identify genetic associations that remain undetected when analyses are restricted to SNPs from a single reference genome (Schreiber et al., 2024; Hu et al., 2025).

3.4 Genomic selection

Pangenomes can expand the marker and haplotype information available for genomic prediction by incorporating variants that are absent from a conventional reference genome. The resulting increase in genomic information can improve the representation of genetic diversity in training populations and may support more accurate selection for complex traits. Recent studies have demonstrated the potential of pangenome-based haplotypes and expanded variant sets for genomic selection in crops (Hu et al., 2025). Genomic selection itself can accelerate genetic gain by enabling selection of superior individuals using genome-wide marker information rather than relying entirely on repeated phenotypic evaluation (Ma et al., 2024).

3.5 Marker-assisted breeding and precision breeding

Genes and genomic variants identified through pangenome analysis can be converted into molecular markers for marker-assisted selection and marker-assisted backcrossing. Pangenomes can also support precision breeding by revealing cultivar-specific sequences and alleles that can be considered when designing targeted genome-editing strategies. Thus, pangenomics can help connect genetic diversity discovery with the development of improved breeding lines and cultivars (Hu et al., 2025; Li et al., 2024).

3.6 Integration with multi-omics and machine learning

Combining pangenomes with transcriptomics, proteomics, metabolomics and epigenomic information can improve the functional interpretation of variable genomic regions and facilitate the prioritization of candidate genes. The increasing integration of pangenomics with machine learning and genomic prediction is expected to improve the analysis of complex genotype–phenotype relationships and support data-driven breeding decisions (Hu et al., 2024; Li et al., 2025).

4. Pangenomics for Abiotic Stress Tolerance

Abiotic stresses such as drought, salinity, heat and cold are major constraints to crop growth and productivity, and their impacts are becoming more important under changing climatic conditions (Zhang et al., 2025). Pangenomics provides an opportunity to investigate the genetic basis of stress adaptation by capturing genomic variation that may be absent from a single reference genome.

4.1 Discovery of stress-associated genetic variation

Pangenome analysis can identify presence/absence variations, structural variants, novel genes and alternative haplotypes associated with stress responses. Such variation can provide additional genetic markers and candidate regions for studying tolerance to drought, salinity, temperature extremes and other environmental stresses (Varshney et al., 2024; Jayakodi et al., 2025).

4.2 Drought tolerance

Drought tolerance is a complex trait controlled by multiple genes and regulatory pathways. Pangenomic resources can improve the identification of genetic variants associated with traits such as root architecture, water-use efficiency, osmotic adjustment and stress-responsive regulation. The inclusion of landraces and wild relatives is particularly useful for accessing alleles that may have been underrepresented in modern breeding populations (Varshney et al., 2024).

4.3 Salinity and temperature tolerance

Pangenomics can also support the identification of genomic variation associated with salinity and temperature stress. Comparative analysis of diverse genotypes can reveal genes and structural variants involved in ion homeostasis, osmotic regulation, antioxidant defence and stress signalling. Integrating these genomic data with transcriptomics and metabolomics can provide a more comprehensive understanding of stress-response mechanisms (Zhang et al., 2025; Sarfraz et al., 2025).

4.4 Application in breeding stress-resilient crops

The identification of stress-associated variants through pangenomics can be linked with GWAS, genomic selection and marker-assisted breeding to facilitate the development of stress-resilient cultivars. Pangenome-derived haplotypes and structural variants can complement conventional SNP markers and broaden the genetic information used in breeding programmes (Varshney et al., 2024; Jayakodi et al., 2025). The integration of pangenomics with multi-omics and high-throughput phenotyping may further improve the prediction and selection of genotypes adapted to complex environmental conditions (Sarfraz et al., 2025).

5. Pangenomics for Biotic Stress Resistance

Biotic stresses caused by pathogens and insect pests are major constraints to crop productivity. Plant pangenomics provides a broader framework for identifying genetic variation involved in disease and pest resistance because resistance-associated genes can be highly variable among individuals and may be absent from a single reference genome (Bayer et al., 2020; Schreiber et al., 2024).

5.1 Discovery of resistance-associated genes

Pangenomic analysis can identify genes and genomic regions that are present only in particular accessions and may contribute to resistance against specific pathogens or pests. This is particularly relevant for resistance gene families such as nucleotide-binding leucine-rich repeat (NLR) genes, which show substantial variation in gene number, sequence and genomic organization among plant individuals (Tamborski and Krasileva, 2020; Schreiber et al., 2024).

5.2 PanNLRomes and disease resistance

The complete repertoire of NLR genes represented across the genomes of a species is increasingly studied as a panNLRome. Pangenome-based analyses of NLR loci can reveal presence/absence variation, copy-number differences and structural variants that may contribute to differences in disease resistance among genotypes. Recent studies indicate that panNLRomes can provide valuable resources for identifying candidate resistance genes and understanding the evolution of plant immunity (Barragan and Weigel, 2021; Guo et al., 2025).

5.3 Identification of resistance loci and structural variants

Structural variation is particularly important for resistance loci because resistance genes can occur in complex genomic regions containing duplications, deletions and rearrangements. Pangenome graphs can represent these alternative genomic configurations and improve the detection of resistance-associated variants that may be missed by single-reference approaches (Zanini et al., 2022; Schreiber et al., 2024).

5.4 Utilization of wild relatives and diverse germplasm

Crop wild relatives and landraces can contain resistance alleles that are absent or rare in cultivated germplasm. Incorporating these materials into pangenome resources can help identify novel resistance genes and broaden the genetic base available for breeding. Recent pangenomic studies have highlighted wild relatives as important reservoirs of disease-resistance diversity (Schreiber et al., 2024; MacNish et al., 2026).

5.5 Application in breeding for durable resistance

Pangenomic information can be integrated with GWAS, resistance-gene enrichment sequencing, transcriptomics and functional genomics to identify and validate resistance-associated genes. The resulting markers and candidate genes can support marker-assisted selection, genomic selection and targeted genome editing. Thus, pangenomics provides a pathway from the discovery of previously hidden resistance variation to its practical utilization in developing disease- and pest-resistant cultivars (Schreiber et al., 2024; Li et al., 2024).

6. Pangenomics and Crop Improvement

Pangenomics provides a comprehensive framework for utilizing genetic diversity in crop improvement by incorporating genomic information from cultivated varieties, landraces and wild relatives. Compared with a single reference genome, a pangenome can capture additional genes, haplotypes and structural variants that may be associated with agronomically important traits (Schreiber et al., 2024; Hu et al., 2024).

6.1 Improvement of yield and related traits

Pangenomic resources can support the identification of genomic variants associated with yield and its component traits. Structural variants, presence/absence variations and alternative haplotypes can be integrated

with phenotypic data and GWAS to identify candidate genes and favourable genomic regions for yield improvement (Schreiber et al., 2024). Such information can complement conventional SNP-based analyses and provide breeders with a broader range of markers for selection.

6.2 Improvement of nutritional and quality traits

Pangenomes can also contribute to the improvement of nutritional and quality characteristics by revealing variation in genes involved in metabolic pathways, storage compounds and other quality-related processes. Integrating pangenomic information with transcriptomic and metabolomic data can help identify candidate genes and regulatory regions controlling valuable quality traits (Hu et al., 2024).

6.3 Utilization of landraces and wild relatives

Crop wild relatives and landraces are important reservoirs of genetic diversity for crop improvement. Pangenome analysis can identify genomic regions that are enriched in wild or locally adapted germplasm and may have been reduced or lost during domestication and modern breeding. These resources can provide alleles associated with disease resistance, abiotic stress tolerance, environmental adaptation and other useful traits (Schreiber et al., 2024; Hu et al., 2025).

6.4 Pangenomics-assisted precision breeding

The integration of pangenomes with genomic selection, marker-assisted selection and genome editing provides opportunities for more precise crop improvement. Pangenome-derived variants can be used to develop molecular markers and identify candidate genes for targeted validation or editing. Genome-editing technologies can subsequently be used to modify selected genes or regulatory regions associated with desirable traits (Li et al., 2024; Hu et al., 2025).

6.5 Integration with multi-omics and predictive breeding

Combining pangenomic data with transcriptomics, proteomics, metabolomics and high-throughput phenotyping can improve the functional interpretation of genomic variation. Integration with genomic prediction and machine-learning approaches may further enhance the identification of favourable genotypes and accelerate breeding cycles (Hu et al., 2024; Hu et al., 2025).

Overall, pangenomics shifts crop improvement from reliance on a single reference genome towards a broader population-level view of genetic diversity. This approach can help breeders access previously underutilized genetic variation and develop cultivars with improved yield, quality, stress resilience and adaptation to changing environments (Schreiber et al., 2024).

7. Challenges and Limitations of Plant Pangenomics

Despite its considerable potential, plant pangenomics faces several technical, computational and biological challenges. The quality of a pangenome depends strongly on the number, diversity and quality of the genomes included. Limited sampling may fail to capture rare or population-specific sequences, whereas very large datasets can substantially increase the requirements for sequencing, storage and computational analysis (Hu et al., 2024; Schreiber et al., 2024).

7.1 Genome assembly and annotation

Generating accurate, chromosome-level assemblies remains challenging for many plant species because of large genome sizes, repetitive sequences, heterozygosity and polyploidy. Accurate annotation of newly identified genes and non-coding regions is also difficult, which can limit the biological interpretation of pangenomic variation (Hu et al., 2024; Jayakodi et al., 2025).

7.2 Computational complexity

The increasing number of genomes and genomic variants creates substantial demands for computational resources. Graph-based pangenomes are particularly challenging to construct, store, visualize and analyse at large scale. Their performance can be affected by graph size, memory requirements, alignment efficiency and the number of genomes incorporated (Hu et al., 2024; He et al., 2025).

7.3 Repetitive regions and structural variation

Highly repetitive genomic regions, including transposable-element-rich regions and complex resistance-gene clusters, remain difficult to assemble and genotype accurately. Current graph-based methods may show reduced performance in these regions because similar sequences can create ambiguous read mapping and variant identification (He et al., 2025). Long-read sequencing and improved genome assemblies can help overcome some of these limitations, but accurate analysis of complex regions remains an active area of research.

7.4 Reference bias and methodological differences

Reference-based approaches may preferentially detect variation that can be aligned to the selected reference, potentially resulting in underrepresentation of divergent or reference-absent sequences. In addition, different assembly pipelines, variant-calling methods and graph-construction strategies can produce different pangenome representations, making comparisons between studies more difficult (Hu et al., 2024; Schreiber et al., 2024).

7.5 Linking genomic variation with phenotype

The identification of a genomic variant does not necessarily establish that it is responsible for a particular phenotype. Pangenomes can reveal thousands of candidate variants, but distinguishing causal variants from linked or neutral variation requires integration with phenotypic, transcriptomic, functional and environmental data. Therefore, experimental validation remains essential for translating pangenomic discoveries into breeding applications (Schreiber et al., 2024; Jayakodi et al., 2025).

7.6 Standardization and data accessibility

Differences in genome assembly quality, annotation standards, variant definitions and analytical pipelines can reduce interoperability among pangenome resources. Developing standardized formats, reproducible workflows and accessible databases will be important for enabling researchers and breeders to efficiently compare and reuse pangenomic information (Hu et al., 2024).

Overall, these challenges indicate that successful plant pangenomics requires not only increased genome sequencing but also improved assembly quality, computational methods, functional annotation, standardized analytical frameworks and comprehensive phenotypic evaluation. Addressing these limitations will be essential

for converting pangenomic resources into practical tools for crop improvement (Schreiber et al., 2024; Hu et al., 2024).

8. Future Perspectives

The future of plant pangenomics is expected to move beyond species-specific resources towards broader genomic frameworks that integrate cultivated plants, landraces and wild relatives. Recent developments in super-pangenomes, which extend pangenomic analysis across related species or genera, provide an opportunity to capture a wider range of genetic diversity and identify rare alleles and structural variants relevant to crop improvement (Raza et al., 2026; Hu et al., 2025).

The integration of pangenomics with multi-omics approaches will be important for understanding how genomic variation influences gene expression, metabolism and complex agronomic traits. Combining genomics with transcriptomics, epigenomics, proteomics, metabolomics and high-throughput phenotyping can improve the functional interpretation of variable genomic regions and strengthen genotype–phenotype relationships (Hu et al., 2025; Raza et al., 2026).

Artificial intelligence and machine learning are also expected to contribute to future pangenome analysis. These approaches may assist in analysing large graph-based genomic datasets, predicting trait-associated variants and improving genomic prediction. Integration of AI-assisted analysis with pangenomic resources could help breeders identify useful genetic combinations more efficiently (Raza et al., 2026).

Another important direction is the integration of pangenomics with precision breeding and genome editing. Pangenome-derived genes, haplotypes and structural variants can provide new targets for targeted modification, while genome-editing technologies can enable precise manipulation of genes or regulatory regions associated with desirable traits (Li et al., 2024; Schreiber et al., 2024).

Future pangenomic research should also place greater emphasis on underutilized and orphan crops. These species may contain valuable genetic variation for nutritional quality, environmental adaptation and stress tolerance, but many remain poorly represented in genomic databases. Developing accessible pangenome resources for such crops could broaden the genetic foundation of future agriculture (Hu et al., 2025).

Finally, translating pangenomic discoveries into routine breeding remains a major priority. Development of breeder-friendly databases, standardized pipelines, affordable genotyping platforms and effective integration of genomic and phenotypic data will be essential for moving pangenomics from genomic research into practical crop improvement. Overall, the combination of pangenomics, super-pangenomics, pan-omics, AI and precision breeding has the potential to accelerate the development of high-yielding, stress-resilient and nutritionally improved crops (Schreiber et al., 2024; Raza et al., 2026).

9. Conclusion

Plant pangenomics has emerged as a powerful approach for representing genetic diversity beyond the limitations of a single reference genome. By incorporating multiple genomes, pangenomes enable the identification of core and variable genomic components, including presence/absence variations, structural variants and novel genes that may contribute to important plant traits (Schreiber et al., 2024; Hu et al., 2024).

The integration of pangenomic resources with GWAS, multi-omics, genomic selection and genome editing

provides new opportunities for discovering and utilizing favourable genetic variation in crop breeding. The inclusion of landraces and wild relatives further expands the genetic resources available for improving yield, quality, stress tolerance and disease resistance (Schreiber et al., 2024; Hu et al., 2025).

Despite challenges related to genome assembly, computational complexity, functional annotation and translation of variants into breeding applications, continued advances in sequencing and bioinformatics are expected to improve the accessibility and practical value of pangenomes. Overall, pangenomics is likely to become an increasingly important component of modern plant genetics and precision breeding, supporting the development of productive, resilient and climate-adapted crops.

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Soil-Borne Diseases of Pigeonpea: A Hidden Threat to Crop Productivity

Dr. G. Padmaja¹, D. Meghana², Dr. G. Seshu¹, Dr. B. Kranthi¹, Dr D. Veeranna¹ and Dr. M. Sreedhar¹

¹-PJTAU-Regional Agricultural Research Station, Warangal.

²-PJTAU- College of Agriculture, Rajendranagar.

Corresponding Author: Padmajaagri@pjtau.edu.in

Abstract:

Pigeonpea (*Cajanus cajan* (L.) Millsp.) is a crucial pulse crop in tropical and subtropical drylands, providing dietary protein, sustaining smallholder livelihoods, and enhancing soil fertility through biological nitrogen fixation. However, its productivity is severely constrained by soil-borne fungal pathogens, primarily causing Fusarium wilt (*Fusarium udum*), dry root rot (*Macrophomina phaseolina*), and Phytophthora blight (*Phytophthora drechsleri* f. sp. *cajani*). These cryptic pathogens colonize the root and collar regions unnoticed, persist in soil and crop residue across seasons, and intensify under abiotic stresses such as drought, poor drainage, and nutrient imbalances. Sustainable mitigation demands shifting focus from single-pathogen eradication to managing the broader soil–plant–microbe system. Fostering a biologically active rhizosphere rich in antagonists—such as *Trichoderma*, *Bacillus*, and *Pseudomonas*—enhances natural disease suppression via competition, antibiosis, and induced systemic resistance. Effective long-term management relies on Integrated Disease Management (IDM) frameworks that combine host-plant resistance, certified seed, crop rotation, soil health optimization, and biocontrol agents, supported by judicious fungicide intervention. Leveraging microbiome insights and indigenous microbial inoculants offers promising, ecosystem-based solutions to suppress soil-borne complexes and secure sustainable pigeonpea production.

Keywords: Pigeonpea, Diseases, Soil borne, Biological control and Integrated Disease Management (IDM)

Introduction:

Pigeonpea (*Cajanus cajan* (L.) Millsp.) is one of the most important pulse crops cultivated in tropical and subtropical regions worldwide. It is valued not only as an important source of dietary protein but also for its contribution to nutritional security, soil fertility and the livelihoods of millions of small and marginal farmers. In India, pigeonpea is a prominent pulse crop and an important component of rainfed and dryland farming systems. The crop is particularly suited to relatively warm environments and can withstand periods of moisture stress better than many other crops, making it an important crop in regions where rainfall is uncertain. Pigeonpea is an environmentally valuable crop (Gaiwal *et al.*, 2026). As a legume, it forms a symbiotic association with *Rhizobium* and contributes to biological nitrogen fixation. Its deep and extensive root system helps the crop explore



deeper soil layers for water and nutrients, while crop residues can contribute organic matter to the soil (Ramana *et al.*, 2015)

The productivity of pigeonpea is constrained by several biotic and abiotic stresses. Among these, soil-borne diseases are particularly important because they attack the crop below or near the soil surface and often go unnoticed during early infection. Unlike foliar diseases, which can frequently be recognized by visible spots, lesions or discoloration on leaves, soil-borne pathogens may establish themselves around roots and the collar region before clear above-ground symptoms become apparent. The problem becomes more serious because many soil-borne pathogens can survive in soil, infected crop residues and plant debris for extended periods. Once established in a field, they may continue to threaten subsequent crops. Disease development is also strongly influenced by environmental and soil conditions, including temperature, soil moisture, drainage, nutrient availability and the physical and biological properties of the soil.

Among the important soil-borne diseases affecting pigeonpea are Fusarium wilt, dry root rot, collar/root rot and other root-associated diseases. These diseases can cause root deterioration, vascular damage, wilting, premature drying and, in severe cases, plant death. An important aspect of soil-borne diseases is that the pathogen alone does not determine disease. The interaction among the host plant, pathogen, soil environment and beneficial microorganisms in the rhizosphere plays an important role in determining disease development. This makes soil health and the rhizosphere important components of sustainable disease management.

Therefore, managing soil-borne diseases of pigeonpea requires a shift from simply controlling the pathogen to understanding and managing the entire soil–plant–microbe system. Integrated approaches involving resistant or tolerant cultivars, healthy seed, crop rotation, balanced nutrition, appropriate agronomic practices, biological control agents and judicious use of fungicides can contribute to healthier crops and more sustainable pigeonpea production.

What are soil-borne diseases?

Soil-borne diseases are caused by pathogens that survive in the soil, crop residues or around plant roots and infect susceptible plants through their roots or lower stem regions. In pigeonpea, these diseases can interfere with root function, restrict water and nutrient uptake and eventually cause yellowing, wilting, root decay and plant death (Reddy *et al.*, 2012). Unlike many foliar diseases, soil-borne diseases often remain hidden during the early stages of infection. By the time symptoms become clearly visible above the ground, significant damage may already have occurred below the soil surface. Their ability to survive between cropping seasons makes these diseases particularly difficult to manage.



Fusarium wilt



Phytophthora blight



Dry root rot

Major soil borne diseases of pigeonpea:

Disease	Casual organism	Important symptoms
Fusarium wilt	<i>Fusarium udum</i>	Yellowing, wilting, vascular discoloration
Dry root rot	<i>Macrophomina phaseolina</i>	Root decay, sudden wilting, drying of plants
Phytophthora blight	<i>Phytophthora drechsleri</i> f. sp. <i>cajani</i>	Water-soaked lesions, stem girdling and plant death

Why do soil-borne diseases become severe?

Soil-borne diseases in pigeonpea develop due to a combination of factors, not the pathogen alone. Continuous pigeonpea cultivation, repeated cropping, infected crop residues, and the persistence of pathogen survival structures can increase disease pressure in the soil. At the same time, drought, high temperature, poor drainage, inadequate or excessive soil moisture and nutrient imbalance can weaken plants and alter the soil environment (Natarajan *et al.*, 1985). The soil biological community is equally important, as beneficial microorganisms can compete with pathogens and contribute to natural disease suppression. Thus, disease development can be viewed as the outcome of a complex interaction among the pigeonpea plant, pathogen, soil environment and rhizosphere microorganisms.

Soil Health and Natural Disease Suppression:

Soil is much more than a medium that simply supports plant growth. It is a living ecosystem that contains a diverse community of bacteria, fungi and other microorganisms that continuously interact with plant roots and with one another. A healthy soil with good organic matter, balanced nutrients, favourable moisture conditions and diverse microbial communities can contribute to natural suppression of soil-borne diseases. Beneficial microorganisms present in the rhizosphere region of soil influenced by plant roots can compete with disease causing pathogens for nutrients and space, produce compounds that inhibit pathogens, and in some cases stimulate the plant's own defence mechanisms. Microorganisms such as *Bacillus*, *Pseudomonas* and *Trichoderma* are particularly important because of their potential to suppress several soil-borne pathogens and promote healthier root systems (Manikandan *et al.*, 2022) Thus, disease management should not focus only on eliminating the pathogen; maintaining a healthy and biologically active soil can help create an environment in which beneficial microorganisms support plant health and naturally limit disease development.

Integrated Management of Soil-Borne Diseases

- Effective management of soil-borne diseases in pigeonpea requires an integrated disease management approach that combines preventive, cultural, biological and chemical measures. Using healthy, quality seed, along with disease-resistant or tolerant cultivars, is an important first step in reducing the risk of disease establishment.
- Crop rotation with suitable non-host crops and proper management of infected crop residues can help reduce the accumulation and survival of soil-borne pathogens. Appropriate seed treatment with recommended fungicides or compatible biological control agents such as *Trichoderma* spp. and *Bacillus* spp. can protect crops during the early stages of establishment.
- Maintaining optimum soil moisture, balanced nutrient availability, and favorable soil conditions is also essential for sustaining healthy root development and improving plant resilience. Biological control agents can suppress disease through competition, antibiosis, mycoparasitism, and other antagonistic mechanisms.
- Recommended fungicides may be incorporated judiciously as part of an integrated program rather than used as a sole management strategy.
- An integrated approach that combines host resistance, sound agronomic practices, soil-health management, biological control and judicious chemical intervention can provide more effective and sustainable management of soil-borne diseases in pigeonpea.

Future Perspectives:

Future management of soil-borne diseases in pigeonpea is increasingly moving toward sustainable, ecosystem-based approaches that address both the pathogen and the health of the crop and soil. Greater emphasis is being placed on the development and use of disease-resistant or tolerant cultivars, improved agronomic practices, balanced soil fertility management and conservation of beneficial microorganisms in the rhizosphere. Advances in microbiome research, microbial biotechnology and molecular tools are providing new opportunities to identify beneficial microorganisms and understand their interactions with pigeonpea roots and soil-borne pathogens. Using indigenous, effective microbial antagonists, along with improved knowledge of soil–plant–microbe interactions, could support the development of location-specific, environmentally sustainable disease-management strategies. Integrating these approaches with conventional disease-management practices offers promising opportunities for maintaining soil health, improving plant resilience and reducing the impact of soil-borne diseases on pigeonpea production (Bagale *et al.*, 2026)

Conclusion:

Soil-borne diseases are an important constraint to sustainable pigeonpea production, particularly because their pathogens can persist in soil and infect plants through the root and collar regions. Effective management therefore requires a broader approach that considers not only the pathogen but also the health of the soil, plant and rhizosphere microbial community. The integration of resistant or tolerant cultivars, healthy seed, crop rotation, balanced nutrition, proper soil and moisture management, biological control agents and judicious use of fungicides can help reduce disease pressure and maintain crop productivity. Greater attention to

beneficial soil microorganisms and soil–plant–microbe interactions can further strengthen sustainable disease-management strategies. Ultimately, protecting pigeonpea from soil-borne diseases begins with maintaining healthy soil and a balanced rhizosphere.

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Pumpkin Seeds- Power House Of Nutrition With Healthpromoting Properties And Food Applications

Ms. K. B. Nirmala ¹, Dr. Jessie Suneetha W^{2*}, Dr. J. Hemantha Kumar³, Ms. P. Parimala¹ and Ms. B. Akshita¹

¹ Post Graduate & Research Centre, PJTAU, Rajendranagar, Hyderabad 500030

² AICRP on Women in Agriculture, PJTAU, Rajendranagar, Hyderabad 500030

³ Agricultural College, PJTAU, Aswaraopet, Bhadradi Kothagudem – 507301

Corresponding Author: wjsuneetha@yahoo.com

Introduction: Seeds and nuts have gained more attention in recent years due to their impressive nutraceutical and therapeutic benefits and pumpkin seeds are no exception. Pumpkin (*Cucurbita* sp.) is a fruit vegetable native to the western hemisphere and widely grown in tropical Asian countries like Indonesia, Malaysia and Philippines. The economically important species are *C. pepo* (the most common), *C. maxima*, *C. moschata*, *C. mixta* and *C. stilbo* although numerous varieties are cultivated worldwide. Pumpkins are cultivated globally for commercial, ornamental and agricultural purposes. Researchers are interested in pumpkins because they play a significant role in many traditional medical practices.

Although often considered agro-industrial waste, pumpkin seeds are packed with nutrients and offer fascinating nutraceutical benefits. The seeds constitute about 1–2% of the pumpkin fruit, have traditionally been consumed as snacks or incorporated into various culinary preparations. Pumpkin seeds are packed with nutrients and have gained attention for their complex chemical composition and health benefits. They are rich in unsaturated fatty acids like palmitic, stearic, oleic and linoleic acids. These essential fatty acids like Ω -3 and Ω -6 fatty acids offer impressive nutritional value and play a key role in various metabolic processes. The growing consumer demand for plant-based and natural foods has further increased their importance as a component of a balanced diet and in nutraceutical formulations.

Nutritional composition of pumpkin seeds: Pumpkin seeds are nutrient-dense and provide an optimal balance of macronutrients and micronutrients. The proximate composition of pumpkin seeds contained approximately 30.0–35.0% protein, 40.0–50.0% fat, 5.0–10.0% carbohydrates and 4.0–6.0% dietary fiber depending on the species and growing conditions. The protein fractions are of high biological value containing all essential amino acids notably arginine, glutamic acid and leucine which play vital roles in muscle metabolism and immune function.

The lipid fraction of pumpkin seeds is predominantly composed of unsaturated fatty acids with linoleic (omega-6) and oleic (omega-9) acids as the major components. These fatty acids contribute to cardiovascular protection by improving lipid profiles and reducing low-density lipoprotein (LDL) cholesterol. The presence of phytosterols particularly β -sitosterol further supports cholesterol-lowering effects.

Pumpkin seeds are also an excellent source of micronutrients including magnesium, zinc, iron, phosphorus, manganese and copper. Magnesium and phosphorus are essential for bone and energy metabolism, while zinc contributes to immune function, wound healing and reproductive health. The seeds also provide small amounts of vitamin E (tocopherols) and carotenoids which possess strong antioxidant properties.

Bioactive compounds with their functional properties: The therapeutic value of pumpkin seeds arises from

their diverse bioactive constituents. These include phenolic acids, flavonoids, squalene and phytosterols which exhibit antioxidant, anti-inflammatory and antimicrobial activities. The presence of L-tryptophan, a precursor of serotonin and melatonin has been linked with improved mood regulation and sleep quality. Furthermore, pumpkin seed oil contains conjugated linoleic acid (CLA) and tocopherols both of which contribute to lipid metabolism and cellular protection against oxidative stress.

Table 1. **Major nutritional and bioactive constituents of pumpkin seeds**

Component	Functional properties
Protein	Supplies essential amino acids and supports protein enrichment
Unsaturated fatty acids	Predominantly linoleic and oleic acids; contribute to favourable lipid quality
Dietary fibre	Supports gastrointestinal function and dietary quality
Magnesium	Important for enzymatic reactions and energy metabolism
Zinc	Essential for immune and cellular functions
Iron	Important constituent of haemoglobin and iron-dependent enzymes
Phosphorus	Involved in energy metabolism and bone mineralisation
Tocopherols	Antioxidant activity and protection against lipid oxidation
Phytosterol	Associated with modulation of cholesterol metabolism
Phenols and flavonoids	Contribute antioxidant and other biological activities
Lignans	Important phytochemicals investigated for biological activity

Therapeutic and health promoting effects: These include:

Cardiovascular health: Regular consumption of pumpkin seeds or their oil has been shown to reduce blood pressure and serum cholesterol levels. Magnesium, potassium and unsaturated fats collectively help in maintaining vascular tone and reducing the risk of hypertension and atherosclerosis.

Glycemic control: Due to their low glycemic index and balanced composition of protein, fiber and unsaturated fats, pumpkin seeds help in stabilizing postprandial blood glucose levels. Experimental studies indicate that their consumption improves insulin sensitivity and may assist in diabetes management.

Prostate and urinary tract health: Pumpkin seed extract and oil are traditionally used in the management of benign prostatic hyperplasia (BPH) and urinary disorders. Clinical evidence suggests that phytosterols and lignans in pumpkin seeds inhibit 5- α -reductase activity, thereby improving urinary flow and reducing prostate enlargement.

Antioxidant and anti-inflammatory actions: The polyphenolic compounds and tocopherols in pumpkin seeds neutralize reactive oxygen species, minimizing oxidative damage to cellular structures. Their anti-inflammatory potential has been associated with reduced risk of chronic conditions such as arthritis, cardiovascular disease and certain cancers.

Sleep and neurological benefits: Pumpkin seeds are one of the few natural sources of tryptophan which promotes serotonin synthesis and aids melatonin production. Combined with magnesium, this property may enhance sleep quality and reduce anxiety-related symptoms.

Dietary applications: Whole pumpkin seeds are consumed as roasted snacks, salad toppings, breakfast

ingredients and confectionery products and are also incorporated into gluten-free foods, extruded snacks, nutrition bars, cereals, crackers and cakes.

Pumpkin seed flour prepared from whole or partially defatted seeds is a promising value-added ingredient owing to its high water and oil-holding capacities and favourable emulsifying, foaming, swelling and gelation properties. These attributes support its application in bakery and cereal-based products while improving their nutritional quality.

Pumpkin seed oil is another valuable product rich in unsaturated fatty acids, tocopherols, phytosterols and carotenoids with applications as an edible oil and functional food ingredient. The protein-rich press cake obtained after oil extraction can be further processed into flour or protein concentrates enabling efficient utilisation of the seed fractions and supporting sustainable, low-waste valorisation of pumpkin seeds.

Conclusion: Pumpkin seeds present a valuable functional food ingredient with high nutritional and therapeutic potential. Their balanced composition of proteins, unsaturated fatty acids, minerals and antioxidants contributes to multiple physiological benefits including cardioprotective, antidiabetic, immunomodulatory and anti-inflammatory effects. Regular dietary inclusion of pumpkin seeds can support general health and help in the prevention of metabolic and degenerative diseases. Given their versatility, affordability and sustainability, pumpkin seeds can play a significant role in promoting nutrition security and improving public health outcomes.



Green pumpkin seeds



Pumpkin seed flour