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Precision and Digital Agriculture

Editors:
Dr. Priyanka Chand
Dr. Gautam Handique
Dr. Seema Bhagowati
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PREFACE

Agriculture is undergoing a remarkable transformation in the digital age. With increasing pressure to feed a growing global population, optimize natural resources, reduce environmental impact, and improve farm profitability, traditional farming practices are rapidly evolving. The book "Precision and Digital Agriculture" brings together emerging trends, innovative technologies, and analytical approaches that are reshaping modern agricultural systems.

Precision agriculture focuses on site-specific crop and soil management based on accurate, data-driven decision-making. Digital tools such as sensors, GPS mapping, remote sensing, drones, Internet of Things (IoT) devices, and artificial intelligence enable farmers to monitor field variability, manage inputs efficiently, and predict outcomes with greater reliability. These technologies not only enhance productivity but also reduce wastage, conserve water, and minimize the overuse of agrochemicals—key steps toward sustainable agriculture.

This volume presents research insights and case studies that illustrate how digital platforms and precision tools are being applied across diverse agricultural landscapes. Topics include smart irrigation systems, predictive analytics, automated farm machinery, soil health monitoring, crop disease diagnostics, and climate-smart farming models. By integrating digital solutions with practical field experience, the chapters aim to provide a comprehensive view of the opportunities and challenges associated with adopting advanced agricultural technologies.

One of the central goals of this book is to promote awareness, knowledge, and interdisciplinary collaboration among researchers, agri-tech developers, farmers, policy planners, and students. As agriculture becomes increasingly knowledge-intensive, leveraging real-time data and digital innovation becomes essential for improving efficiency, sustainability, and resilience.

We extend our heartfelt appreciation to all contributing authors and reviewers for their expertise and commitment. Their collective efforts have enriched this volume and made it a useful resource for academic institutions, agricultural professionals, and stakeholders interested in the future of farming. It is our sincere hope that this book will inspire continued exploration and implementation of technological advancements in agriculture for a more sustainable and productive tomorrow.

- Editors

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STRUCTURAL DEVELOPMENT OF SEED IN FLOWERING PLANT

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Introduction:

A seed comprises multiple vital components, each with a specific purpose that supports its survival and eventual development into a plant. Understanding the *seed structure* reveals the remarkable journey that the seed takes from being a tiny seed to a strong plant. All components, from the embryo to the endosperm, collaborate to ensure that the germination and growth processes are effective. The seed plants are a monophyletic lineage within the lignophytes. The major evolutionary novelty that unites this group is the seed. A seed is defined as an embryo, which is an immature diploid sporophyte developing from the zygote, surrounded by nutritive tissue and enveloped by a seed coat. The embryo generally consists of an immature root called the radicle, a shoot apical meristem called the epicotyls, and one or more young seed leaves, the cotyledons; the transition region between root and stem is called the hypocotyls (Bareke, 2018).

Seed evolution eliminates requirement for water during sexual reproduction and allows fertilization event to occur over long distances. The germination of seeds in a particular situation and season is determined by the interaction between the dormancy releasing factors, which influence on the termination of dormancy or initiation of germination and seedling growth in many plant species like phyto-hormones, light, temperature, water, nutrients, moisture or mechanical cues. The variations either observed in physical or chemical compositions of seeds of different crop plants or different plants of a single crop or different seeds of a single plant. The variability in the physiology of seeds of a plant is known as seed polymorphism.

Determination of Physiological Maturity

The physiological maturity is an important stage in plant growth at which the structural development of seed is completed. The identification of the time of physiological maturity has been a controversial subject among different authors studying seed maturation. Among the differing physiological maturity concepts, three are dominant:

a. Physiological maturity is identified as maximum seed dry matter accumulation

b. Physiological maturity is reached when there is no further significant increase in seed dry weight
c. Physiological maturity occurs when seeds reach maximum dry weight, germination and vigor.

Seed Development

The seed development is a series of predetermined cell divisions and cell differentiations in a zygote give rise to an embryo. This process is known as embryogenesis. The embryo then germinates and grows into an adult plant. The embryogenesis occurs within the embryo sac of the ovule. The first division almost always occurs at the right angles to the longitudinal axis, resulting in a terminal cell next to the micropyle and basal cell at the distal end. Depending on the pattern of subsequent divisions, proembryos are classified as Crucifer, Asterad, Solanad, Caryophyllad, Chenopodiad and Pipered. Seed growth and development typically comprise three partially overlapping phases;

Phase I

- Initial lag phase, characterized by cell proliferation and minimal dry weight gain.
- Various seed tissues and domains are specified and established, including vital transfer cells, a filial conduit with the mother plant vascular tissue that nourishes the developing seed.
- Endosperm and cotyledons development.
- Uptake of sucrose, which is rapidly converted to hexoses via cell wall-bound invertase activity.
- Critical for seed development and grain yield, its contribution is indirect and little contribution in biomass.

Phase II

- Seed filling, a linear phase of large dry weight gain associated with cell enlargement and accumulation of storage compounds.
- Endosperm or cotyledon cells generated in phase I accumulate storage compounds.
- Cell enlargement due to cell growth and cell expansion, and a peak in seed water content.
- Endoreduplication (also known as endopolyploidization, endocycling, or endoreplication), a type of cell cycle that leads to polyploidy.

Phase III

- Final phase of reduced dry weight gain associated with desiccation and dormancy.
- Water concentration decreases dramatically and physiological maturity is reached.

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Types of Seeds

1. Based on presence or absence of endosperm

a. Endospermic (albuminous) seed:

The seeds which possess a well-developed endosperm in mature seed is called endospermic seed. In some crops *viz.* cereals, castor bean, date palm and endospermic legumes like fenugreek, carob, honey-locust etc. endosperm occurs relatively in a larger area and carries substantial food reserves within the mature seed. The endosperm is surrounded by a layer of living cells *i.e.* aleurone layer. Endosperm provides nutrition for germination embryo and in some cases like in fenugreek seed it also regulates the water balance during germination.

b. Non-endospermic (ex-albuminous) seed:

In many seeds endosperm is completely consumed by developing seeds and embryo generally present in a remnant form. These are known as non-endospermic or ex-albuminous seeds. In these seeds cotyledon functions as storage part and prove nutrition for germination seeds. Eg. Soybean, lettuce, peanut etc.

2. Based on number of cotyledon (s)

a. Monocot seeds:

Seeds, which consist only single cotyledon known as monocot seed. Sometimes, modification in single cotyledon has also observed in plant species like in poaceae where a shield shaped cotyledon present known as scutellum and a short axis lie in a groove at one end of the endosperm. Eg. Rice, wheat etc.

b. Diocot seeds:

Presence of two seed leaves or cotyledons in the embryo of seed is known as dicot seed. The seed coat of dicot seed made up of two layers *i.e.* testa and tegman, which can easily identify and can separate from each other. Legume crops like soybean, pea, gram, beans etc. consists two cotyledons in their seeds.

Seed Structure

A seed typically consists of a seed coat, embryo, endosperm, and occasionally perisperm. The seed coat protects the seed and can help in its dispersal. The embryo is the part that develops into the root, stem, and leaves of a new plant. The endosperm provides nourishment to the growing embryo whiles the perisperm, when present, also functions as a food storage tissue.

Embryo:

The mature angiosperm embryo consists of an embryonic axis with a single cotyledon (monocots) or a pair of cotyledons (dicots). (Black *et al.,* 2006). The embryonic axis bears the radicle, hypocotyl, epicotyl and plumule (shoot apex); often there is a transition zone between the radicle and hypocotyls. The radicle contains the root meristem and develops into the primary root once germination occurs. In some seeds, the cotyledons are large and fleshy, functioning as storage organs that supply nutrients to the developing seedling, commonly seen in **non-**endospermic seeds. In contrast, endospermic seeds possess thin, flat cotyledons since the nutrient reserves remain stored in the endosperm. (Bewley and Black, 1994). The basal sheath of cotyledon is elongated to take shape of coleoptiles, while in some cases e.g, Maize, the hypocotyl is modified to form mesocotyl. The base of Hypocotyl sheathing the radicle is termed as coleorhizae.

Endosperm:

Based on whether a mature seed retains a well-developed endosperm, seeds can be classified into two main types: endospermic (albuminous) and non-endospermic (exalbuminous). In many plants such as cereals, castor bean, date palm, and certain legumes like fenugreek, carob, and honey-locust, the endosperm remains prominent in the mature seed and acts as a major storage tissue. In these seeds, the endosperm accumulates significant food reserves during development, often at the expense of cytoplasmic content, resulting in mostly non-living cells by maturity.

Surrounding this storage tissue is the aleurone layer**,** a single layer of living cells. Although it contains few stored nutrients, its primary role is enzymatic—it releases enzymes that help break down and mobilize the endosperm's stored food during germination. However, not all seeds that develop an endosperm retain it in a functional form. Some seeds are still classified as non-endospermic despite forming an endosperm during early development. This occurs for two main reasons:

1. The endosperm may degenerate or be reduced to remnants by the time the seed matures—as seen in soybean and peanut.
2. The endosperm may persist but be extremely reduced, sometimes only one to a few cell layers thick, as in lettuce.

In such cases, the cotyledons take over the role of food storage, supplying nutrients for the seedling during germination.

Seed Coat:

The seed coat, (testa), is a maternal tissue that encloses the embryo, endosperm, and, when presents, the perisperm. It plays a vital role in protecting the internal seed components from biotic stress, desiccation, and mechanical injury. Additionally, it supports gas exchange, water absorption, and serves as a conduit for nutrient transfer to the developing embryo and endosperm. In some species, the seed coat also aids in seed dispersal. According to (Black *et al.,* 2006), these functions significantly influence seed viability, longevity, dormancy, and germination potential. Moreover, the structural features of the seed coat can be useful in plant taxonomy, as observed in families such as Fabaceae.

During seed development, the integuments that give rise to the seed coat differentiate into multiple layers composed of specialized cells. Some of these layers may accumulate significant amounts of biologically active compounds like phenolics, pigments, or mucilage. These biochemical components contribute to the protective and physiological functions of the seed coat. Such cellular differentiation is crucial for the seed's overall performance and adaptability (Moise *et al.,* 2005).

In certain plant families, the seed coat may be reduced or degraded, especially when mechanical protection is provided by other structures such as the fruit wall (pericarp), as seen in Poaceae, or by the endocarp, as in Apiaceae, Fagaceae, and Urticaceae. Similarly, in some small, wind-dispersed seeds from dehiscent fruits, like those in Orchidaceae, the seed coat is often minimal due to reduced requirements for mechanical protection.

Perisperm:

In some species the nucellar region of the ovule gives rise to a storage tissue called the Perisperm. The perisperm is typically found in mature seeds along with the endosperm, varying in its amount, position, and form. It occurs in certain monocot families such as Zingiberaceae, as well as in several dicot families including Piperaceae, Nymphaeaceae, Cactaceae, Amaranthaceae, and Chenopodiaceae. In some plant species, such as Quinoa and Yucca, the perisperm serves as the main storage tissue, while the endosperm is completely absent (Bewley and Black, 1994).

Monocot Seed and Dicot Seeds

Monocotyledonous (monocot) seeds have only one seed leaf, or cotyledon. This single cotyledon is usually thin because it does not store food; instead, the food needed for the growing plant is kept in a separate tissue called the endosperm. Examples of monocot seeds include rice, wheat, and maize. These seeds tend to be more symmetrical than dicot seeds due to having just one cotyledon. They are often larger as well, mainly because they contain a large amount of endosperm, which acts as a food reserve for the developing embryo. Since monocot seeds retain their endosperm, they are also known as albuminous seeds.

Dicotyledons, or dicots, are a major group of flowering plants (angiosperms) characterized by having two seed leaves, or cotyledons, within their seeds. With around 175,000 species, this group includes a wide variety of plants such as trees, shrubs, garden flowers, and crops like beans, peas, and sunflowers. Dicots typically display floral parts in multiples of four or five, leaves with a net-like vein structure, and a ring-like arrangement of vascular tissues in their stems. Many dicots are woody, featuring branching growth patterns and a central taproot. The two cotyledons serve as nutrient stores that support the early development of the plant embryo.

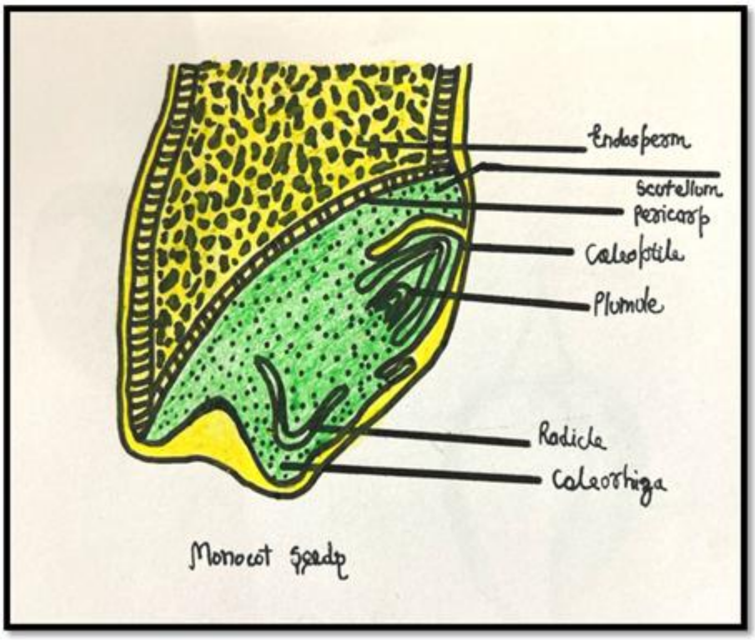

Figure 1: Anatomy of monocot seed (eg. wheat)

Structure in Monocot Seeds

1. **Seed coat:** The seed coat is membranous and attached to the fruit wall.
2. **Endosperm:** Endosperm is a bulky storage organ that nourishes the growing embryo. Monocots are generally endospermic with few exceptions, like an orchid.
3. **Aleuron layer:** It is the proteinous layer in between the outer membrane of endosperm and embryo that secretes the enzyme for the degradation of reserve food.
4. **Embryo:** The embryo is a small fleshy body present in the groove at the end of the endosperm. The embryo is diploid. It consists of the following parts:
   a. **Scutellum:** This is the single large, shield-shaped cotyledon that nourishes the growing embryo
   b. **Embryonal axis:** They are radicle and plumule formed at two ends of the seed. The radicle grows downward and gives rise to the root of a new seedling, while the plumule grows upward and gives rise to a shoot or stem.
   c. **Coleoptile and coleorhiza:** Radicle and plumule are enclosed in a sheath called coleoptile and coleorhiza, respectively.

Structure in dicot seeds

Seed coat: It is developed from the integument of the ovule and has the following parts.

- **Testa:** It is the outer thick layer that performs a protective function.
- **Tegman:** It is an inner thin membranous layer that protects the inner layer of the seed.

- **Hilum:** It is the point on the seed coat from which the seed is attached to the endocarp of the fruit. It is equivalent to the naval of humans.
- **Micropyle:** It is the small round pore above the hilum for the entry of pollen tube, water, and oxygen into the embryo.
- **Raphe:** It is the ridge portion in the groove that remains fused with testa.

Embryo: The embryo of a seed consist the following parts.

- **Cotyledon:** They are the fleshy structure present in the embryonal axis and provide nutrition for developing embryos. Dicot has two cotyledons.
- **Embryonal axis:** It is the miniature plant present in between the two cotyledons and consists of plumule and radicle, which later developed into shoot and root, respectively. The portion between cotyledon and radical is called hypocotyl, whereas the point between cotyledon and plumule is called epicotyl.

Characteristics of Monocotyledonous Seeds

- Monocotyledonous seeds, commonly referred to as monocots, are identified by the presence of a single cotyledon. This lone cotyledon aids in absorbing nutrients and helps the young plant begin its growth.
- When a monocot seed starts to germinate, it develops only one initial leaf. This leaf is generally slender and elongated, resembling the mature leaves of the plant. While the seed may appear somewhat round, it contains just one cotyledon.
- Leaves of monocot plants are typically long and narrow, with veins that run in straight lines from top to bottom. In some cases, these veins may run parallel from one side of the leaf to the other or spread out from the center.
- The stems of monocots are usually soft, unbranched, and do not thicken over time. As new leaves emerge, they are often enclosed and protected by the older ones forming a sheath.
- In contrast, dicotyledonous (dicot) plants generally have short, fibrous roots, and many also form bulbs.
- Monocot flowers typically have floral parts in groups of three. Sometimes, you might observe six petal-like structures if the sepals match the petals in color. The number of stamens usually corresponds to the number of petals.

Characteristics of Dicotyledonous Seeds

- The seed coat is the protective outer layer of a dicot seed.
- The hilum is a scar on the seed coat, marking the point where the seed was attached to the fruit during development.

- The micropyle is a minute opening situated close to the hilum of the seed. It facilitates the absorption of water during germination, enabling the activation of metabolic processes that lead to seed growth.
- Enclosed within the seed coat is the embryo, which includes an embryonic axis and a pair of cotyledons. These cotyledons are typically swollen and rich in stored nutrients to support the seedling's early growth.
- In some seeds, endospermic tissue is present to store food for the developing embryo. Examples of such seeds include castor, cotton, and coffee.
- Seeds like bean, gram, and pea are non-endospermic, meaning they do not contain endosperm; instead, their cotyledons hold the food reserves.

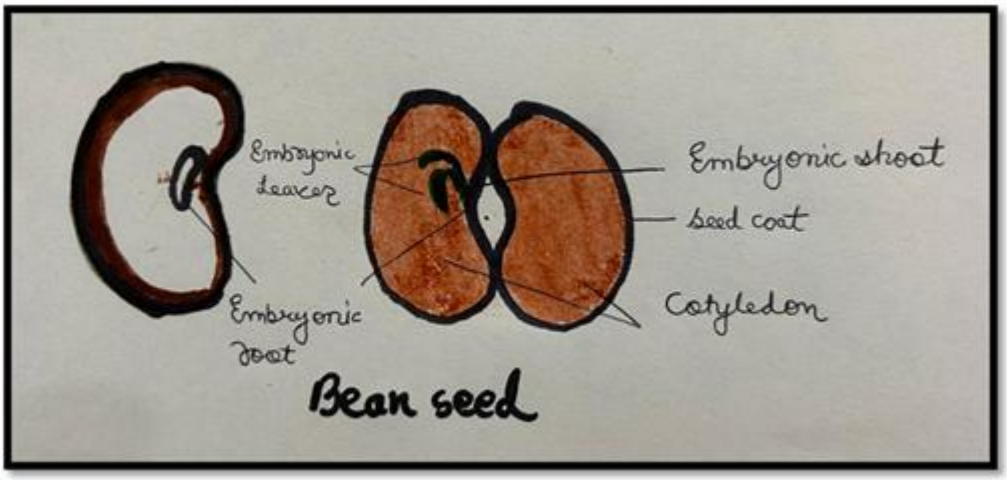

Figure 2: Dicot seed structure (eg. Bean)

Seed Coat

The seed coat, which forms the outer covering of a seed, can sometimes remain attached to the fruit wall. It develops from two layers of maternal tissue called integuments—the outer one being the testa and the inner one the tegmen. In certain monocot plants, these layers may not be clearly distinguishable and are occasionally fused with the fruit wall. When the outer layer is identifiable, it can feature specific textures, such as hair patches or surface patterns. In some species, the seed coat may develop hair-like structures or wing-like extensions that help with wind dispersal. Additionally, some seed coats are equipped with waterproof substances that protect the seed from drying out or decaying, particularly in water-dispersed seeds.

Cotyledons

The cotyledon, or seed leaf, is a key part of the seed embryo, typically taking up most of the internal space and serving as a source of nourishment and protection for the developing plant. Seeds of dicotyledonous plants contain two cotyledons, while those of monocots have just one. In monocots, this single cotyledon is modified into a structure known as the scutellum, which

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does not perform photosynthesis but instead helps absorb nutrients from the endosperm. Some plant species, like cypress and pine, have multiple cotyledons—up to 24 in some cases. The duration cotyledons remain active varies across species; in some plants, they persist only for a few days, while in others, they can function for up to a year.

Hypocotyl

The hypocotyl is the part of the seedling located between the cotyledons (seed leaves) and the radicle (embryonic root). While it eventually becomes part of the stem, its main role during germination is to lift the cotyledons above the soil surface. Though it doesn't grow as rapidly as the epicotyl, the hypocotyl is the first part to emerge from the soil. Together, the radicle and hypocotyl create a path for the epicotyl to grow. Since epicotyl cells are delicate, they are at risk of being damaged as they develop.

Embryo

The embryo is a basic multicellular structure made up of undifferentiated cells, formed when a haploid egg cell is fertilized by a sperm cell. It develops within the seed and is protected by structures like the seed coat or the endosperm. Following fertilization, the resulting zygote divides asymmetrically, producing one small and one large cell. This zygote carries genetic material from both the ovule and the pollen.

The smaller, upper (apical) cells give rise to a structure known as the connective, which links the embryo to the endosperm. This connection plays a vital role in supporting the embryo's growth and facilitates functions like cell division, metabolism, respiration, and nutrient storage.

In monocots, the embryo lies in a groove along the endosperm and is surrounded by a large, shield-like cotyledon called the scutellum. Additional components of the embryo include the plumule, radicle, hypocotyl, and epicotyl, all of which are part of the embryo axis and contribute to the plant's development.

Epicotyl

The epicotyl is the part of the seedling found above the cotyledon stalks and plays a vital role in germination. It is responsible for the initial growth of the stem that rises above the ground. In hypogeal germination, the epicotyl grows more rapidly than other parts of the embryo, leading to the plumule (the young shoot) emerging above the soil, while the cotyledons stay below the surface. This region connects the shoot apex—which will develop into the plant's first true leaves—to the expanding cells of the epicotyl. The definition of the epicotyl varies slightly between monocots and dicots: in monocots, it refers to the shoot that emerges from the soil or seed, whereas in dicots, it specifically describes the portion of the shoot that grows above the cotyledons.

Radicle

The radicle is the part of the embryo that gives rise to the root system of a plant. It is the first structure to emerge from a germinating seed, growing downward into the soil due to its positive geotropism. The radicle typically exits the seed through an opening called the micropyle. Radicles are categorized into two types based on their orientation: antitropous radicles grow in the direction opposite to the hilum of the seed coat, while syntropous radicles grow towards it. In monocot plants, the radicle is enclosed by a protective layer known as the *coleorhiza*, which is absent in dicots. In both cases, however, a root cap develops to shield the radicle during its initial growth phase.

Plumule

The plumule is a component of the seed's embryo that eventually develops into the shoot system, forming structures like stems and leaves. Unlike the radicle, the plumule exhibits negative geotropism, meaning it grows upward, away from gravity. It often appears as a small bud on one end of the embryo and may already include early leaf structures.

In some plants, such as sunflowers, the plumule does not initially display any leaf development, and growth begins only once the cotyledons emerge above the soil. In contrast, other plants show early leaf development while the cotyledons remain underground. In monocotyledonous plants, the plumule is protected by a sheath called the coleoptile, which is not present in dicotyledonous seed.

Endosperm

The endosperm is a tissue formed during fertilization in seed development and plays a crucial role in nourishing and protecting the embryo. One of its distinctive features is that its cells are triploid, meaning each nucleus contains three sets of chromosomes. The endosperm is mainly composed of three types of cells: the starchy endosperm, the basal layer, and the aleurone layer. The starchy endosperm makes up the majority of this tissue and consists of dead cells packed with starch granules and protein bodies. The basal cells are notable for their thickened cell walls and membranes—about 22 times thicker than those of regular plant cells—due to inward cell wall projections. The aleurone layer, though usually only one cell thick, may consist of up to three layers in monocots, and it encases both the embryo and the starchy endosperm. In Dicots, the endosperm is either absent or reduced and the major role of providing nutrition is fulfilled by the cotyledon

The endosperms are very vital parts of the fertilized embryo. An endosperm forms the surrounding tissue of the growing embryo. They are the primary storage tissue and their main function is to provide starch and other nutrients to the growing embryo. But before understanding these types, we need to understand what gives rise to the endosperm. A phenomenon called as 'double fertilization'. Each pollen grain consists of two male gametes. Once they reach the ovary, one of the male gametes fuses with the female gamete and forms the zygote (Berger F 2003, Rudall 2010).

A pollen grain is made of two male gametes. During double fertilization, one of the male gametes fuses with the female gamete (gametes are always haploid), resulting in zygote (diploid cell) formation and later as an embryo. This consists of a tiny embryonic axis which on germination of the seed forms a plant. The other male gamete fuses with the central diploid cell resulting in the formation of a triploid endosperm nucleus. The developing embryo receives its nourishment from the endosperm. Further repeated mitotic cell divisions result in the formation of an endosperm and are a triploid tissue.

Structural Adaptation in Seeds

Seeds have developed many adaptations to improve their survival and dispersal effectiveness. Some of adaptations are as follow-

1. Seed Dormancy; to overcome the unfavourable conditions the seeds undergo in dormant state. Some seeds are adapted to stay inactive for long durations until the conditions become favorable to protect the embryo from unfavorable conditions. Eg. Lotus seeds.
2. Hard Seed Coat; Some seeds contain a hard seed coat that shields the embryo from severe environmental conditions, animal digestion, and mechanical damage. E.g. Date Palm, Coconut.
3. Lightweight Seeds; Some seeds are adapted as lightweight, designed for wind dispersal, which ensures extensive colonization E.g. Dandelion, Cotton, etc.
4. Fleshy Fruits; Fleshy fruit containing seeds attract animals that eat the fruit and disperse seeds through digestion (e.g., Apple, Mango).
5. Floating Seeds – Some seeds are designed to allow water dispersal, assisting plants to spread throughout aquatic and coastal areas (e.g., Coconut, Lotus).
6. Explosive Mechanism – Certain seeds explode forcefully to distribute offspring over a large distance (e.g., Balsam, Pea).
7. Symbiotic Germination – Certain seeds, such as Orchids, need special fungi for germination, establishing mutualistic relationships.

Hormonal Regulation in Seed Development

Plant hormones (phytohormones) are chemical compounds involved in the regulation of growth and development, thus also known as plant growth regulators. Seed development is a highly coordinated process regulated by complex interactions among genetic, physiological, and hormonal signals. Plant hormones, also known as phytohormones, play essential roles in directing the key stages of seed formation: embryogenesis, endosperm development, seed coat formation, reserve accumulation, maturation, desiccation, and the transition to dormancy. The major hormones involved in seed development are auxins, cytokinins, gibberellins (GAs), abscisic acid (ABA), and ethylene, with recent studies also implicating brassinosteroids (BRs), jasmonic acid (JA), and salicylic acid (SA) in more nuanced regulatory roles. Here's an overview of how these hormones influence seed development. Role of major hormons in seed development are as follow-

A. Auxin

- Auxin activates the expression of transcriptional factor like *MONOPTEROS (*MP), which triggers the expression of its target genes such as *TMO5,* in *Arabidopsis.* MP regulates formation of vascular tissue
- Hypophysis specification is regulated by the plant hormone auxin.
- Auxin regulates its own transport by controlling the expression of PIN genes.
- Auxin is produced in the cells of the suspensor (basal cell of the zygote and its derivatives develop into a nutritive tissue, the suspensor)

B. Cytokinin

- Cytokinin (CK) plays a role in root vascular patterning. Auxin-CK interaction promotes periclinal cell division (in *Arabidopsis*)
- The most commonly occurring cytokinin in plants is **zeatin**, which isolated from corn

C. Gibberellins

- All gibberellins are derived from the ent- gibberellane skeleton.
- They are named as GA_1……GAn in order of discovery.
- GA_3 (Gibberellic acid) was the first gibberellin to be structurally characterized.
- About 150 GAs identified.
- GA1 and GA4 active in seeds, where they occur naturally.
- GA break dormancy and promote germination.
- Parthenocarpic (seedless) fruit development.

D. Abscisic Acid (ABA)

ABA acts as a key regulator of seed dormancy, preventing premature germination and maintaining the seed in a quiescent state until favorable conditions arise. ABA is often referred to as the "stress hormone" and plays a central role in seed maturation and the induction of seed dormancy. During seed development, ABA levels increase, promoting the accumulation of storage proteins and lipids, which prepare the seed for desiccation and dormancy.

E. Ethylene

Ethylene acts as a positive regulator of seed germination, overcoming ABA-mediated dormancy and promoting radicle emergence. Ethylene is involved in the later stages of seed development, particularly in seed maturation and germination. It promotes seed coat softening and the initiation of seedling growth by breaking down mechanical barriers in the seed coat. Ethylene also interacts with ABA, often counteracting its effects by promoting seed germination.

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SUSTAINABLE FARMING METHODS AND TOOLS FOR EFFICIENT RICE CULTIVATION

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Abstract:

Sustainable production of Paddy needs to implementing methods like Alternate Wetting and Drying (AWD), the System of Rice Intensification (SRI), Mechanized SRI (MSRI), besides tools and methods for efficient use of water and soil management, like trickle irrigation and conservation cultivation. These strategies can remarkably improve productivity and water use efficiency, minimise input expenses and boost long-term environmental and economic viability by minimizing adverse impacts on soil and water, even though their efficiency differs as per local conditions. Tools like SPAD meter, Leaf Colour Chart (LCC), Remote sensing and GIS are help farmers asses the right amount of nitrogen status of the paddy leaves in real time and preventing overdose application.

Keywords: Sustainable Paddy Production, Water Use Efficiency, Nitrogen Monitoring, Productivity

Introduction:

Global agriculture faces the formidable challenge of providing sufficient food for an ever-growing population amidst increasing water scarcity. In Asia, where irrigated agriculture accounts for about 90% of freshwater usage, rice farming alone consumes nearly 50% of this water. Between 1955 and 1990, per capita water availability in Asia dropped by 40-60%, and it is expected to decline by another 15-54% in the coming years. This poses a significant threat to global food security, which heavily relies on irrigated lowland rice as the primary source of rice supply.

To address these issues, it is essential to develop alternative water-saving irrigation techniques that minimize water usage while maintaining or enhancing yields to support a growing population. Practices like Alternate Wetting and Drying (AWD), the System of Rice Intensification (SRI), Mechanized SRI (MSRI). These innovations are crucial in the context of the global energy crisis and water scarcity.

High-yielding varieties (HYVs) are crucial for meeting the increased food demand. However, these varieties require significant nutrient inputs, particularly nitrogen, to achieve their yield potential. Real-time nitrogen management approaches, which involve diagnostic tools to measure leaf chlorophyll content, can match fertilizer application with plant needs, avoiding excessive nitrogen use and enhancing nitrogen use efficiency (Hasanain *et al.,* 2025).

The cultivation of irrigated rice faces several water-related challenges, including the degradation of existing water supplies and irrigated cropland, groundwater depletion, increasing pollution and declining water quality, transboundary water disputes, and the impacts of erratic and deficit rainfall due to climate change (Zaveri *et al.,* 2016). Effective water management also entails understanding and mitigating the specific water requirements and outflows during different stages of rice growth, from land preparation to the final harvest, to ensure the sustainability and success of rice cultivation.

Methods of Conservation Tillage

Excessive tillage is a major driver of land degradation and erosion, significantly impacting soil health and productivity. In contrast, systems that incorporate high crop residue addition and no-tillage practices can transform the soil into a net carbon sink. Conservation tillage (CT) emerges as a more sustainable strategy, capable of producing rice yields comparable to those achieved under conventional puddling methods.

Laser Land Levelling

Laser land levelling is a precision technique that employs laser-guided equipment to achieve highly accurate field levelling with the desired grade. This method is fundamental to precision agriculture, significantly enhancing water application efficiency and conserving 25-30% of water compared to traditional approaches.

Alternate Wetting and Drying (AWD)

Alternate Wetting and Drying (AWD) is an innovative irrigation method made for rice cultivation, where water is applied intermittently to create alternating flooded and non-flooded soil conditions. The core principle of AWD is to enhance yield per unit of transpiration, minimize non-beneficial water depletion, optimize rainfall utilization, and reduce water outflow.

The System of Rice Intensification (SRI) significantly contributes to resource conservation technologies for sustainable rice production through its innovative practices that optimize the use of natural resources.

Direct Seeded Rice (DSR)

Direct Seeded Rice (DSR) is an innovative and sustainable approach of rice cultivation that involves direct seed placement in the field, eliminating the traditional nursery and transplanting stages. This approach offers numerous benefits, including significant water savings, reduced labor requirements, and lower greenhouse gas emissions. By optimizing the use of natural resources, DSR contributes to more sustainable and efficient rice production systems. This essay will explore the key practices, benefits, challenges, and overall impact of DSR on sustainable rice production.

Green Seeker

The Green Seeker (GS) canopy sensor is a widely used, commercially available active optical sensor that emits red (650±10 nm) and near-infrared (NIR) (770±15 nm) wavebands. It has a field of view ranging from 52 to 145 cm^2 and measures spectral reflectance expressed as spectral vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). NDVI is crucial for assessing photosynthetic efficiency, crop productivity potential, and expected crop yield. NDVI is calculated as:

$$\text{NDVI} = \frac{\text{NIR reflected - Red reflected}}{\text{NIR reflected + Red reflected}}$$

With the help of Green Seeker, farmers can deliver the appropriate dose of nitrogen at the right site and time, boosting yield. For instance, in Rajasthan, the grain yield of barley increased significantly to 5.06 t/ha under 70% of the recommended N, with full P_2O_5 and K_2O as basal fertilizer, plus Green Seeker-based N top dressing according to the Soil Test Crop Response (STCR) based nutrient application (Mali *et al.,* 2016).

Working Principle of Green Seeker

Green Seeker computes NDVI utilizing red and NIR radiation. The principle relies on the fact that absorption of red light by plants during photosynthesis. Healthy plant leaves absorb more red light efficiently while reflecting more amount of NIR radiation, resulting in higher NDVI values, which indicate better plant health and greater biomass.

SPAD chlorophyll meter

The SPAD chlorophyll meter, developed by Minolta, offers a rapid and non-destructive means to estimate leaf nitrogen (N) status by measuring chlorophyll content. This process leverages Visible (at 650 nm) and infrared (at 940 nm) radiation to determine the chlorophyll concentration, providing immediate feedback key for effective nitrogen management in crops like paddy. Here are the two primary methods for using the SPAD chlorophyll meter for nutrient recommendation:

Fixed Threshold Value Approach

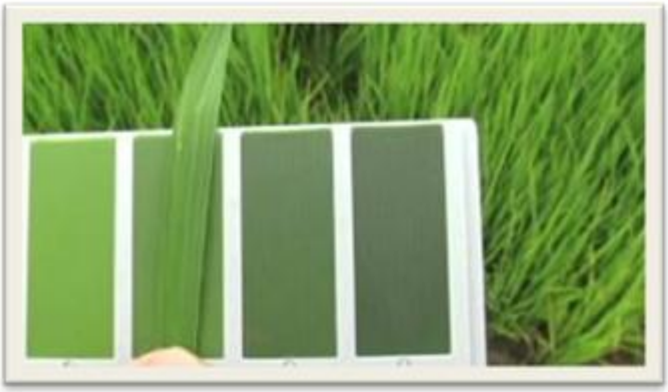
The Fixed Threshold Value Approach involves applying fertilizer-N when the chlorophyll meter reading falls below a predetermined threshold value. This SPAD threshold value is established through field trials and calibration, representing the limit below which crop yield may decline.

Sufficiency Index Value Approach

The Sufficiency Index Value Approach benefits from being auto-regulating for spatial, temporal, and varietal variations by establishing SPAD threshold readings relative to reference plot. According to Suresh *et al.,* (2017), nitrogen application in rice, applying nitrogen at a SPAD value of less than 41 led to a significantly higher yield of 5.86 tons hectare compared to the Leaf Color Chart (LCC) based nitrogen application, which yielded 5.62 tons per hectare, and the Recommended Dose of Fertilizers (RDF) treatment, which yielded 5.13 tons per hectare, at Hyderabad.

Leaf Color Chart (LCC)

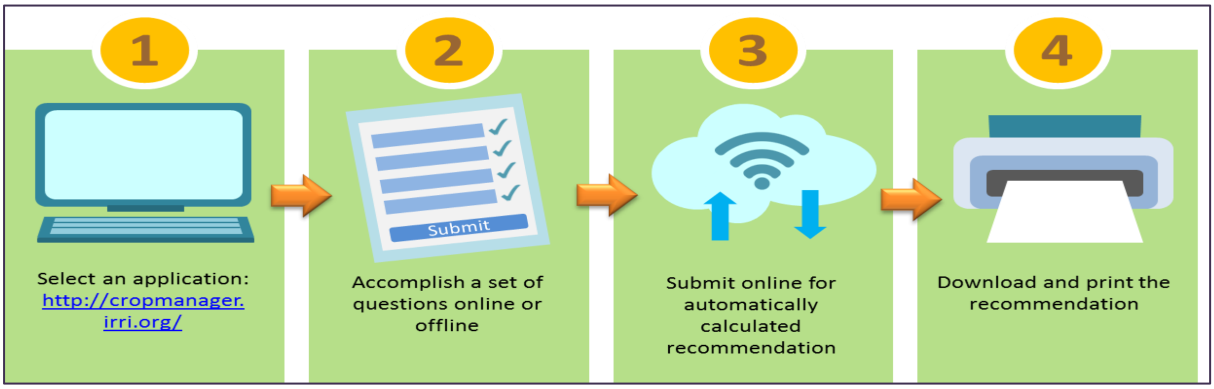
The Leaf Color Chart (LCC) was developed in Japan in the late 1980s and later refined by the Philippine Rice Research Institute (PhilRice) and the International Rice Research Institute (IRRI), with a version released in 2003. The LCC is a reliable tool for real-time N management, used to monitor the relative greenness of leaves quickly and accurately, which indicates their N status. It is applicable to crops like wheat, rice and maize, with different models tailored to specific locations according to local conditions and varieties of crops (Suresh *et al.,* 2017).



Leaf color chart

Crop Manager

Crop Manager is a computer and mobile phone-based application designed to provide small-scale rice, maize and wheat farmers with precision recommendations for fertilizer application. This innovative tool allows farmers to modify input applications according to crop needs by considering factors such as soil physico-chemical properties, water management strategies, and variety of crop.



Crop Manager

Micro Irrigation

Micro irrigation is an advanced and efficient irrigation method that significantly contributes to resource conservation, particularly in the realms of water and fertilizer use, while boosting agricultural productivity. This method includes systems like sprinkler and drip irrigation, which deliver water directly to the root zones of plants, thereby reducing water loss due to runoff and evaporation.

Efficiency of NPK Fertilizer Use (%) by Different Methods (Source: Biswas, 2010)

Nutrient	Soil Application	Drip + Soil Application	Drip + Fertigation
N	30-50	65	95
P_2O_5	20	30	45
K_2O	60	60	80

Nutrient Expert

Nutrient Expert is a user-friendly, interactive decision support software built by the International Plant Nutrition Institute (IPNI), USA, for site-specific nutrient management (SSNM), particularly aimed at smallholder farmers. This software requires only basic computer skills, making it accessible to farmers in remote areas without soil testing facilities. By utilizing previous crop management data, which need not be sophisticated, Nutrient Expert provides recommended nitrogen doses based on the input data. It is designed to account for location and time-the supply of nutrient, ensuring site specific application. The software also considers the availability of inputs for estimate yield targets, offering a highly interactive and rapid assessment of fertilizer requirements for specific fields.

Soil Test Crop Response (STCR)

The Indian Council of Agricultural Research (ICAR) established the All India Coordinated Research Project (AICRP) on Soil Test Crop Response (STCR) in 1967. The STCR concept, developed by Ramamoorthy in 1987, aims to provide a precise quantitative basis for adjusting fertilizer doses according to varying soil test results and crop performance, targeting specific levels of crop production. STCR establishes the relationship between soil test results and crop performance (Dwevedi *et al.,* 2024)

Azolla in Rice Production

Using Azolla, a water fern, as a biofertilizer in rice production is one of the most economical and eco-friendly methods available. This approach not only increases productivity and income but also lowers the reliance on inorganic fertilizers and improves soil health (Chanapanchai *et al.,* 2025). To create Azolla compost, fresh and excess Azolla is harvested from cultivation tanks and allowed to decompose for about 45 days. The compost is then applied at the dosage of ten tons per hectare and enriched with rock phosphate (RP) to boost its nutrient content. This practice provides essential nutrients to the rice plants and supports sustainable agriculture by enhancing soil fertility and structure.

Brown Manuring

Brown manuring is similar to green manuring, with the key difference being that rice and Sesbania spp. (or Dhaincha) are grown together. When these companion plants surpass the rice plants in height, typically around 25 days of co-culture, a herbicide (2,4-D) is applied to kill the Sesbania or Dhaincha plants. Within 4-5 days of spraying, the plants turn brown and begin to decompose, providing organic matter and nutrients to the soil (Biswas *et al.,* 2024).

Crop Residue Retention Practices

Efficient management of residues, stubbles, roots and weed dry matter can significantly enhance soil fertility by introducing organic residues and essential nutrients, thereby improving overall soil condition. Paddy straw, for instance, contains valuable organic materials and nutrient like nitrogen (N) ranging from 0.5% to 1.5%, phosphorus (P) from 0.2% to 1.0%, and potassium (K) from 0.8% to 1.0% (Mongkol and Anan, 2006).

Remote Sensing and GIS

Remote sensing involves the detection and monitoring of the physical characteristics of an area by measuring its reflected and emitted radiation from a distance, typically using satellites or aircraft. On the other hand, a geographic information system (GIS) is a computer system designed for capturing, checking, storing and presenting data related to points on the surface of Earth. GIS allows for the visualization of various data types, such as buildings, streets and vegetation on a single map. This capability enables users to analyze and understand patterns and relationships more effectively, contributing to informed decision-making and spatial analysis.

Conclusion:

Sustainable farming approaches and smart tools play a crucial role in improving the resilience efficiency and productivity of rice cultivation. Precision nutrient management, integrating water-saving strategies and advanced decision-support technologies improve resource-use efficiency while minimizing environmental negative impacts. These approaches not only lower input costs but also boost soil quality and long-term agroecosystem sustainability. Tools such as LCC, Green Seeker, SPAD and GIS empower farmers with real-time insights for precise field decisions. Overall, the integrating these innovations is crucial for maintaining sustainable rice farming and future food security.

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BRIDGING THE DIGITAL DIVIDE: CHALLENGES AND OPPORTUNITIES IN ADOPTING PRECISION AGRICULTURE IN DEVELOPING ECONOMIES

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Abstract:

Precision agriculture uses digital tools such as sensors, drones and artificial intelligence to enable site-specific farm management and this approach holds transformative potential for improving productivity, enhancing sustainability and strengthening climate resilience. However, in many developing regions the digital divide gaps in internet access, affordability and digital skills impedes technology diffusion. This chapter examines the major challenges arising from inadequate infrastructure, high costs, limited digital literacy and policy gaps, and it highlights successful models that have effectively addressed these barriers. It reviews notable examples such as India's AgriStack, the Digital Agriculture Mission and the electronic National Agricultural Market, along with African innovations including Hello Tractor, various digital advisory services and extension initiatives such as Digital Green. The chapter also discusses the roles of public–private partnerships, open data platforms and farmer training in enabling inclusive tech uptake. Bridging this divide is crucial to ensure that smallholders can leverage precision tools for higher yields, climate adaptation and equitable growth.

Keywords: Precision Agriculture, Digital Divide, Developing Economies, Smart Farming and Technology Adoption

1. Introduction:

Precision agriculture and digital agriculture refer to using information and communication technologies to optimize farm decisions. Precision farming involves observing, measuring and responding to within field variability via GPS guided equipment. More broadly, digital agriculture integrates IoT sensors, satellite data, drones and AI to enhance yield and resource use efficiency. These technologies promise site-specific fertilizer and irrigation management, real-time pest/disease alerts and market information, redefining traditional farming. However, this digital transformation remains uneven. In developing countries, structural barriers create a persistent digital divide where many rural farmers lack reliable internet, affordable devices and tech skills. For example, an FAO (Food and Agricultural Organization) study notes that digital advisory services are unequally distributed between urban and rural populations and low e-literacy in remote areas limits uptake. Addressing these access and literacy gaps is as critical as the technology itself. Efforts must strengthen last-mile infrastructure such as broadband connectivity, mobile network coverage, open data standards to support platforms like AgriStack and comprehensive on-ground training for farmers. Only with these foundational elements in place can digital farm management tools effectively reach the smallholder families who produce a significant share of the world's food.

2. Evolution of Precision Agriculture

Precision agriculture is not entirely new concept it dates back decades, but recent advances have greatly expanded its scope. Early systems (1990s–2000s) featured GPS-driven tractor auto-steer and yield monitors, allowing farmers to map soil and crop variability. Today's precision tools have become much more sophisticated. Global Navigation Satellite Systems (GNSS) now enable centimetre level accuracy in planting and spraying. Variable rate technology lets farmers apply fertilizers and pesticides at site-specific rates within the same field, reducing waste. More recently, advances in GIS mapping, drones, remote sensing and machine learning have opened new frontiers. For example, drone-mounted multispectral cameras can survey crop stress patterns from the air and AI models analyze the data to predict water or nutrient needs. In laboratory and pilot studies, convolutional neural networks have been applied to UAV (Unmanned Aerial Vehicle) imagery to enable real-time disease detection in rice and other staple crops. When combined with Internet of Things systems such as soil probes and automated weather stations, machine learning can generate highly sophisticated decision rules for irrigation scheduling. Precision agriculture has evolved from simple GPS-plots to an agriculture 4.0 toolkit driven by AI, big data and connectivity.

3. Understanding the Digital Divide in Agriculture

The digital divide in agriculture encompasses multiple dimensions of inequality.

a) Access:

Many rural areas lack broadband infrastructure or cell coverage. OECD (Organisation for Economic Co-operation and Development) data note that significant connectivity gaps persist between urban and rural regions. A Harvard report finds that only 84 per cent of global croplands even have a 2G connection and many smallholders still wait for adequate coverage.

b) Affordability:

Even where networks exist, the cost of smartphones, data plans or precision hardware where drones and sensors can be prohibitive. Farmers often have tight cash flows and limited credit.

c) Literacy/Skills:

Digital literacy is the ability to understand and use technology and data is often low among older or less-educated farmers. Effective adoption requires not just usage skills but also interpreting data. In practice, the rural digital divide means extension services and market programs may not reach many farmers. A study of extension services reports that smallholders often lack internet or devices and this is especially pronounced in poorer nations with underdeveloped infrastructure. Altogether, lack of connectivity, technology cost and inadequate training form the core barriers under the digital divide in farming communities.

4. Challenges in Adoption

Key challenges hindering precision agriculture adoption in developing contexts include:

a) Poor Infrastructure:

Many remote farms lack reliable electricity and mobile data. Internet connectivity is patchy or expensive. Without basic broadband or even 3G/4G coverage, advanced tools such as cloud analytics and real-time sensors cannot function. Government reports highlight that large regions of Sub-Saharan Africa and South Asia still suffer from low digital penetration. The high cost of deploying rural towers exacerbates this divide.

b) Economic Constraints:

Smallholder farmers often have very limited capital. Precision tools such as GPS units, drones and IoT (Internet of things) kits entail upfront investment and maintenance costs. Studies show that small farms face budget constraints and have less access to financing, reducing their ability to buy such technology. Crop yield gains may not immediately compensate for these costs, especially if farms are tiny. Credit availability is also a factor; without microfinance or subsidy programs many farmers cannot afford the equipment or smartphones needed.

c) Scale and Landholding Size:

Fragmented landholdings make precision agriculture seem less viable. A 1–2-hectare farm has less to gain from an expensive drone survey than a 100-hectare estate. Economic return on investment is harder to achieve at small scale.

d) Low Awareness and Skills:

Many farmers particularly older or less-educated ones are simply unaware of precision options or find them complex. Low levels of digital literacy limit usage of apps or interpretation of soil/market data. Extension agents themselves often lack training in these tools. As one review notes, smallholders' slow adoption is tied to low levels of digital illiteracy and limited technical training.

e) Policy and Institutional Gaps:

In many developing regions, supportive policies lag. There may be no national strategy or funding to promote digital farming. Data governance laws are weak, raising farmer privacy concerns when platforms collect data. In some cases, import tariffs make equipment expensive. Bureaucracy and lack of coordination between agriculture, IT and telecom agencies can prevent rollout of tech-driven programs.

For example, without good rural broadband, digital literacy training has limited impact and vice versa. Overcoming them requires concerted action in multiple domains.

5. Opportunities and Case Studies

Despite barriers, many promising solutions and success stories demonstrate how to bridge the divide:

a) Data Platforms and Identity (India's AgriStack/ Digital Agriculture Mission):

India's Digital Agriculture Mission (2024) is building AgriStack, a national farm data architecture. AgriStack will assign every farmer a digital ID and tie it to geospatial farm maps like soil and land records. It also plans a Crop sown registry, using mobile surveys to record what each farmer plants each season. Combined, this creates an interoperable data ecosystem. The vision is that once AgriStack is live, farmers can easily access subsidies, credit and market info tailored to their ID-linked profile. Similarly, India's e-NAM (National Agriculture Market) platform now links 1,522 wholesale markets and 1.7 crore farmers, giving smallholders direct market access and transparency in pricing.

b) Digital Extension and Advisory (Digital Green):

Community-driven tech can accelerate learning. Digital Green is an NGO program that produces localized how to farming videos. J-PAL reports that Digital Green's video-based approach often shared via village screens or mobile increased yields and profits among women farmers in India. By 2025 it had scaled to 7.2 million farmers across 12 countries. This low-bandwidth, human centered tech bridges literacy gaps where videos in local languages show trusted peers demonstrating practices, so even semi-literate farmers learn. Governments in India and elsewhere have adopted or replicated such models for agronomic advice.

c) Smart Mechanization (Hello Tractor):

In Africa, startup Hello Tractor has developed a mobile platform and pay as you go financing to connect smallholders with tractor services. Farmers or local booking agents use the Hello Tractor app to schedule nearby tractors. The company's IoT-enabled tractors and PAYG model (5%

down payment via app) let even poor farmers rent mechanization. Studies show Hello Tractor enables users to plant up to 40 times faster than manual methods. In Kenya alone, the service connected 360,000 farmers to 700 tractors, vastly expanding mechanization without each farmer owning equipment. The model has spread to 16 African countries, illustrating how digital platforms plus microfinancing can overcome both affordability and access barriers.

d) Market & Advisory Apps:

Mobile platforms that provide real-time market price information, such as Skymet Weather and Kisan Suvidha, along with applications that support input procurement, including DeHaat and Kisan Credit Card services, are rapidly proliferating across South Asia. For example, agritech startups DeHaat and Agribazaar provide half a million Indian farmers with access to inputs, credit and real-time market linkage. Similarly, satellite-based advisories (e.g., IRRI's Rice Advice) have delivered site-specific fertilizer recommendations, yielding 25 per cent yield gains in trials in Ethiopia and Nigeria. In Kenya, a national Agricultural Observatory platform provides weather and agronomy forecasts to 1.1 million farmers, helping them time planting and manage climate risk.

e) Public–Private Partnerships (PPPs):

A World Economic Forum funded proposal in India identified four PPP pillars for agriculture tech: open data sharing, shared infrastructure, academia partnerships, and farmer engagement. For instance, the Sahamati initiative in Karnataka, India aggregates data from more than 7 million farmers to share with startups through an open platform. Likewise, states like Telangana use common service centre's like digital kiosks and self-help groups to extend technology services to villages. These PPP efforts pool government resources such as extension and e-Gov portals with private innovation such as apps and sensors to scale solutions affordably.

f) Climate-Smart Inputs:

Digital channels are also spreading improved seeds and practices. The CGIAR's Technologies for African Agricultural Transformation (TAAT) program has used digital catalogs and mobile alerts to distribute climate-resilient seed varieties to over 12 million African farmers in three years. Such programs show how ICT can scale access to new technologies even in remote areas.

Targeted examples across Asia and Africa illustrate that with the right design, digital tools can reach smallholders. Key factors in these successes include local language content, affordability mechanisms like PAYG finance and integration with trusted institutions or cooperatives.

6. Policy and Institutional Support

Realizing these opportunities requires enabling environments. Policymakers and institutions can support digital agriculture by:

a) National Digital Agriculture Strategies:

Many governments are launching digital agricultural policies. For instance, India's ICAR (Indian Council of Agriculture Research) and Ministry of Agriculture both endorse the 2024 Digital Agriculture Mission, which coordinates data integration (AgriStack) and geospatial decision systems (Krishi DSS). Similarly, the African Union's Digital Transformation Strategy (2020) explicitly targets agriculture efficiency and climate resilience by 2030. Such high-level strategies mobilize funding and set standards for data sharing and privacy.

b) Extension and Training Programs:

Traditional extension must evolve into digital extension. FAO recommends building e-extension platforms and upskilling extension agents and farmers in ICT. For example, governments can sponsor trainings on smartphone apps and provide helplines. Investments in last-mile digital literacy including digital libraries and rural tech centres are key. Training programs can partner with local NGOs to reach women and youth, who often have higher digital aptitude.

c) Data Governance and Open Standards:

Access to data and trust in its use are crucial and policymakers should create open data frameworks like AgriStack's open APIs that allow private apps to use public farm data. At the same time, data privacy laws are needed so that farmers own their data. Standards such as the Farmstack reference architecture ensure interoperability between systems. A recent commentary stresses that equitable digitalization requires protecting farmer agency in data and ensuring smaller producers benefit from data-driven markets.

d) Public–Private Partnerships (PPP):

Governments can catalyze PPPs for agri-tech deployment. This means co-funding pilot projects, subsidizing tech purchases, or offering investment incentives to startups. As noted earlier, India's budget has earmarked funds for PPP-driven Agri tech services. Similarly, the World Bank and UN agencies often co-finance digital agricultural accelerators. PPPs can also leverage social enterprises *e.g.* digital cooperatives to distribute technology.

e) Infrastructure Investment:

Finally, bridging the digital divide starts with basic infrastructure. Rural broadband expansion and affordable connectivity even via satellite/broadband sharing must be policy priorities. Governments may negotiate with telecom companies for rural coverage or subsidize internet hardware. Only when the connectivity base is strong can higher-level digital agriculture programs succeed.

By aligning policy, financial incentives and capacity-building, institutions can create an ecosystem where precision tools diffuse widely rather than remaining niches.

7. Future Prospects

Looking ahead, emerging technologies promise to further empower smallholders if accessibility issues are addressed:

a) Artificial Intelligence & Predictive Analytics:

AI-driven platforms will grow in precision. We can expect more machine-learning tools embedded in smartphone apps: for instance, image-recognition apps diagnosing crop disease from photos, or AI chatbots providing real-time farming advice via text. Predictive algorithms may integrate weather forecasts and market data to optimize planting schedules and supply chains. Already, research projects use convolutional neural networks on drone imagery for disease and nutrient deficiency detection.

b) Enhanced Connectivity (5G and Satellites):

Next-generation networks such as 5G and low-Earth orbit satellites will dramatically improve rural internet access. Initiatives like SpaceX's Starlink and other satellite constellations aim to blanket even remote croplands with high-speed internet. This will enable real-time IoT sensor networks on farms and seamless cloud analytics. Mobile internet penetration is projected to rise sharply, one report notes 94 per cent global coverage by 2020, suggesting the divide may narrow. Affordable 5G-enabled IoT devices could bring high-quality connectivity to village levels.

c) Affordable Sensor and Drone Technologies:

The cost of sensors and drones continues to decline, making these technologies increasingly accessible to resource-constrained farming communities. Community-shared devices, such as village-level drone services, along with open-source hardware including low-cost soil probes and weather stations, are expected to expand rapidly. Do-it-yourself agricultural technologies, such as smartphone-based spectrometers, have the potential to further democratize access to precision inputs. With the growing availability of online tutorials and maker spaces, farmers themselves may increasingly develop and adapt locally relevant technological solutions.

d) Inclusive Platforms:

Future digital agriculture platforms are likely to embed equity features: multilingual interfaces, voice-based tools for low-literacy users, micro-loans built into apps as Hello Tractor does. Blockchain or distributed ledger technologies might be used to secure land records or supply chain traceability, benefiting smallholders in accessing global markets.

e) Climate-smart Innovations:

Satellites and IoT sensors will increasingly be used for climate adaptation. For instance, low-cost mobile tools could monitor groundwater levels or trigger micro-irrigation on demand. AI could optimize seed recommendations for changing conditions. Ensuring smallholders benefit from these will require ongoing investment in rural research and subsidy programs for adopting new tech.

The technical promise is vast from 3D-printed seed coatings to robot pollinators. But realizing this promise for all farmers hinges on closing the remaining gaps in connectivity, cost and know-how.

Conclusion:

Precision agriculture offers a route to higher yields, efficient resource use and climate resilience, but without concerted efforts its benefits risk widening inequalities. Bridging the digital divide means simultaneously pushing the frontier of technology and ensuring it is accessible. The dual goal is clear where advancing in innovation while advancing inclusion. Key to this will be collaborative frameworks involving governments, agritech companies, research institutions and farmer organizations. Public–private partnerships can share costs of infrastructure and R&D, while open-data policies and digital literacy programs can ensure smallholders are not left behind. As one analysis emphasizes, policy must balance quick wins along expanded rural broadband, affordable data plans with long-term capacity building such as education, regulatory frameworks. Closing the digital divide between technology-rich and technology-poor farmers is essential to ensure that agricultural modernization fosters both productivity and social equity. With targeted strategies and partnerships, developing economies can jump to sustainable, tech-enabled farming systems. Closing this gap is not only a technological challenge but a social one and overcoming it is vital for global food security and fair growth.

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INTRODUCTION TO SAMPLING AND SAMPLING FUNDAMENTALS

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Introduction:

Studying sampling is necessary because it is cost-effective and time-efficient, allowing researchers to draw generalizable conclusions about a large population by studying a smaller, representative subset. It makes studies that would otherwise be impossible to conduct because of their sheer scale, and by selecting an appropriate sample, researchers can achieve more accurate and precise measurements than they could with a less careful approach to data collection.

Benefits of Studying Sampling:

a. **Time and cost savings:** It is often impractical and expensive to collect data from an entire population. Sampling provides a more manageable and affordable way to get the information needed for a study;
b. **Feasibility:** For very large populations, it can be physically impossible to collect data from every individual. Sampling makes research feasible by allowing studies that would otherwise be impossible;
c. **Accuracy and precision:** A well-selected sample allows for more accurate measurements and more precise findings. The larger the sample size (within reason), the more confident you can be that the results reflect the entire population;
d. **Generalizability:** If a sample is truly representative of the population, researchers can generalize their findings to the entire group. This allows for a broader understanding of the subject of the study and
e. **Efficiency:** A study on a sample can be completed more quickly than one on a whole population, allowing for faster results and decision-making.

Sampling:

The word sampling is because of sample. It is the process of obtaining information about an entire population by examining only a part of it. In simple terms, it is the process of selection of sample.

Universe/Population:

From statistical point of view, the term 'universe' refers to the total of the items or units in any field of inquiry whereas the term 'population' refers to the total of the items about which information is desired. In simple terms, population is nothing but the number of individuals.

Types of Universe or Population:

a. **Finite population**: if the population is countable, it is called finite population. E. g. human population
b. **Infinite population**: If the population cannot be counted or it is limitless population. Then, it is known as infinite population. E.g. no of stars in the galaxy.
c. **Existence population**: Existence universe refers to a population of concrete objects like the number of persons having a certain income or the number of books with a certain number of pages etc.
d. **Hypothetical universe**: Hypothetical universe is one which does not consist of concrete objects. E.g. if a disc is tossed, each draw is an individual unit and we can construct a universe by throwing the disc a large number of times and recording its result.

Sample: Small portion of population is called sample. Small portion is taken either from finite or infinite or existence or hypothetical population.

Sampling theory: Theory which deals with the relationship between sample and the population are called sampling theory.

Sampling error: Sampling errors are those errors which arise on account of sampling and they generally happen to be random variations (in case of random sampling) in the sample estimates around the true population values. The magnitude of the sampling error depends upon the nature of universe. The more homogeneous the universe, the smaller the sampling error. Sampling error is inversely related to size of the sample i.e. sampling error decreases as the sampling size increases and vice-versa. Sampling error is worked out by:

Sampling error= Critical value at certain level of significance X Standard error

In other words, the difference between the sample value and the population value is called sampling error.

Why do we go for sampling? Sometimes, it is very difficult to study the whole population because of shortage of time and funds then, we resort to sampling. This implies that we study the population through sampling or we want to draw the inference about the population through sampling. E.g. soil sampling.

How should to draw sample? Our sample should be a through representative of the population. Otherwise, purpose of drawing sample about the population fails.

Object of sampling: The most important aim of sampling study is to obtain maximum information about the population phenomenon under study with the least sacrifice of money, time and energy.

Sampling design: It refers to the techniques or the procedure; the researcher would adopt in selecting some sampling units from which inferences about the population is drawn. These are census survey and sample survey.

Statistics and parameter: Statistics is a characteristic of the sample whereas; parameter is a characteristic of the population. E.g. Population mean 'u' is a parameter whereas; sample means '$\bar{x}$ 'is a statistic. To obtain the estimate of a parameter from a statistic constitutes the prime objective of sampling analysis.

Sampling and non-sampling error: Sampling error is that error which arises on account of sampling and they generally happen to be random variation in the sample estimate around the true population value. The sampling error usually decreases with increase in sampling size (number of units selected in the sample) and in fact in many situations decrease is inversely proportional to the square root of the sample size. Sampling error is not existed in case of complete enumeration survey, since the whole population is surveyed. However, the error mainly arising at the stages of ascertainment and processing of data, which are termed as non-sampling error, are common in both complete enumeration and sample surveys. Non-sampling error is likely to me more in case of complete enumeration survey than in case of sample survey, since it is possible to reduce the non-sampling error to a great extent by using better organization and suitably trained personnel at the field and tabulation stage. The non-sampling error is likely to be increased with increase in sample size.

Sample space: Sample space is the totality of all the sample points. E.g. suppose the set {1, 2, 3, and 4} and take any two numbers of these together which is called the sample point and the total number is called the sample space.

Sampling fraction: The ratio of the sampling size to the population size is known as sampling fraction. If the sample of size 'n' is taken from a population of size 'N' then, the sampling fraction is denoted by n/N.

Sampling procedure: It is the method of selection of sample from the population. Sampling procedure is said to be random if it is governed by the law of probability, i.e. its unit in the population is assigned some pre-determined probability of selection. The sample which is not selected by the random process is known as non-random

Accuracy and Precision: Accuracy refers to the amount of deviation of the estimate from the true value, whereas precision refers to the size of this deviation by repeated application of sampling procedure. Precision is the range within which the population average (or other parameter) will lie in accordance with the reliability specified in the confidence level as a percentage of the estimate ± or as a numerical quantity. For instance, if the estimate is Rs. 4000 and the precision desired is ± 4 per cent, then the true value will be no less than Rs. 3840 and no more than Rs. 4160. This is the range (Rs. 3849 to Rs. 4160) within which the true answer should lie.

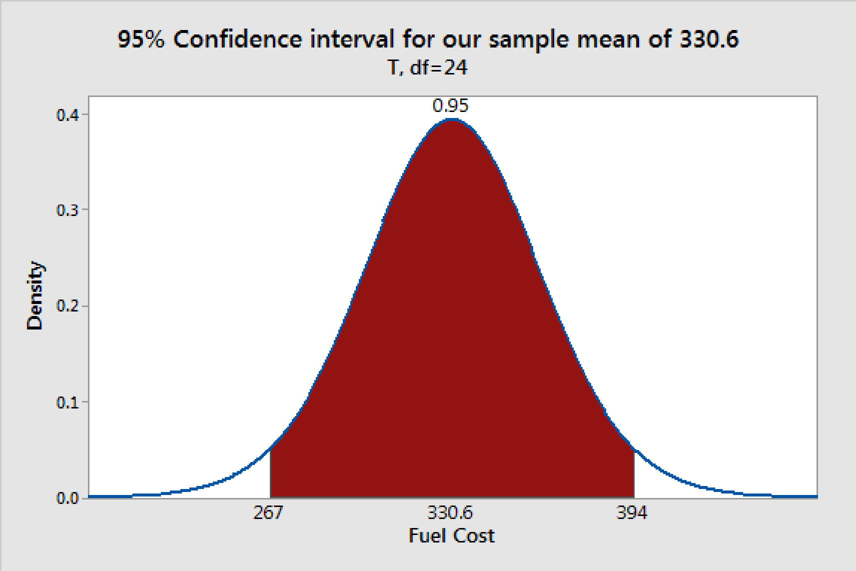
Relative accuracy: The relative accuracy of two samples which differ in respect of method of sampling or the size of sample or both may be defined as the reciprocal of the ratio of sampling variance of the estimates given by the two methods when the same number of units is taken.

Efficiency and relative efficiency: The efficiency is measured by the inverse of the sampling variance of the estimator. The relative efficiency of the two different methods of sampling on the same type of sampling unit may be defined as the reciprocal of the ratio of the number of units required to attain a given accuracy with the two methods.

Estimator and estimate: The random variable such as sample mean ($\bar{x}$) and sample variance (σ_s^2) used to estimate the population parameter such as population mean (μ) and population variance (σ_p^2) are called estimator while, specific value of these say sample mean ($\bar{x}$)=105, and sample variance (σ_s^2)=21.44 are referred to as estimate of the population parameter. Estimate always has a numerical value.

Estimation: It is the process of finding the value of population parameter.

Confidence level and Significance level: The confidence level or reliability is the expected percentage of times that the actual value fall within the stated precision limits. Thus, if we take a confidence level of 95%, then we mean that there are 95 chances in 100 (0.95 in 1) that the sample results represent the true condition of the population within specified precision range against 5 chances in 100 (or 0.05 in 1) that it does not. Precision is the range within which the answer may vary and still be acceptable; confidence level indicates the likelihood that the answer will fall within that range. One should always remember that if the confidence level is 95%, then the significance level will be 5% (100-95) and if the confidence level is 99%, then the significance level will be 1% (100-99) and so on. We should also remember that area under the normal curve within precision limits for the specified confidence level constitutes the acceptance region and the area under the normal curve outside these limits in either direction constitutes the rejection regions. The region of rejection is known as critical region and when the critical region is expressed in terms of probability, it is known as level of significance (LOS).



A normal curve diagram for a 95% confidence level shows the central area as the acceptance region and the two outer tails as the rejection regions. The acceptance region is shaded and represents 95% of the data, while the two unshaded tails, each representing 2.5% (LOS), are the rejection regions.

Sampling Distribution: We are often concerned with sampling distribution in sampling analysis. It is a probability distribution of a statistics that is obtained through repeated sampling of a specified population. It describes a range of possible outcomes from a statistic such as mean or mode of some variable, of a population. Distribution shows the trend on which the variable taking the different values. Some of the important sampling distributions, which are commonly used, are:

(a) Sampling distribution of mean; (b) Sampling distribution of proportion;

(c) Student's t-distribution; (d) F-distribution; and (e) Chi-square distribution

How we can increase the precision of the sample estimate? Precision can be increased (a) by increasing the sample size but, we can't increase the sample size beyond certain limit and (b) to reduce the heterogeneity in the population. More the precision of the sample estimate more will be the reliable estimation for the population.

Note: we estimate the value of population mean (μ) with the help of sample mean ($\bar{x}$). Closer the value of sample means ($\bar{x}$)) to population mean (μ), better is the estimate. The accuracy or precision of the sample depends upon-(a) sample size (n) & (b) heterogeneity in the population. More the value of sample size (n), closer the value of population parameters. But we can't increase the value of 'n' beyond certain limit. If the population is homogeneous, sample estimates give better parameter i.e. heterogeneity is removed. The conclusion in sampling studies is based not no certainty but on probability

Effective Sample Size: It is the actual distinct unit in that particular sample. E.g. In 111, ESS =1 and in 121, ESS =2.

Estimation of population parameter: There are two types of estimates pertaining to estimation of population parameter.

Point estimate and Interval estimate: The estimate of a population parameter may be one single value or it could be a range of values. In the former case, it is referred as point estimate, whereas in the later case it is termed as interval estimate.

a. Point estimate: A particular value of sample statistics which is used to estimate the parameter value is called the point estimate. E.g. average production of wheat in India is 40 q/ha.

b. Interval estimate: The limit within which the parameter value is estimated is called interval estimate. E.g. average production of wheat in India lies between 40-50 q/ha.

Small sample size and large sample size: When we have $n \leq 30$, it means it is a small sample and when $n > 30$, it means we have large sample size

Sampling frame: It consists of a list of items from which the sample is to be chosen (source list).

Sampling Design

Census Survey: All the items under consideration in any field of inquiry constitute a "universe or population". A complete enumeration of all the items in the "population" is known as census survey. As all the items are included in this type of survey, therefore it must be having the highest accuracy. But, in practice this may not be true. Even the slightest element of bias in such an inquiry will get larger and larger as the number of observation increases. This method requires lot of time, money and energy. Therefore, when the field of inquiry is large, this method becomes difficult to adopt because of the resources involved. When the universe or the population is large, then this method is beyond the reach of an ordinary researcher. Government is the only institution which can get the complete enumeration carried out. Even the government adopts this method in very cases such as population census conducted once in a decade.

Sample Survey: When field studies are undertaken in practical life, consideration of time and cost almost invariably lead to a selection of respondents i.e. selection of only a few items. The respondents selected should be a representative of total population as possible in order to produce a miniature cross-section. The selected respondents constitute what is technically called s "Sample" and the selection process is called "Sampling Technique". The survey so conducted is known as "Sample Survey". For example, let the size of the population be "N". if a part of population say "n" units i.e $n<N$ is selected according to some rule then, n is called the sample.

Implications of a Sampling Design: It refers to the technique or the procedure the researcher would adopt in selecting items for the sample. Sample design indicates the number of items to be included in the sample i.e the size of the sample. Sample design is determined before the data are collected.

Steps in Sampling Design:

(a)Type of universe: First of all, the universe to be studied is defined. The universe can be finite or infinite. In finite universe, the number of items is certain, but in case of infinite universe, the number of items is infinite i.e. we cannot have the idea about the total number of items. The populations of a city, the number of workers in a factory are the example of finite universe. Whereas, the number of stars in the sky, listeners of a specific radio programme, throwing of a disc etc are the example of infinite universe.

(b) Sampling Unit: Sampling unit is to be decided before selecting sample. Sampling unit may be a geographical one such as state, district, village, etc. or it may be a social unit such as family, club, school, etc, or it may be an individual.

(c) Source list: It is also known as "Sampling Frame" from which sample is to be drawn. It contains the names of all the items of the universe (in case of finite universe only). If the source list is not available, the researcher has to prepare it. Such a list should be comprehensive, correct, reliable and appropriate.

(d) Size of Sample: This refers to the number of items to be selected from the universe to constitute a sample. The size of the sample should neither be excessively large, not too small. It should be optimum. An optimum sample fulfills the requirements of efficiency, representativeness, reliability and flexibility. Costs, time and budgetary constraints dictate the size of the sample.

(e) Parameters of interest: In determining the sample design, one must consider the question of the specific population parameters which are of interest.

(f) Budgetary Constraints: Cost considerations, from practical point of view, have major impact upon the decisions relating to not only the size of the sample but also to the type of sample.

(g) Sampling Procedure: Finally, the researcher must decide the type of sample he will use i.e. he must decide about the technique to be used in selecting the items for the sample. There are several sample designs out of which the researcher must choose the one for his study.

Criteria for Selecting a Sampling Procedure: In this context, one must remember that two costs are involved in the sampling analysis viz., the cost of collecting the data and the cost of incorrect inference resulting from the data. The researcher must keep in view the two causes of incorrect inferences viz., systematic bias and sampling error. A systematic bias result from errors in the sampling procedure and it cannot be reduced or eliminated by increasing the sample size. A systematic bias is due to the following one or more factors: - inappropriate sampling frame; - defective measuring device; -non-respondents; -indeterminacy principle; and –natural bias in the reporting of data.

Sampling errors are the random variations in the sample estimates around the true population parameters. Since they occur randomly and are equally likely to be in either direction, their nature happens to be of compensatory type and the expected value of such errors happens to be equal to zero. Sampling error decreases with increase in sample size and it happens to be of smaller magnitude in case of homogeneous population. The measurement of sampling error is usually called the "precision of the sampling plan". If we increase the sample size, the precision can be improved. But, increasing the size of sample leads to increases the cost of collecting data and so enhances the systematic bias. Therefore, to increase precision, one must select a better sampling design which has a smaller sampling error for a given sample size at a given cost. In practice, however, people prefer a less precise design because it is easier to adopt the same and also because of the fact that systematic bias can be controlled in a better way in such a design.

Characteristics of a Good Sample Design:

(**a**) it should be representative one;

(**b**) it must be free from sampling error;

(**c)** it must be viable in the context of funds available for research study;

(**d**) it must be of the type that systematic bias can be controlled in a better way;

(**e**) it should be such that the results of the sample study can be applied, in general, for the universe with a reasonable level of confidence.

Types of sampling/Different methods of selection of sample: There are different techniques for the selection of sample so that our sample should be a thorough representative of the population. These techniques are:

1. Random sampling or Probability sampling;

2. Purposive or deliberate sampling;

3. Stratified random sampling**;**

4. Quota sampling;

5. Multistage sampling;

6. Convenience sampling;

7. Self selected sampling;

8. Cluster sampling;

9. Systematic sampling and

10. Sequential sampling

Now we shall discuss each of these sampling methods one by one.

1. Random sampling or Probability sampling: According to Pertan-"Random sampling is a form applied when the method of selection assured each individual or element in the universe an equal chance of being chosen." A random sample is more suitable in more homogeneous and comparatively large groups. When the universe is composed of differing groups of extremely varied sizes, then this method cannot be successfully used.

Methods of Drawing a Random Sample: Following four methods are generally used for drawing out a sample on random basis.

a. **Lottery Method:** Under this system, numbers or names of various units of the universe are written on chits, capsules or balls. They are put in a container. Then required numbers of chits are drawn from the container. The practical utility of such a method is very much limited.

b. Table or Random Number: Table or random number sampling have been constructed by Tippett's (1927), Fisher& Yates (1963), and Smith and Kendell (1939). Generally, Tippett's random number table is used for this purpose. Tippett gave 10,400 four figure number. He selected 41,600 digits from the census reports and combined them into fours to give his random numbers which may be used to obtain a random sample. **For Example:** let us we have first 30 sets of Tippett numbers

2953	**6641**✓	**3992**✓	**9792**	**7979**✓	**5911**✓
3170✓	**5624**✓	**4167**✓	**9525**	**7545**✓	**1396**
7203✓	**5356**✓	**1300**	**2693**	**2370**	**7483**✓
3408	**2729**	**3563**	**6107**	**6913**	**7691**
0506	**5246**	**1112**	**9025**	**0008**	**8126**

Let us suppose that we are to take a sample of ten units from a population of 5000 units which bears a numbers from 3001 -8000. So, we are to select 10 such figures from the above table which are not less than 3001 and greater than 8000.

c. Selecting from Sequential List: Under this method, all the units of the universe are arranged according to some particular order which may be alphabetical, geographical or simply serial. Then, every 5^{th}, 10^{th}, 100^{th} or nth is selected as random number from the list. For example, if every tenth unit is to be selected, the selection may begin from 7^{th} and then 17^{th}, 27^{th}, 37^{th} etc. may be selected.

d. Grid System: It is used for selecting a sample of area. According to this method, a map of entire area is prepared. Then a screen with squares is placed upon the map. Some of the squares are selected random. Then the screen is placed upon the map and areas falling within the selected squares are taken as sample.

Advantage of Random Sampling: --(a) It is free from bias; (b) Generally more representative; (c) It is very simple and (d) Assessment of sampling error can be made.

Disadvantage of Random Sampling : (a) It is difficult to have a completely catalogued universe and thus selection according to strictly random basis is frequently not possible; (b) Cases selected may be too widely dispersed or even impossible to contact and thus adherence to whole sample may not be possible; (c) If the universe is of heterogeneous in nature then, this method is unsuitable.

2. Purposive or Deliberate Sampling: When the researcher deliberately or purposively selects certain units for study from the universe, it is known as purposive selection. In this type of sample selection, the choice of the selection is supreme and nothing is left to chance.

Merits: -(a)t can be widely used in business decision making; (b) Useful in stratified random sampling; (c) Very simple method of sampling.

Demerits: (a) There is possibility of inquiry being influenced by personal prejudice (judgment) and bias; (b) It is impossible to have an idea of degree of accuracy.

3. Stratified Sampling: It is a combination of both random sampling and purposive selection. Under this method, the universe is first divided into a number of groups or strata. Then from each group or stratum certain numbers of items are taken on random basis. Thus in the selection of strata we use purposive selection method, but in selecting actual units from each stratum, random method is used.

Process of Stratification: Following points may be kept in mind while constructing strata:

(i) First of all we should note the different variables involved in the study of the problem. The common variables used for stratification are generally region; income, sex etc. then divide the population into these groups and get the sample of required units from each group. In selecting the variables, care should be taken that they are related to study. (ii) The size of each stratum in the universe should be large enough to provide selection of items on random basis. (iii) There should be perfect homogeneity in the different units of strata. (iv) It is desirable that the number of items to be selected from each stratum should be in the same ratio as the total number of units in the stratum bear to the unit in the whole universe. (v) The strata should be clear cut and free from overlapping of units.

Kinds of Stratified Sampling: Stratified sampling itself is of the following three types:

a.) Proportional Stratified Sample: In this method, the number of units to be drawn from each stratum is in the same proportion as they stand in the universe. i.e. if P_i represents the proportion of population included in stratum ‘ i’ and ‘n’ represent the total sample size. Then the number of elements selected from each stratum ‘i’ will be equal to n (P_i).

Example: let us suppose that we want a sample of size n=30 to be drawn from a population of size N=8000 which is divided into three strata of sizes N_1=4000, N_2=2400, N_3=1600. Adopting proportional allocation, we shall get the sample sizes as under for three strata:

For strata with N_1, we have P_1= 4000/8000

Therefore, $n_1= n.P_1= 30.(4000/8000)=15$

Similarly, for strata with N_2=2400, we have

$n_2= n.P_2 = 30. (2400/8000)= 9$ and

For strata with N3=1600, we have

$n_3= n. P_3= 30(1600/8000) =6$

Thus, using proportional allocation, the sample sizes for different strata are 15, 9, and 6 respectively which is in proportion to the sizes of the strata viz., 4000: 2400: 1600.

Proportional allocation is considered most efficient and an optimal design when the cost of selecting an item is equal for each stratum. There is no difference in within stratum variances, and the purpose of sampling happens to be to estimate the population value of some characteristics.

b.) Disproportionate Stratified Sample: But in case the purpose happens to be to compare the differences among the strata, then equal sample selection from each stratum would be more efficient even if the strata differ in sizes. In case where the strata differ not only in size but also in variability and it is considered reasonable to take larger samples from more variable strata and smaller sample from a less variable strata, then we can account for both (differences in stratum size and differences in stratum variability) by using disproportionate sampling design.

Disproportionate sampling design requiring

$n_1/N_1\sigma_1 = n_2/N_2\sigma_2$ =---------------= $nk/N_k\sigma_k$

Where, k is the number of strata

σ_1, σ_2……….. are the standard deviations of the strata

$n_1, n_2…n_k$ denote the sample size of k strata

N_1, N_2----N_K denote the sizes of k-strata.

This is called optimum allocation in the context of disproportionate sampling. The allocation in such a situation results in the following formula for determining the sample sizes for different strata.

n_iN_i **σi**

ni = ---------------------------

N_1 σ_1 + N_2 σ_2 +-----+ N_k σ_k

Example: A population is divided into three strata so that N_1 = 5000, N_2= 2000, N_3 = 3000. The respective standard deviation is: σ_2= 15, σ_2 =18 and σ_3 =5. How should a sample of size n=84 be allocated to the three strata, if we want optimum allocation using disproportionate sampling design.

Solution: Using the disproportionate sampling design for optimum allocation, the sample sizes of different strata will be determined as under:

Sample size for strata with N_1 = 5000

84(5000) (15)

n_1 = -- = 63, 00,000/ 1, 26,000 = 50

(5000)(15)+ (2000)(18)+ (3000)(5)

Sample size for strata with N_2 = 2000

84(2000) (18)

n_2 = -- = 30, 24,000/1, 26, 00 = 24

(5000)(15) + (2000) (18) + (3000) (5)

Sample size for strata with N_3 = 3000

84(3000) (5)

n_3 = -- = 12, 60,000/1, 26, 00 = 10

(5000)(15) + (2000) (18) + (3000)(5)

In addition to differences in stratum sizes and differences in stratum variability, we may have differences in stratum sampling cost, and then we can have cost optimum disproportionate stratified sampling design by requiring

$n_1/N_1.\sigma_1.\sqrt{C_1}$= $n_2/N_2.\sigma_2.\sqrt{C_2}$=----------= $nk/N_k.\sigma_k.\sqrt{C_k}$ where,

C_1 = Cost of sampling in strata 1

C_2 = Cost of sampling in strata2

C_k = Cost of sampling in strata 3

The allocation in such a situation results in the following formula for determining the sample sizes of different strata:

n_iN_i σ_i/ $\sqrt{C_i}$

ni = --

N_1 σ_1/ $\sqrt{C_1}$ + N_2 σ_2 /$\sqrt{C_2}$ +-------- -----+ N_k σ_k/ $\sqrt{C_k}$

For i = 1, 2, 3…..k

Merits of Stratified Sampling:- (a) In case of highly skewed population, this method is most suitable; (b)It gives better representation to characteristics of population in the sample; (c)It gives high degree of accuracy; (d) Less time is required because stratified sample are most concentrated geographically.

Demerits of Stratified Sampling: - (a) Subjected judgments often affect the accuracy of results; (b) The results may be misleading in case the basis of stratification is not properly determined; (c) Random selection of items for each stratum is essential.

4. Quota Sampling: This is a special form of stratified sampling. Under this method, the universe is first divided into different strata. Then the number to be selected from each stratum is decided. This number is known as quota. The field investigators are generally asked to select the quota from the stratum according to their will. Example, Let us suppose a sample of 500 families is to be selected, then the houses to be approached will be decided first and the field investigators will be asked to select one family from each house at their will.

Merits: -(a) Helpful in making research institutions and public opinion studies; (b) Satisfactory results are obtained.

Demerits: (a) There are chances of personal bias and prejudice entering the enquiry; (b) Accurate results are not obtained.

5. Multi-stage Sampling: This method is generally used in selecting a sample from a very large area, like an entire country, state etc. Under this method, the selection of the sample is made in different stages. Under multi-stage sampling, the first stage may be to select large primary sampling units such as states, then district, then towns and finally certain families within town. If the technique of random sampling is applied at all stages, the sampling procedure is described as multi-stage random sampling.

6. Convenience Sampling: It is generally known as unsystematic, careless, accidental or opportunistic sampling. According to this method, a sample is selected according to the convenience of the sampler. This convenience may be in respect of source list, accessibility of the units etc. although this method is most unscientific, yet quite a large number of samples are selected according to this method. This method is used in any one or more of the following cases:

-When the universe is not clearly defined; -Sampling unit is not clear; -A complete source list is not available.

7. Self- Selected Sampling: Sometimes a sample is not actually selected but people themselves opt to be included or not to be included in the sample. Suppose, for example, an enquiry has to be made about the people's liking for particular radio program me, and an announcement to this effect is made on the radio. In such a case, the sample is not fixed. Those who care to reply from the part of the sample. Such a sample is known as self –selected sample.

8. Cluster Sampling and Area Sampling: Clusters refers to the particular area and thus cluster sample implies area sample. Cluster sample is mainly concerned with the particular geographical area or a particular aspect of population. The region of a country, blocks, and countries may constitute the cluster and within each group all units present may be included. In this method, the universe is first divided into some recognizable sub-groups which are called clusters. After this a simple random sample of these clusters is drawn and then all the units belonging to the selected clusters constitute the sample. Cluster or area sampling is practiced in sample survey.

9. Systematic Sampling: In some instances, the most practical way of sampling is to select every i^{th} item on a list. Sampling of this type is known as systematic sampling. In this method, first item is selected randomly from the list and then every i^{th} unit is selected automatically at fixed intervals. Example, if 4 per cent sample is to be drawn, then first item would be selected randomly from the first 25 and thereafter every 25^{th} item would automatically be included in the sample.

10. Sequential Sampling: Under this method, a small number of items are tested and the whole lot from which this small number is taken is either selected or rejected on the basis of the results obtained from the list.

Merits: (a) This is widely used in quality control; (b) In the selection of manufactured products or raw materials, this method is used.

Demerits:-This method gives confusing results.

Sampling with Probability Proportional to Size: If the cluster sampling units do not have the same number or approximately the same number of elements, it is considered appropriate to use a random selection process where the probability of each cluster being included in the sample is proportional to the size of the cluster. The following procedure is to be used.

Procedure: - (a) list the number of elements in each cluster irrespective of the method of ordering the cluster; (b) Take a sample systematically of the appropriate number of elements from the cumulative totals; (c) The actual number selected in this way do not refer to individual elements but indicate which clusters and how many from the cluster are to be selected by simple random sampling or by systematic sampling; (d) The results of this type of sampling are equivalent to those of a simple random sampling and the method is less cumbersome and is also relatively less expensive. We can illustrate this with the help of **an example.**

Following are the number of departmental stores in 15 cities: 35,17,10,32,70,28,26,19,26,66,37,44,33,29,and 28. If we want to select a sample of ten stores, using cities as clusters and selecting within clusters proportional to size, how many stores from each city should be chosen? (Use a starting point of 10).

City Number	No. of Departmental Stores	Cumulative Total	Sample
1	35	35	10
2	17	52	
3	10	62	60
4	32	94	
5	70	164	110 160
6	28	192	
7	26	218	210
8	19	237	
9	26	263	260
10	66	329	310
11	37	366	360
12	44	410	410
13	33	443	
14	29	472	460
15	28	500	

Since in the given problem, we have 500 departmental stores from which we have to select a sample of 10 stores.

The appropriate sampling interval= 500/10 = 50

As we have to use the starting point of 10, so we add successively increments of 50 till 10 numbers have been selected. The numbers, thus obtained are: 10, 60, 110, 160, 210, 260, 310, 360, 410, and 460 which have been shown in the last column of the above table against the concerning cumulative totals.

From this we can say that two stores should be selected randomly from the city number five and one each from city number 1, 3, 7, 9, 10, 11, 12, and 14.

This sample of 10 stores is the sample with probability proportional to size.

Note: if the starting point is not mentioned, then same can randomly be selected.

Limitation of sampling: Sample studies can give better results only if the samples are drawn systematically, their size is adequate and an appropriate sample designs is used. Besides, these sample survey suffer from certain limitations and if they are not properly conducted, they may give erroneous inferences.

If, for example, some selected units of sample did not respond and are left out or if the person conducted the survey are not qualified then, the sample results may be highly misleading. Sometimes, sample survey may need more time and labor also if the sample size is large and the sampling technique is complicated.

Sample size and its determination: In sampling analysis, the most ticklish question is: what should be the size of the sample or how large or small should be "n"? If the sample size (n) is too small, it may not serve to achieve the objectives and if it is too large, we may incur huge cost and waste resources. Therefore, the size of the sample should be determined keeping in view the following points:

(a)Nature of universe: Universe may be either homogeneous or heterogeneous. If the items of the universe are homogeneous, a small sample can serve the purpose. But, if the items are heterogeneous, a large sample would be required; **(b)** Number of classes proposed; **(c)** Nature of study; **(d)** Type of sampling; **(e)** Standard of accuracy and acceptable confidence level; **(f)** Availability of finance and **(g)** other considerations.

There are two alternative approaches for determining the size of the sample.

(i) Determination of sample size through approach based on precision rate and confidence level and **(ii)** Bayesian Statistical Approach.

The first approach is capable of giving mathematical solution and as such is a frequently used technique of determining the size of the sample (n). The second approach is theoretical optimal, but it is seldom used because of the difficulty involved in measuring the value of information.

Determination of sample size through the approach based on precision rate and confidence level: In the sampling study process there are chances of sampling error which can be controlled by selecting a sample of adequate size. Therefore, the researcher must specify the precision that that he wants in respect of his estimates concerning the population parameters. For instance, a researcher must like to estimate the mean of the universe within ± 3 of the true mean with 95% confidence. So, it means the desired precision is ±3 i.e. if the sample mean is 100, the true value of the mean will be no less than Rs. 97 and no more than Rs. 103. This means that the acceptable error (e) is equal to 3. Keeping this in view, we can now explain the determination of sample size so that specified precision is ensured.

Sample size (When estimating a mean): The confidence interval for the universe mean, **μ**, is given by

$\bar{X} \pm Z. \sigma_p / \sqrt{n}$

Where, $\bar{X}$ is sample mean; Z is the value of standard variate at a given confidence level (to be read from the table giving area under the normal curve and it is 1.96 for 95% confidence level; n is the size of the sample and σ_p is the standard deviation of population.

Suppose we have σ_p= 4.8 and if the difference between population mean (μ) and sample mean ($\bar{X}$) or the acceptable error is to be kept within ±3 of the sample mean with 95% confidence, then we can express the acceptable error (e) as equal to

$e = Z. \sigma_p/ \sqrt{n}$ or $3 = 1.96. (4.8)/ \sqrt{n}$

Hence, $n = (1.96)^2 (4.8)^2/ (3)^2 = 9.834 = 10$

Generally, if we want to estimate μ in a population with standard deviation σ_p with an error no greater than "e" by calculating a confidence interval with confidence corresponding to Z, the necessary sample size becomes:

$n= [(Z.\sigma_p)/e]^2$

The above formula is applicable when the population happens to be infinite. But, in case of finite population, the above stated formula for determining the sample size becomes:

$n= (N.Z^2.\sigma_p^2)/[(N-1)e^2 + Z^2.\sigma_p^2]$

Where, N is the size of the population; n is the size of the sample; e is the acceptable error or precision; σ_p is the standard deviation of population; and Z is the value of standard variate at the given confidence level.

Illustration: Determine the size of the sample for estimating the true weight of cereal containers for the universe with N = 5000 on the basis of the following information:

(1) The variance of weight = 4 ounces on the basis of past records.

(2) Estimate should be within 0.8 ounces of the true average weights with 99% probability.

Will there be a change in the size of the sample if we assume infinite population in the given case? If so, explain by how much.

Solution: Given that N = 5000;

σ_p = 2 ounces (since the variance of weight = 4 ounces);

e = 0.8 (since the estimate should be within 0.8 ounces of the true average weight);

Z = 2.57 (as per the table of area under the normal curve for the given confidence level of 99 %)

Hence, the confidence interval for **μ is given by:**

$\bar{X} \pm Z. \boldsymbol{\sigma_p / \sqrt{n}. \sqrt{(N-n)/ (N-1)}}$

And accordingly the sample size can be worked out as under:

$n= (N.Z^2.\sigma_p^2) / [(N-1)e^2 + Z^2.\sigma_p^2]$

By substituting the values we get:

$n = (2.57)^2.(5000).(2)^2 / [(5000-1)(0.8)^2 + (2.57)^2(2)^2]$

$n = 132098/ [3199.36 + 26.4196] =132098 / 3225.7796 = 40.95 = 41$

Hence, the sample size, n, = 41 for the given precision and confidence level in the above question with finite population. But, if we take population to be infinite, the sample size will be worked out as under:

$n = [(Z.\sigma_p)/e]^2$

By substituting the values we get: $n = (2.57)^2 (2)^2 / (0.8)^2 = 26.4196 / 0.64 = 41.28 = 41$.Thus, in the given case, the sample size remains the same even if we assume infinite population.

Sample size (when estimating a percentage or proportion): Here, we shall have to specify the precision and the confidence level and then we will work out the sample size as under:

Since the confidence interval for the universe proportion, is given by

$p \pm Z.\sqrt{pq/n}$

Where p is the sample proportion; q=1-p; Z is the value of standard variate at a given confidence level and to work out from the table showing area under the normal curve; and n is the size of the sample.

With the given precision rate, the acceptable error 'e' can be expressed as under:

$e = Z.\sqrt{pq/n}$ or $e^2 = Z^2pq/n$

Hence, $n = (Z^2.p.q)/e^2$

The above formula gives the size of the sample in case of infinite population when we are to estimate the proportion in the universe. But, in case of finite population, the formula becomes:

$n = (Z^2.p.q.N)/[e^2(N-1) + Z^2.p.q]$

Illustration: What should be the size of the sample if a simple random sample from a population of 4000 items is to be drawn to estimate the per cent defective within 2 per cent of the true value with 95.5 per cent probability? What would be the size of the sample if the population is assumed to be infinite in the given case?

Solution: We have, N = 4000;

e = 0.02 (since the estimate should be within 2% of true value);

Z = 2.005(as per the table of area under the normal curve for the given confidence level of 95.5 %)

As we have not been given the p value being the proportion of defectives in the universe, let us assume it to be p = 0.2 (This may be on the basis of our experience or on the basis of past data or may be the result of a pilot study).

Since $n = (Z^2.p.q.N)/[e^2(N-1) + Z^2.p.q]$

By substituting the values, we get:

$n = (2.005)^2 (0.2)(1-.02) (4000) / [(0.02)^2 (4000-1) + (2.005)^2 (0.2) (1-.02)]$

$n = 315.1699 / [1.5996 + 0.788] = 315.1699 / 1.6784 = 187.78 = 188$

This is the sample size in case of finite population. But, if the population happens to be infinite, then our sample size will be as under:

$n = (Z^2.p.q)/e^2$

By substituting the values, we have:

$n = (2.005)^2(0.02)(1-0.02) / (0.02)^2 = 0.0788 / 0.0004 = 196.98 = 197$

Thus, the sample size in case of infinite population is 197.

Case Study: The method of scientific social research may broadly be divided into two parts: -The statistical methods and the case study methods.

Statistical methods are based on large scale collection of facts, while case study is based on intensive study of comparatively fewer persons, sometimes confined to a very small number of cases only. The case study is thus more intensive in nature. The field of study is comparatively limited but has more of depth in it. It aims at studying everything about something rather than something about everything as in the case of statistical methods.

According to P.V.Young describes case study is a method of exploring and analyzing the life of a social unit, be that a person, a family, an institution, cultural group or even entire community.

Census versus sample enumeration

Sample data can be collected either on the basis of census type of enquiry or on the basis of sample method.

Census: It means complete enumeration. Human /population census is always conducted after ten years while, livestock census is always conducted after five years.

Census method/ complete enumeration: In the census type of enquiry, there is a complete enumeration of all the items of the universe and the question of taking a sample does not arise. It is used when the complete information is needed about the entire universe. It is also used when the size of the universe is not big and the need for accurate result is great. It gives exact and accurate results. It is suitable where area of inquiry is not vast; it is suitable where there is enough time available for data collection; it is also suitable where there is higher degree of accuracy is required; it is also suitable where there is enough finance available to meet the expenditure on the collection of statistics.

Limitations of this method: -very expensive if the size of universe is large; -it requires more time for completion; -it needs substantial man power and administrative control.

Sample survey/ sample census: In this, we study some selected items from the universe for drawing general inferences. It is suitable where the census method cannot be used especially where area of inquiry is wide; it is suitable where financial constraint is there on the collection of statistics; it is suitable where there is difficult to get the complete data; and it is also suitable where the goods or the items of inquiry is very changeable.

Merits/ advantage of sampling method: This method has the advantages of speed, economy, adaptability, time saving and it has a scientific approach. It takes less time; it is less expensive; and it is more dependable.

Demerits of Sampling Method: (a) Change of bias- A bias in the sample may be caused either by faulty method of sampling or the nature of the phenomenon itself**; (b)** Difficulties of a representative sample; **(c)** Need for specialized knowledge**; (d)** Difficulties in sticking to sample; and **(e) Impossibilities of Sampling-** Sometimes the universe is too small or too heterogeneous so that it is impossible to draw a representative sample. In such cases, census study is the only alternative.

Different steps in large scale sample survey:

i) Planning stage;

ii) Execution stage;

iii) Analysis and reporting stage.

(i) Planning stage consists of the following steps:

a. Defining the objectives; **b.** Defining the population; **c.** Determination of data should be collected; **d.** Deciding on the method of data collection i.e. whether interview method (house to house enquiry for the collection of data) or mail questionnaire method (mailing of the questionnaire to individual of population for filling in and returning them); **e.** Choice of sampling unit; **f.** designing the survey; **g.** drawing the sample; **h.** Training of personnel

(ii) The execution stage involves the identification of the sampled individual in the field and the filling up the questionnaire.

(iii) The analysis and reporting stage again consists of the following step:

a. Scrutiny of data; **b.** Tabulation of data; **c.** Statistical analysis; **d.** Reporting; **e.** Storing of information for future survey.

Data and the different lines of data collection

Data summarizes the fact about the phenomenon under investigation. These facts may be of various types and derive from various sources. They may be fundamentally qualitative, quantitative or both**.**

Types of Data:

Primary and secondary data: Primary data are those which are collected a fresh and for the first time and thus happens to be original in character. While, the facts and figures that have already been collected by someone else and which have already been passed through the statistical process are called the **secondary data.**

Qualitative and Quantitative data: Qualitative data refers to situations, attitudes, positions, qualitative characteristics, marital status, and condition of country (industrialized, poor, developing, etc), sex, and education. No numerical measure exist for such qualitative facts whereas, quantitative data are numerically measured.

Time series and cross-sectional data: Quantitative data are of two types i.e. Time-series and cross-sectional. Time series data refers to a set of observation on a particular variable at different points of time, while cross-sectional data refers to a set of observation on different variables at a given point of time. **For example**- production of wheat in Kangra during 1990-91 to 2000-01 is time series while, the production of wheat in different district of Himachal Pradesh during one agricultural year is cross-sectional data.

Experimental and non-experimental data: Experimental data are obtained from controlled experiments conducted by the researcher whereas; non-experimental data are obtained when the problem under investigation is not subject to any control. Generally the data obtained in the natural or biological sciences are the experimental data or controlled data, whereas in social sciences like agricultural economics where the underlying conditions are not subject to control are the non-experimental data.

Sources of Data:

Published sources:

International publications (IMF,ILO,UNO.World Bank); Governmental publications (Central, State. Local); Semi-governmental publications (Boards and Corporations); Reports of Commissions and Committees; Research Publications; Research institutions; News papers, Periodicals, Magazines; and Individuals.

Unpublished sources:

Scholars; Research workers; Trade associations; Chamber of commerce; and Labor bureau

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ADVANCEMENTS IN INDIAN APICULTURE: TECHNOLOGIES AND VALUE ADDITION FOR SUSTAINABLE DEVELOPMENT

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1. Introduction:

Beekeeping, or apiculture, has undergone remarkable transformation over the years as it progressed from traditional honey hunting practices to modern scientific management. In earlier times, communities in India relied on indigenous methods that used earthen pots, hollowed tree logs, and bamboo baskets to attract and retain honey bee colonies. These traditional structures provided limited scope for colony inspection or manipulation, often resulting in the destruction of combs and disturbance of bees during honey collection. The traditional systems were widespread across Asia but were constrained by low productivity and inefficient management.

A major technological breakthrough came with the introduction of the Langstroth hive, which incorporated the principle of "bee space" and allowed movable frames that could be inspected without damaging the colony. This innovation revolutionized honey production by enabling systematic colony management, easier pest and disease control, and improved honey extraction techniques. In the Indian context, modernization of apiculture accelerated significantly with the pioneering work of Dr. A. S. Atwal, who introduced the European honey bee, *Apis mellifera*, into Punjab during the 1960s (Atwal, 1970). Compared to the native *Apis cerana*, *A. mellifera* exhibited superior foraging abilities, higher honey yields, and better adaptability for large-scale beekeeping.

The efforts of Atwal and subsequent researchers laid a strong foundation for scientific beekeeping and the growth of commercial honey production in India. As noted by Singh and Saini (2008), the introduction of *A. mellifera* enabled the establishment of migratory beekeeping, which further boosted honey productivity and crop pollination. Today, improved management practices, technological tools, and advanced understanding of bee behavior continue to strengthen apiculture as an income-generating and pollination-supporting enterprise (Sharma *et* *al.,* 2015). The shift from traditional to scientific beekeeping has thus transformed Indian apiculture into a modern, sustainable agricultural industry.

2. Modern Beekeeping Equipment

Modern beekeeping has advanced significantly with the development of specialized hives and tools that support efficient colony management, honey production, and pest control. The choice of hive design plays a pivotal role in determining the productivity and sustainability of beekeeping operations. Globally, the ten-frame Langstroth hive remains the most widely adopted system, owing to its movable-frame design and optimal internal spacing, which enables bees to build brood nests in the lower boxes and store honey in the upper supers. In India, this design has proven effective under diverse agro-climatic conditions, and it continues to be the preferred choice for both stationary and migratory beekeeping. The eight-frame Langstroth hive, being smaller and lighter, is particularly suitable for small-scale farmers and hobbyists. Its reduced weight makes it easier to handle during inspections and transport, especially in migratory beekeeping systems (Singh & Saini, 2008).

Natural and sustainable beekeepers often opt for alternative hive models such as the Top-Bar Hive (TBH) and the Warré Hive, which allow bees to construct their own combs without pre-formed foundation sheets. These designs promote natural brood patterns, reduce stress on the colony, and are considered beneficial for bee health in low-input systems (Moldenke, 2015). The Warré hive, in particular, uses a vertical top-bar system intended to mimic the natural nesting cavities of wild bees, encouraging minimal intervention and promoting thermal stability within the colony.

One of the most notable innovations in recent years is the Flow Hive, which integrates specially engineered plastic frames that split internally when a key is turned, allowing honey to flow directly from the comb into a collection container without opening the hive. This reduces disturbances to the colony and simplifies the extraction process, making it particularly appealing to beginners and non-commercial beekeepers. Similarly, BeeMax® Polystyrene Hives offer improved insulation properties compared to traditional wooden hives. Their ability to maintain more stable internal temperatures enhances brood development and reduces energy expenditure by bees during extreme weather (Berry & Delaplane, 2001). Another specialized component is the American Copper Hive Top, which provides durability and protects colonies from heavy rainfall, strong winds, and UV exposure.

Beyond hive design, modern beekeeping relies heavily on accessories and tools that support colony health and management. Sundance pollen traps allow controlled collection of pollen without harming the bees, offering income opportunities for beekeepers while ensuring that sufficient pollen remains for colony nutrition. Cell bar frames are essential for queen rearing and royal jelly extraction, enabling the production of high-quality queens for colony multiplication and commercial queen trading. Varroa shims, another critical tool, are used to monitor and assess levels of *Varroa destructor* mite infestation. Early detection through such monitoring systems allows timely interventions and reduces colony losses.

Collectively, advancements in hive technology and specialized equipment have transformed beekeeping into a more productive, sustainable, and scientifically managed enterprise. These innovations empower beekeepers to optimize honey yield, maintain colony health, and adapt to changing environmental conditions.

3. Foraging Behaviour

Foraging is a vital behavioural process that forms the ecological bridge between a honey bee colony and its surrounding environment, enabling the collection of nectar, pollen, propolis, and water that are essential for colony nutrition, brood rearing, and honey production. Foraging intensity is strongly influenced by environmental conditions, particularly temperature, humidity, wind speed, and the seasonal availability of floral resources. Bees typically initiate foraging when ambient temperatures rise above a minimum threshold and floral scents become detectable through olfactory cues. Under favourable conditions, foragers optimize their energy expenditure using learned routes known as "traplines" and communicate profitable floral patches through waggle dances, a mechanism that enhances colony-wide efficiency. Research indicates that optimal foraging activity occurs around 20°C, while foraging sharply declines as temperatures rise beyond biological comfort limits due to increased metabolic stress (Alqarni, 2006). Comparative studies reveal that *Apis mellifera jemenitica*, a subspecies adapted to arid climates, exhibits significantly higher foraging activity and heat tolerance than Italian and Carniolan bees, demonstrating the adaptive significance of race-specific traits in extreme environments (Alqarni, 2006).

Beyond environmental factors, genetic regulation plays a central role in shaping foraging behaviour. Gene expression studies have shown that the *Amfor* gene, which encodes a cGMP-dependent protein kinase, increases markedly as nurse bees transition into foragers, indicating its influence on behavioural maturation (Ben-Shahar *et al.,* 2004). Similarly, the *Malvolio* gene, associated with manganese transport, has been linked to sucrose responsiveness and sensory modulation, further affecting foraging efficiency (Ben-Shahar *et al.,* 2004). These findings underscore the complex interplay between genetic, physiological, and environmental drivers of honey bee foraging dynamics. In managed apiculture, attempts to enhance foraging behaviour have included the application of synthetic brood pheromones, which mimic natural signals produced by larvae and stimulate worker bees to increase pollen collection, thereby improving brood nutrition and colony growth (Pankiw, 2007). Octopamine treatments have also been found to increase foraging intensity by modulating neurosensory pathways associated with motivation and learning (Schulz & Robinson, 2001).

Floral scent recognition is another critical determinant of foraging success. Bees exhibit strong responses to volatile organic compounds emitted by flowers, enabling efficient discrimination among floral sources and enhancing plant–pollinator interactions. Behavioural studies show that attractive floral scents significantly increase visitation rates and pollination efficiency, reinforcing the role of chemical ecology in foraging decisions (Young & Stanton, 2007). In addition to natural pheromones and floral volatiles, synthetic pheromones such as the Nasonov pheromone have been widely used in apiculture. The Nasonov pheromone, naturally secreted by worker bees to guide nestmates, is often applied synthetically to attract swarms to bait hives, facilitate hive establishment, and improve colony management during artificial swarming procedures (Williams *et al.,* 2008). Overall, the integration of genetic insights, pheromone technologies, and environmental management can significantly enhance foraging efficiency, thereby strengthening colony productivity and supporting sustainable apiculture.

4. Pests and Diseases

Honey bees are susceptible to a wide range of pests and diseases that can drastically impact colony strength, honey production, and pollination efficiency if not managed properly. Among the major pests, the greater wax moth **(***Galleria mellonella***)** and lesser wax moth (*Achroia grisella*) are highly destructive, especially in weak colonies. These pests tunnel through brood combs, feed on wax and pollen, and leave behind silken webs that disrupt colony activities. As Ellis (2005) notes, wax moth infestations often indicate poor colony management and inadequate hive hygiene. In addition to wax moths, wasps and hornets—including *Vespa orientalis*, *Vespa tropica*, *Vespa velutina*, and *Vespa mandarina*—pose significant threats by attacking foragers and robbing hives of honey.

Another growing pest of concern is the small hive beetle (*Aethina tumida*)**.** Although more prevalent in Africa and the Americas, it is increasingly reported in Asia. The beetle's larvae burrow through combs, defecate in honey, and cause fermentation. Management strategies often involve the use of oil-filled traps placed between hive frames, which effectively attract and immobilize adult beetles (Neumann & Ellis, 2008).

Honey bee diseases also contribute significantly to colony stress and mortality. American foulbrood (AFB), caused by *Paenibacillus larvae*, is one of the most devastating brood diseases. It leads to larval death, foul odor, and highly infective spores that remain viable for decades. In contrast, European foulbrood (EFB), caused by *Melissococcus plutonius*, affects unsealed brood and often occurs during periods of nutritional stress. Both AFB and EFB can be suppressed with antibiotics such as oxytetracycline, though careful administration is crucial to avoid antibiotic resistance. Chalkbrood, caused by the fungus *Ascosphaera apis*, results in mummified larvae and tends to spread in cool, damp conditions. Sacbrood virus (SBV) causes larvae to fail to pupate, producing sac-like remains in brood cells.

Adult bees are particularly affected by Nosema disease, a microsporidian infection caused by *Nosema apis* or *Nosema ceranae*. This disease reduces foraging efficiency, shortens lifespan, and weakens the colony. Fumagillin remains the commonly recommended treatment (Higes *et al.,* 2008). However, among all pests, the Varroa destructor mite poses the greatest global threat to honey bees. It feeds on bee fat bodies, transmits deadly viruses, and causes colony collapse if untreated. Effective management strategies include organic acids such as formic acid and thymol, and synthetic acaricides like tau-fluvalinate and amitraz (Rosenkranz *et al.,* 2010). Regular hive inspections, maintaining strong colonies, and practicing strict hygienic measures remain essential components of integrated pest and disease management.

5. Migratory Beekeeping

Migratory beekeeping plays a crucial role in enhancing honey production and improving pollination efficiency across diverse cropping systems. This practice involves the seasonal movement of bee colonies to regions with abundant nectar and pollen resources, thereby ensuring that honey bees have continuous access to floral blooms throughout the year. The migratory beekeeping is one of the most effective ways to maximize honey yield, as it aligns bee activity with peak flowering periods. In India, this system has become increasingly important due to diverse agro-climatic zones that offer sequential flowering of crops, trees, and wild flora. During the hot summer months, beekeepers typically move colonies from the plains to the hilly regions, where floral sources such as litchi, eucalyptus, and various wildflowers are abundant. As winter approaches, colonies are shifted back to the plains to utilize crops such as mustard, sunflower, and coriander, ensuring continuous nectar availability (Ghosh, 2014).

The productivity benefits of this approach are substantial. Sharma *et al.,* (2015) reported that commercial beekeepers practicing migratory beekeeping often achieve honey yields of 50–60 kg per colony annually, compared to only 10–20 kg from stationary hives. This difference is attributed to greater access to diverse floral sources, improved brood rearing conditions, and stronger colony development. Furthermore, migratory beekeeping significantly enhances crop pollination, increasing yields of fruits, vegetables, oilseeds, and nut crops. In India, crops such as apple, cardamom, mustard, and cucurbits show marked yield improvements when supplemented with managed pollination services.

Globally, migratory beekeeping is integral to modern agricultural systems. In the United States, the practice is highly organized and commercialized. For instance, thousands of hives are transported annually to California's Central Valley for almond pollination—a practice considered the largest managed pollination event in the world. After the almond bloom, these colonies are moved to states such as Maine and Michigan for blueberry and cranberry pollination, followed by migration to the Midwest for alfalfa and clover honey production. This year-round movement greatly enhances colony productivity and supports both honey and pollination markets.

Despite its benefits, migratory beekeeping also presents challenges. Transporting colonies over long distances can induce stress, weaken bee immunity, and increase susceptibility to diseases such as Nosema and pests like *Varroa destructor*. According to vanEngelsdorp and Meixner (2010), migratory colonies tend to exhibit higher pathogen loads due to environmental changes and exposure to diverse landscapes. Additionally, logistical issues such as fuel costs, road conditions, and availability of safe apiary sites can influence profitability. Climate change has further altered flowering patterns, making the timing of migration increasingly unpredictable.

Nevertheless, with proper planning, supplementary feeding during dearth periods, regular disease monitoring, and effective queen management, migratory beekeeping remains one of the most profitable and sustainable systems in apiculture. It not only boosts honey production but also ensures reliable pollination services essential for global food security.

6. Honey Processing and Quality

Modern honey processing has evolved significantly with the introduction of advanced technologies that enhance efficiency, maintain nutritional quality, and ensure food safety. Traditional methods of honey extraction required manual uncapping and slow draining, which often exposed honey to contaminants and temperature fluctuations. Today, motorized extractors**,** chain-drive uncapping machines, and automated clarifiers streamline honey removal from combs while minimizing human contact and maintaining hygiene standards. The mechanized extraction systems reduce processing time, improve honey purity, and prevent excessive heat exposure, which can degrade enzymes and sensory attributes.

Temperature control plays a crucial role in maintaining honey quality. During extraction, honey is typically warmed to reduce viscosity, making it easier to filter and bottle. However, excessive heating can inactivate essential enzymes such as diastase and invertase, which serve as indicators of honey's freshness and authenticity. Temperature management also helps slow the growth of yeast cells that cause spoilage in high-moisture honey.

Innovative processing techniques, such as ultrasound treatment, have gained attention for their ability to delay crystallization without compromising nutritional value. The Rural Industries Research and Development Corporation reported that ultrasound disrupts glucose crystal formation and enhances honey clarity, offering a gentler alternative to traditional heating methods. This is particularly valuable for monofloral honeys like mustard and sunflower honey, which crystallize rapidly due to high glucose content.

Filtration is another key step in honey processing. Fine straining removes wax particles, pollen clusters, and other impurities while maintaining natural beneficial compounds. According to Almeida-Muradian *et al.,* (2007), appropriate filtration improves shelf life and consumer acceptability without stripping honey of its antioxidant components. Moisture content also determines honey quality; honey with more than 20% moisture risks fermentation by osmotolerant yeasts. Maintaining moisture levels below 18% through controlled storage conditions is essential for preventing spoilage (Terrab *et al.,* 2002).

Proper storage further ensures honey stability. Airtight, food-grade containers—preferably glass or stainless steel—protect honey from humidity, chemical contamination, and odors. Honey should be stored at stable temperatures (around 20–25°C) to preserve flavor, color, and enzymatic activity. Shelf life is influenced not only by storage conditions but also by honey's botanical origin, mineral content, and initial handling practices. Preventing exposure to direct sunlight and high temperatures helps reduce hydroxymethylfurfural (HMF) formation, a heat-induced compound used as an indicator of honey degradation (Fallico *et al.,* 2004).

Overall, advancements in honey processing—from mechanized extraction to ultrasound treatment—have greatly improved product quality, safety, and marketability. By maintaining optimal temperature, filtration, and storage practices, beekeepers can ensure that honey retains its natural enzymes, nutritional compounds, and sensory attributes, meeting both domestic and international quality standards.

7. Honey Bee Products

Honey bees produce a diverse range of high-value products that have significant commercial, nutritional, and therapeutic importance. These include honey, beeswax, propolis, royal jelly, pollen, and bee venom—each contributing uniquely to various industries such as pharmaceuticals, nutraceuticals, cosmetics, and food technology. Honey, the primary product, is prized for its nutritional richness, antioxidant properties, and medicinal value. The honey contains over 200 bioactive compounds including enzymes, amino acids, vitamins, and phenolics, making it a natural remedy for coughs, wounds, and digestive ailments. Beeswax, another key product, is widely used in candle making, cosmetics, ointments, and traditional medicines. Its antimicrobial properties and natural aroma make it highly suitable for premium cosmetic formulations (Hepburn, 1986).

Propolis, a resinous substance collected by bees from plant exudates, has gained global attention for its strong antibacterial, antifungal, and antiviral properties. Research shows that propolis-rich supplements are increasingly used in alternative medicine and immune-boosting formulations (Banskota *et al.,* 2001). Royal jelly, the exclusive diet of queen larvae, is a highly valued nutraceutical known for its anti-aging, hormonal, and antioxidant benefits. Studies by Ramadan and Al-Ghamdi (2012) highlight its role in improving human fertility, immunity, and skin health, making it a major ingredient in premium dietary supplements and cosmetics.

Bee pollen is another nutrient-dense product containing proteins, minerals, vitamins, and flavonoids. It is recognized as a "superfood" and is widely consumed as a dietary supplement to enhance vitality and metabolic health (Komosinska-Vassev *et al.,* 2015). Bee venom, though harvested in small quantities, has high pharmaceutical value. It contains melittin, apamin, and other bioactive peptides used in apitherapy for treating arthritis, neural disorders, and inflammation (Son *et al.,* 2007). With increasing interest in natural therapies, demand for venom-based products has risen sharply.

Globally, the market for honey bee products continues to expand, driven by rising consumer preference for natural and organic products. Asia, especially countries like China, India, and Vietnam, remains a leading producer of honey, beeswax, and royal jelly, contributing significantly to global exports. In India, the beekeeping sector is rapidly growing, supported by government initiatives and increasing awareness of the health benefits of honey and related products.

Value addition plays a critical role in enhancing the profitability of beekeeping. Entrepreneurs and self-help groups are increasingly producing honey-based value-added products such as honey candies, herbal honey blends, honey-coated nuts, energy drinks, soaps, creams, and nutraceutical supplements. These products offer higher market returns, require minimal investment, and cater to the growing health-conscious consumer base. As Singh and Singh (2019) emphasize, value addition not only boosts rural incomes but also creates employment opportunities, especially for women and small-scale producers.

With expanding markets, improved processing technologies, and rising global demand for natural wellness products, honey bee products continue to offer significant potential for income generation, rural development, and sustainable entrepreneurship.

8. Major Beekeeping Organisations

1. National Bee Board (NBB), New Delhi
2. Central Honey Bee Research and Training Institute (CHBRTI), Pune
3. ICAR–AICRP on Honey Bees and Pollinators, Hisar
4. International Bee Research Association, UK
5. USDA Bee Research Laboratory, USA
6. The British Bee Keepers Association, UK
7. Honey Bee Research and Extension Lab, University of Florida, USA
8. Australian Honey Bee Industry Council (AHBIC)
9. Mid-Atlantic Apiculture Research and Extension Consortium, USA
10. Honey Bee Research Institute, Asheville, USA

Conclusion:

The modernization of Indian apiculture hinges on the widespread adoption of innovative hive technologies, improved and region-specific bee races, scientifically managed foraging strategies, and advanced honey extraction and processing techniques. As climate variability and changing land-use patterns continue to influence floral resources, strengthening adaptive beekeeping practices becomes essential for sustaining colony health and productivity. Integrating modern tools—such as digital hive monitoring systems, migratory beekeeping logistics, and refined quality-control measures—can significantly enhance honey yield, value addition, and market competitiveness. Equally important is the role of institutional support: government schemes, cooperative models, and targeted subsidies must be expanded to make scientific beekeeping accessible to small and marginal farmers. Research collaboration between universities, Krishi Vigyan Kendras (KVKs), ICAR institutes, and private stakeholders will accelerate the development of region-specific technologies and standardized protocols for disease management, queen rearing, and product diversification. Capacity-building programs, skill-development workshops, and entrepreneurial training for farmers, rural youth, and self-help groups will further enable the shift from traditional methods to commercial, profit-oriented beekeeping. By integrating scientific advancements with strong policy support and active stakeholder participation, India can achieve sustainable honey production, strengthen pollination-based crop productivity, empower rural livelihoods, and emerge as a global leader in the apiculture sector.

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MULBERRY-BASED INNOVATIONS FOR ENHANCING SERICULTURE PRODUCTIVITY

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Introduction:

Sericulture, the science of silk production, forms an integral component of rural livelihoods and agro-based industries across Asia, particularly in India, China, Japan, and Thailand. Traditionally, the focus of sericulture has centred on the rearing of silkworms (*Bombyx mori*) using mulberry leaves as their primary diet. However, in recent decades, the scope of sericulture has expanded dramatically as researchers and policymakers recognized the multifaceted economic value of the mulberry plant (*Morus* spp.), which extends far beyond its conventional role as silkworm feed. Mulberry cultivation supports a broad spectrum of value-added industries due to its nutraceutical, medicinal, industrial, and agricultural applications. The sericulture sector, therefore, represents a comprehensive biological production system that integrates plant science, animal husbandry, rural enterprise, and sustainable agriculture.

Mulberry leaves are rich in proteins, vitamins, flavonoids, and unique bioactive compounds such as 1-deoxynojirimycin (DNJ), which contributes to antidiabetic and antihypertensive properties (Andallu & Varadacharyulu, 2003). As a result, mulberry leaf tea has gained global popularity as a functional beverage promoted for its ability to regulate blood glucose and lipid profiles. Studies demonstrate that regular consumption of mulberry leaf extracts can significantly reduce fasting blood sugar and improve metabolic health (Mudra, 2001). Similarly, mulberry fruits contain abundant anthocyanins and antioxidants, making them suitable for producing jams, juices, wines, and nutraceuticals. Their high phenolic content offers strong free-radical scavenging activity, adding value to fruit-based industries (Lin & Tang, 2007).

Beyond nutraceutical uses, mulberry has significant industrial relevance. Mulberry wood is lightweight, durable, and rich in cellulose, making it suitable for manufacturing sports goods such as hockey sticks and cricket bats. The wood pulp also serves as an excellent raw material for high-quality handmade paper, while pruned branches are widely used as fuelwood or biodegradable compost in farm systems. In horticulture, mulberry shoots function as staking material in vegetable cultivation and mushroom production due to their strength and biodegradability. Mulberry leaves also act as a valuable cattle feed, known to enhance milk yield and improve livestock nutrition due to their digestibility and protein-rich composition (Kandylis, 2009).

Mulberry's medicinal importance is well-documented in Ayurvedic and folk medicine. Different plant parts—including roots, bark, fruits, and leaves—exhibit therapeutic properties such as laxative, astringent, anti-inflammatory, and anthelmintic effects (Chan *et al.,* 2016). These properties have prompted the pharmaceutical industry to explore mulberry-derived compounds for developing herbal formulations. Furthermore, four major mulberry species—*Morus alba*, *M. indica*, *M. nigra*, and *M. acedosa*—play crucial roles in both sericulture and traditional medicine, each offering unique biochemical and agronomic traits.

Overall, the integration of mulberry into multiple industrial and health sectors illustrates the transformation of sericulture from a single-product industry into a diversified bio-resource enterprise. This expanded utilization enhances rural income, encourages small-scale entrepreneurship, and promotes sustainable agricultural development.

Nutraceutical Value of Mulberry Leaves

Mulberry (*Morus* spp.) leaves, traditionally known as the sole food for the mulberry silkworm *Bombyx mori*, have gained global recognition for their outstanding nutraceutical properties and growing relevance in human health and functional foods. Rich in bioactive compounds such as flavonoids, polyphenols, alkaloids, and vitamins, mulberry leaves are increasingly used in teas, extracts, and dietary supplements, especially in East Asian countries like China, Japan, and Korea (Butt *et al.,* 2008). One of the most significant components of mulberry leaves is 1-deoxynojirimycin (DNJ), a potent α-glucosidase inhibitor that reduces post-prandial blood glucose levels by slowing carbohydrate metabolism, making mulberry leaf tea highly beneficial for diabetic patients (Asano *et al.,* 2001). Studies have also shown that rutin, quercetin, and other flavonoids present in mulberry leaves act as strong antioxidants, protecting the body from oxidative stress, inflammation, and cellular damage (Chan *et al.,* 2016). These antioxidative properties contribute to the prevention of chronic lifestyle disorders such as cardiovascular diseases, hypertension, and metabolic syndrome.

Mulberry leaves also possess notable antihyperlipidemic potential. Regular consumption of mulberry leaf extract has been shown to reduce serum triglycerides and low-density lipoprotein (LDL) levels while improving high-density lipoprotein (HDL) profiles, contributing to improved heart health (Andallu & Varadacharyulu, 2003). Additionally, mulberry leaves contain γaminobutyric acid (GABA) which helps in regulating blood pressure, thereby supporting their traditional use in managing hypertension (Yatsunami *et al.,* 2008). The presence of dietary fiber in mulberry leaves improves digestive health by promoting gut motility and preventing constipation, while their antibacterial and anti-inflammatory compounds enhance immunity and reduce the risk of microbial infections (Park *et al.,* 2003). In many Asian cultures, mulberry leaf decoctions are used as traditional remedies for fever, cough, and throat infections, reflecting their broad therapeutic spectrum.

Recent research has expanded the application of mulberry leaves to functional foods, herbal teas, nutraceutical capsules, and pharmaceutical formulations. Mulberry leaf powders are now integrated into bakery products, nutrition bars, noodles, and beverages due to their health-promoting attributes and natural green pigment (Li *et al.,* 2020). The growing global demand for natural therapies and plant-based health supplements further strengthens the commercial potential of mulberry leaf nutraceuticals within the sericulture value chain. Beyond their use in human nutrition, mulberry leaves are also valuable in animal feed, enhancing milk yield and improving overall livestock health due to their protein-rich composition.

Overall, mulberry leaves represent a significant natural resource with vast medicinal and nutraceutical importance. Their scientifically validated role in controlling diabetes, reducing oxidative stress, improving cardiovascular health, and supporting immune function highlights their potential as a versatile health-promoting agent. As consumer interest in herbal wellness products continues to rise, the integration of mulberry leaves into nutraceutical and functional food industries poses a promising avenue for diversifying income opportunities in sericulture-dependent regions.

Antioxidant and Medicinal Properties of Mulberry Fruits

Mulberry fruits represent one of the most valuable components of the sericulture-based agroecosystem due to their rich nutritional profile, exceptional antioxidant activity, and wide-ranging medicinal properties. The ripe fruits of various *Morus* species—including *Morus alba*, *M. nigra*, and *M. indica*—are widely consumed fresh or processed into products such as juices, jams, wines, syrups, and nutraceutical formulations (Imran *et al.,* 2010). Their health-promoting potential is largely attributed to a diverse array of bioactive compounds including anthocyanins, polyphenols, flavonoids, and vitamin C, all of which contribute significantly to antioxidant activity (Chan *et al.,* 2016). Among these, anthocyanins—particularly cyanidin-3-glucoside—are present in high quantities, especially in dark-coloured species such as *M. nigra* and have been shown to effectively neutralize free radicals, reduce oxidative stress, and support cellular health (Wu *et al.,* 2004).

The antioxidant capacity of mulberry fruits has positioned them as promising candidates for preventing and managing various chronic diseases. Research highlights that the consumption of mulberry extracts helps lower lipid peroxidation, enhances enzymatic antioxidant levels, and protects against oxidative damage in vital organs (Katsube *et al.,* 2006). This has implications for the management of lifestyle disorders such as cardiovascular disease, diabetes, and metabolic syndrome. Studies have demonstrated hypoglycemic effects of mulberry fruit constituents, which help regulate glucose absorption and improve insulin sensitivity, making them beneficial for diabetic individuals (Andallu & Varadacharyulu, 2003). Furthermore, mulberry's rich flavonoid content contributes to its anti-inflammatory, anti-cancer, and hepatoprotective properties, supporting its traditional use in herbal formulations across Asia.

Mulberry fruits also possess significant antimicrobial properties. Extracts of *M. alba* fruits have shown inhibitory effects against a range of pathogenic bacteria including *Staphylococcus aureus* and *Escherichia coli*, suggesting their potential role in natural antimicrobial therapy (Doi *et al.,* 2001). Additionally, mulberry fruit antioxidants contribute to neuroprotection by reducing neuronal oxidative stress and modulating neurotransmitter activity, which may help in preventing neurodegenerative diseases such as Alzheimer's and Parkinson's (Naderi *et al.,* 2004). Beyond clinical importance, mulberry fruits are also used in culinary and traditional medicine systems, where they are valued for their cooling, laxative, and rejuvenating effects. In Ayurveda, mulberry fruit preparations are considered tridosha-balancing and are used to treat fever, inflammation, and digestive disorders.

Due to their nutritive and therapeutic qualities, mulberry fruits offer significant potential for value-added product development in rural sericulture economies. Nutraceutical industries are increasingly exploring mulberry fruit extracts for functional food formulations, health supplements, and antioxidant beverages. As global demand rises for natural antioxidant sources, mulberry fruits provide a sustainable and high-value option for enhancing farmer income and promoting health-oriented agricultural enterprises (Sánchez-Salcedo *et al.,* 2015). Thus, mulberry fruits stand as a critical component of sericulture-based livelihoods, combining ecological adaptability with strong pharmacological and nutritional benefits.

Mulberry Species Diversity and Their Uses

Mulberry (*Morus* spp.) is one of the most diverse and economically significant genera in the Moraceae family, comprising nearly 68 recognized species distributed across tropical, subtropical, and temperate regions of Asia, Europe, and the Americas. Among these, four species—*Morus alba*, *M. indica*, *M. acidosa*, and *M. nigra*—are of major importance to sericulture, agriculture, pharmacology, and food industries. Each species possesses unique morphological traits, environmental adaptations, and biochemical compositions that determine their suitability for different economic uses. *Morus alba*, the most widely cultivated species, is prized for its high leaf yield, rapid growth, and exceptional palatability to the silkworm *Bombyx mori*, making it the backbone of the global sericulture industry (Sarkar *et al.,* 2018). Its high protein content (18–28%), balanced amino acid profile, and abundant moisture make it ideal for larval growth and cocoon production.

In contrast, *Morus indica* and *M. acidosa*, commonly cultivated in South Asia, thrive under rainfed and drought-prone conditions, providing farmers with resilient fodder sources and diverse economic benefits beyond silkworm rearing. These species are also valued for their fruits, which are rich in anthocyanins, polyphenols, and flavonoids, making them suitable for food, nutraceutical, and beverage industries. *Morus nigra*, known for its dark-purple fruits and strong flavour, is particularly valued for making high-quality jams, wines, syrups, and traditional medicines owing to its exceptional antioxidant content (Ercisli & Orhan, 2007).

Mulberry species also provide a diversity of non-fruit benefits, contributing to rural livelihoods and sustainability. Mulberry wood is strong, flexible, and durable, making it useful for manufacturing sports goods such as hockey sticks, cricket bats, agricultural tools, and household items. The white, pliable stem of *Morus alba* provides high-quality cellulose used in paper and chipboard industries. The shoots are commonly used as staking materials for vegetable crops and in mushroom cultivation. Furthermore, mulberry leaves serve as nutritious fodder for livestock, improving milk yield due to their high digestibility and protein content (Sarkar *et al.,* 2018).

The medicinal importance of mulberry species is equally prominent. Various plant parts—leaves, fruits, roots, and bark—are utilised in Ayurvedic and traditional medicine systems. Leaves are used as anti-inflammatory agents, gargles for sore throat, and natural hypoglycemic remedies due to their DNJ (1-deoxynojirimycin) content. Roots exhibit astringent and anti-diarrheal properties, while bark is traditionally used as a purgative and anthelmintic (Ercisli & Orhan, 2007). Fruits of all major species are recognized for their cooling, laxative, and rejuvenating properties, making them a key ingredient in herbal formulations and dietary supplements.

The remarkable species diversity of mulberry thus supports a wide spectrum of uses—from sericulture, livestock feeding, wood-based industries, and food processing to traditional medicine and modern nutraceutical applications. Understanding and conserving this diversity is crucial for sustaining the sericulture sector, enhancing climate resilience, and expanding the industrial value chain associated with mulberry-based rural enterprises.

Economic Importance of Mulberry Byproducts in Sericulture

The economic importance of mulberry byproducts in sericulture is significant, as various components of the mulberry plant contribute to enhancing productivity, diversifying income, and improving sustainability in sericulture-based farming systems. Mulberry leaves, the most valuable byproduct, serve as the exclusive feed for *Bombyx mori* silkworms, and their quality directly influences larval growth, cocoon formation, and ultimately the reelable silk yield (Kumar, 2018). The nutritional richness of mulberry leaves, particularly their protein, moisture, and micronutrient content, plays a critical role in determining silk fiber characteristics, making them indispensable in sericulture. Pruned mulberry stems and branches also hold substantial economic value.

Farmers traditionally utilize these materials as fuelwood, composting substrates, or as raw material for vermicomposting, thereby reducing dependence on external energy sources and chemical fertilizers. When converted into farmyard manure or vermicompost, these residues enhance soil structure and nutrient status, supporting sustainable mulberry cultivation. Mulberry fruits represent another valuable byproduct, with increasing market demand for fresh berries and value-added products such as jams, juices, syrups, wines, and nutraceuticals. Their high antioxidant, vitamin, and mineral content has expanded their relevance to the food and pharmaceutical sectors.

Additionally, mulberry fruit processing offers rural households opportunities for small-scale entrepreneurship, supporting livelihood diversification. Mulberry bark fibers, traditionally used in handmade paper, crafts, and natural dyes, also contribute to the artisanal economy. Leaf waste generated during silkworm rearing, combined with silkworm litter, is rich in nitrogen, phosphorus, and beneficial microorganisms, making it an excellent organic fertilizer for crop fields and mulberry gardens. This nutrient recycling reduces fertilizer costs and enhances ecological sustainability. Even silkworm pupae, though not directly a mulberry byproduct, depend on mulberry-based production systems and can be sold as livestock feed, oil extraction material, or for pharmaceutical uses. Overall, the utilization of mulberry byproducts significantly increases profitability across sericulture farms by reducing input costs, generating alternative income streams, promoting value addition, and enhancing environmental sustainability. The integration of these byproducts into farming systems aligns well with circular economy principles, making mulberry cultivation not only essential for silk production but also a source of diverse economic opportunities for sericulturists.

Mulberry as Fodder: Livestock Nutrition Benefits

Mulberry has emerged as a highly nutritious and economically valuable fodder resource due to its rich nutrient composition and adaptability across diverse agroclimatic zones. The leaves contain high levels of crude protein, ranging from 18% to 28%, making them comparable to conventional protein-rich fodders such as alfalfa. This superior protein content, coupled with high digestibility, makes mulberry an ideal green fodder for ruminants such as cattle, buffalo, sheep, and goats. Mulberry leaves are also rich in essential amino acids, minerals such as calcium, phosphorus, and potassium, and bioactive compounds that promote animal health and productivity. Studies have shown that the inclusion of mulberry leaves in livestock diets enhances feed efficiency, improves rumen fermentation, and increases milk yield in dairy animals, making it a valuable feed supplement in areas with fodder scarcity. Additionally, the low fiber content and high palatability of mulberry encourage voluntary feed intake, supporting better weight gain and growth rates in small ruminants. Mulberry fodder is particularly beneficial for goat farming, as it improves digestibility and supports higher body weight gains compared to conventional fodder sources. Beyond its nutritional value, mulberry plays an important role in sustainable livestock management. The plant can be harvested multiple times a year, providing a continuous supply of green fodder even during dry seasons, reducing farmers' dependence on costly concentrate feeds.

Mulberry hedgerows can also serve as a component of agroforestry systems, offering soil conservation benefits while simultaneously supporting fodder production. The use of mulberry as fodder has been shown to reduce methane emissions in ruminants due to improved digestibility and better nutrient utilization, contributing to environmentally sustainable livestock practices. Mulberry-based silage and leaf meal are additional byproducts that extend the shelf life of the fodder and offer flexible feeding options, especially during periods of fodder shortage. Mulberry leaf meal is widely used in poultry and pig diets due to its high antioxidant content, which enhances immune response and overall performance. In integrated farming systems, mulberry supports circular economy principles, where leaf residues and pruned branches can be used for composting or vermicomposting to enrich soil health, further lowering production costs. Overall, mulberry stands as a multifunctional and highly nutritious fodder resource that not only improves livestock productivity but also contributes to environmental sustainability and improved farm profitability. Its adaptability, high yield potential, and nutritive value make it an important component in modern livestock feeding strategies, especially in smallholder farming systems where resource optimization is crucial.

Food and Beverage Applications of Mulberry Products

Mulberry has gained significant attention in the food and beverage sector due to its rich nutritional profile, natural pigments, bioactive compounds, and versatility in processing. Mulberry fruits—particularly those of *Morus alba*, *M. indica*, and *M. nigra*—contain high concentrations of anthocyanins, flavonoids, vitamins, and organic acids, making them suitable for various value-added products. The fruits are widely used in the production of jams, jellies, squashes, syrups, and candies because of their appealing color, flavor, and antioxidant properties. Research demonstrates that mulberry fruit extracts possess strong free-radical-scavenging capacity, which enhances the functional quality of processed foods (Ghosh & Yadav, 2018). Mulberry juices and concentrates are gaining popularity in health-drink formulations due to their ability to regulate blood glucose, improve immunity, and support cardiovascular health. Fermented beverages such as mulberry wine, vinegar, and probiotic drinks have emerged as high-value products in the functional beverage industry. Studies indicate that mulberry wine retains significant amounts of phenolic compounds even after fermentation, making it a potential nutraceutical beverage (Hu *et al.,* 2020). Mulberry vinegar, produced through acetic fermentation, is valued for its mild flavor and health benefits, including improved digestion and antioxidant activity.

In traditional Asian cuisines, mulberry fruits are incorporated into desserts, ice creams, bakery fillings, and confectioneries. Their natural deep-purple pigment also serves as a safe and stable food colorant, offering an alternative to synthetic dyes often associated with health concerns. Mulberry leaves, known for their high levels of DNJ (1-deoxynojirimycin), are used to prepare herbal teas that help regulate blood sugar levels and are widely consumed in Korea, Japan, China, and increasingly in global markets. Mulberry leaf powder is also incorporated into bakery products, noodles, and health supplements to enhance nutritional value and antioxidant activity. Additionally, mulberry leaf extracts are used in functional beverages and ready-to-drink teas marketed for anti-diabetic and anti-obesity effects. Mulberry root bark and stem extracts, though less commonly used in food, have applications in traditional health tonics and flavor-enhancing products due to their phytochemical content. With the growing consumer demand for natural and health-promoting foods, mulberry-based functional foods align well with market trends emphasizing clean labels, plant-based ingredients, and natural antioxidants. The increasing adoption of mulberry in food processing industries also creates opportunities for farmers to generate additional income by supplying fruits, leaves, and extracts for value-added product manufacturing.

Overall, the broad spectrum of mulberry applications—from desserts and beverages to nutraceuticals and functional foods—demonstrates its potential as a valuable crop for the expanding health-oriented food and beverage market.

Conclusion:

The diverse applications of mulberry and its byproducts highlight the immense potential of sericulture as a value-added, sustainable, and economically rewarding agro-industry. Beyond serving as the exclusive feed for silkworms, mulberry contributes significantly to rural livelihoods through its multifaceted uses in food, medicine, livestock nutrition, and industrial products. Mulberry fruits, rich in antioxidants and natural pigments, support a thriving sector of functional foods, beverages, and nutraceuticals, while mulberry leaves offer critical health benefits through bioactive compounds. Pruned branches, stems, and silkworm litter enhance soil fertility and reduce farm input costs, supporting circular resource use within sericulture systems. Additionally, the medicinal properties of mulberry roots, bark, and leaves reinforce its value in traditional and modern health formulations.

The economic importance of these byproducts strengthens income streams for farmers, women self-help groups, and rural entrepreneurs. As consumer demand for natural, plant-based, and health-promoting products continues to grow, mulberry-based value addition offers expanding opportunities. Overall, the comprehensive utilization of mulberry underscores its significance as a cornerstone of sustainable sericulture, promoting ecological balance, diversified income generation, and enhanced socio-economic resilience in sericulture-dependent communities.

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MECHANISM OF POLLINATION AND REPRODUCTION IN FLOWERING PLANTS

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Introduction:

Pollination and reproduction are the key process in flowering plants which results the development of new generation of plant. A seed is primary outcome of reproduction in flowering plants, formed from a fertilized ovule. It consists of an embryonic plant enclosed within a protective outer covering, along with stored food to support initial growth. A true seed specifically develops from an ovule and includes three essential components: a living embryo, a food reserve (endosperm), and a protective seed coat. Apart from true seeds, other plant structures capable of giving rise to new plants are known as propagules. These include parts obtained through sexual reproduction (such as seeds) or asexual means (such as tubers, rhizomes, and bulbs). In agricultural practices, the term "seed" is broadly used to refer to any plant part used for propagation, including stems (e.g., sugarcane), leaves (e.g., *Bryophyllum*), modified stems (e.g., onions), as well as true seeds (e.g., cereals and pulses). Therefore, in seed production and crop cultivation, "seed" covers any viable plant material used to grow a new plant.

Floral Biology

Flowers are reproductive structures unique to angiosperms (flowering plants), and their evolution is closely linked to their pollinators, especially insects. Since flowers require a significant energy investment from the plant, they often provide rewards—like nectar or pollen—to attract pollinators and promote cross-pollination. Scientists study how flower traits such as size, shape, color, and scent have evolved by weighing the energy costs against the reproductive benefits they offer.

Floral biology also explores when plants begin to flower, how long flowers remain functional, and how they shut down after completing their role in reproduction. These aspects help researchers understand the strategies plants use to maximize reproductive success while managing their energy use. (Llyod,1996).

Complete vs Incomplete Flower

Complete flower, is a flower that consists of all four whorls i.e. Androecium, Gynoecium, Sepals (Calyx), Petals (Corolla). Example: Rose, Tulips, China rose, etc. An Incomplete flower is missing any one or more these essential parts. Example: Wheat, Squash flowers, Zucchini flowers etc.

Perfect vs Imperfect Flower

A typical flower is made up of four main parts: sepals, petals, stamens, and pistils. When a flower contains both stamens and a pistil, it is referred to as a perfect or hermaphrodite flower. It's important to note that every complete flower is also perfect, though not all perfect flowers are complete. For instance, the rice flower, which belongs to the Gramineae family, is a perfect flower even though it lacks some parts, making it incomplete. Other examples of plants with perfect flowers include beans, peas, wheat, and potato.

In contrast, a flower that possesses either stamens or pistil, but not both, is called an imperfect or unisexual flower. If it only has stamens, it's termed a staminate flower; if it only has a pistil; it's called a pistillate flower. These unisexual flowers can be arranged differently depending on the species. In monoecious plants, both staminate and pistillate flowers are found on the same plant. Examples of monoecious species include maize, colocasia, castor, and coconut. On the other hand, in dioecious plants, these flowers grow on separate individual plants, as seen in papaya, date palm, and pistachio.

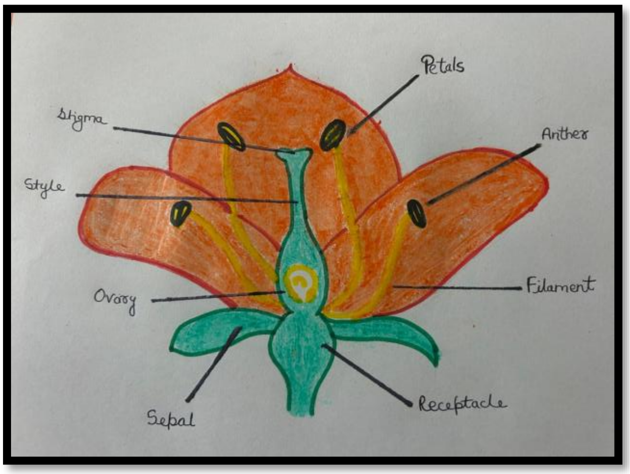

Figure 1: Floral Parts of a flower

Modification in Flower Structure:

The shift from outcrossing to self-fertilization in flowering plants is typically accompanied by a suite of morphological changes known as the selfing syndrome. This evolutionary transition often involves consistent alterations in floral traits that enhance the efficiency of self-pollination while reducing reliance on pollinators. (Ornduff, 1969). Compared to their outcrossing counterparts, self-fertilizing species typically exhibit smaller, less showy flowers, reduced spatial separation between anthers and stigmas (a trait known as herkogamy), and lower pollen-to-ovule ratios (Leavenworth, Lloyd, 1965), Mimulus (Ritland, 1989) and Collinsia (Armbruster *et al.,* 2002).

Self-fertilization in plants is commonly prevented through three main mechanisms. First, in many species, male and female reproductive organs are located in separate flowers. These are known as diclinous species. If both flower types occur on the same plant, the species is monoecious; if on separate plants, it is dioecious.

Second, in some species, although both stamens and pistils are present in the same flower, they mature at different times, preventing self-fertilization—a phenomenon known as dichogamy. When the pistil matures first, the plant is termed protogynous, as seen in Arum species. More commonly, the stamen matures first, a condition known as protandry.

Third, some plants exhibit floral forms with different arrangements of stamens and pistils within the same species, promoting cross-pollination via pollinators. This condition is called heteromorphy. If two floral forms exist, the species is dimorphic; if three, it is trimorphic. These variations enhance pollen transfer between distinct floral forms, thus reducing the likelihood of selfing.

Reproduction in Crop Plants

The first land plants appeared around 468 million years ago (McGhee, 2013) and reproduced through spores. The first seed-producing plants were gymnosperms, which do not have ovaries to enclose their seeds. Reproduction is the biological process through which new individuals (progeny) of the same type and species are produced from existing parents. Like all living organisms, plants also reproduce to ensure the continuation of their species by passing on genetic material to future generations.

The mode of reproduction in plants plays a crucial role in determining their genetic makeup; whether they are predominantly homozygous or heterozygous. This genetic constitution significantly influences the objectives of plant breeding programs. For instance, in self-pollinated crops such as wheat, developing a homozygous line is typically preferred when creating a new variety. In contrast, in cross-pollinated crops like maize, a heterozygous population is often targeted for variety development due to their naturally diverse genetic structure. Understanding the reproductive behavior of crop plants is also essential for hybridization, which involves the creation of artificial hybrids to combine desirable traits from different parents. Modes of reproduction are: Asexual and Sexual.

Asexual Reproduction

Asexual reproduction does not require the fusion of male and female gametes, and meiosis does not occur during this process. Instead, offspring are generated either from vegetative parts of the plant through vegetative propagation, or through apomixis, where the embryo forms directly without fertilization.

Vegetative Reproduction

The formation of new plants can occur through vegetative parts, especially via modified underground and sub-aerial stems or structures like bulbils.

Underground Stem

These are stem modifications that develop below the soil surface. Though they originate from stem tissues, they take on specialized forms to store food and nutrients and assist in producing new plants. Once they establish roots and shoots, they give rise to genetically identical offspring. Common types include; tuber (eg. potato), Bulb (eg. onion and garlic), Rhizome (eg. Ginger and turmeric), Corm (eg. Bunda and Arwi). These structures serve dual purposes: acting as storage organs and enabling vegetative propagation.

Sub-Aerial Stem

These modifications include runner, stolon, sucker etc. Sub-aerial stems are used for propagation of Mint (*Mentha sp.)* and Date palm (*Phoenix dactilifera*) etc.

Artificial Vegetative Propagation:

Vegetative propagation is commonly used to replicate cultivars with desirable traits. Farmers and horticulturists employ this technique to enhance crop quality. Some of the most popular methods of artificial vegetative propagation include: (Forbes *et al.,* 1992). Common methods of vegetative propagation include stem cuttings, which are widely used for crops like sugarcane, grapes, and roses. Other techniques, such as layering, budding, grafting, and goote, are often employed for propagating fruit trees and ornamental shrub.

Significance of Vegetative Reproduction:

Vegetative reproduction offers several advantages, especially in agriculture and horticulture. One key benefit is that the offspring produced through this method are genetic clones of the parent plant. This means that if the parent plant possesses desirable traits, such as disease resistance or high yield, these characteristics are reliably passed down to the new plants. For commercial growers, this method ensures consistency across crops, which is important for maintaining product quality and meeting consumer expectations. Moreover, vegetative reproduction can be more efficient than growing plants from seeds, as it eliminates the variability that can come from sexual reproduction (Hussey, 1978).

Vegetative propagation helps plants skip the expensive and complicated process of making flowers, seeds, and fruits. By reproducing this way, plants save energy and resources that would normally go into producing these sexual reproduction parts, allowing them to grow and spread more quickly (Snow, Allison, 1989).

Apomixis

In apomixis, seeds are produced without fertilization, resulting in embryos that develop asexually. As a result, plants grown from these seeds are genetically identical to the parent plant. In species exhibiting apomixis, sexual reproduction may either be absent or suppressed. When sexual reproduction occurs alongside apomixis, it is called facultative apomixis. However, when sexual reproduction is completely absent, it is referred to as obligate apomixis. While apomixis is common in many crops, it typically occurs in a facultative form, allowing for both asexual and sexual reproduction.

Apomixis as a Tool for Fixing Hybrid Vigour

Hybrid vigor, also called heterosis, is when F1 hybrid plants perform better than their parent plants in important traits like yield. This is a key principle in modern agriculture. Apomixis, which is a form of asexual seed reproduction, has long been seen as a "holy grail" in crop science (Sailer *et al.,* 2016). Scientists have shown that hybrid vigor can be preserved using synthetic apomixis, but several challenges have made it hard to use this method in farming. These challenges include low rates of clonal seed production, poor fertility in plants, and the need for complex procedures. However, a recent breakthrough study by Vernet and colleagues introduced a new all-in-one system that combines apomeiosis and a trigger for parthenogenesis. This approach has overcome most of the previous obstacles in hybrid rice and successfully produced clonal seeds with over 95% efficiency across multiple generations (Vernet *et al.,* 2022).

To successfully create apomixis in plants that normally reproduce sexually, three things are needed: skipping meiosis (called apomeiosis), triggering embryo development without fertilization (parthenogenesis), and proper development of the endosperm (which feeds the embryo). A system called MiMe (Mitosis instead of Meiosis) has been shown to work well in producing egg cells that are genetically identical to the mother plant, in both dicot and monocot species.Parthenogenesis has also been achieved in some cereal crops by forcing the expression of BBM (Baby Boom) genes in the egg cells, which causes them to develop into embryos without fertilization.In an earlier attempt to create synthetic apomixis in rice, researchers used a two-step method. First, they used CRISPR/Cas9 to create MiMe mutations in a rice plant that already had the OsBBM1 gene turned on in its egg cells. This led to the production of clonal seeds, but only at a rate of about 10% to 30% (Khanday *et al.,* 2019).

Vernet and colleagues have shown that synthetic apomixis can now be achieved in rice using a one-step method. They created a special vector (a DNA tool) that included guide RNAs targeting three key MiMe genes (PAIR1, REC8, and OSD1), along with the OsBBM1 gene controlled by an egg cell-specific promoter. This vector was introduced into callus tissue made from embryos of F1 rice seeds. In the first generation (T0), researchers identified the plants with MiMe mutations and checked the DNA content (ploidy) of their offspring. In this setup, diploid (clonal) offspring are only produced if both apomeiosis and parthenogenesis happen together. If not, the offspring turn out to be tetraploid.

Interestingly, most of the MiMe mutant plants produced diploid offspring at very high rates—over 80%, and in some cases even above 97%. This shows that the one-step, all-in-one system works very well for creating clonal rice plants.

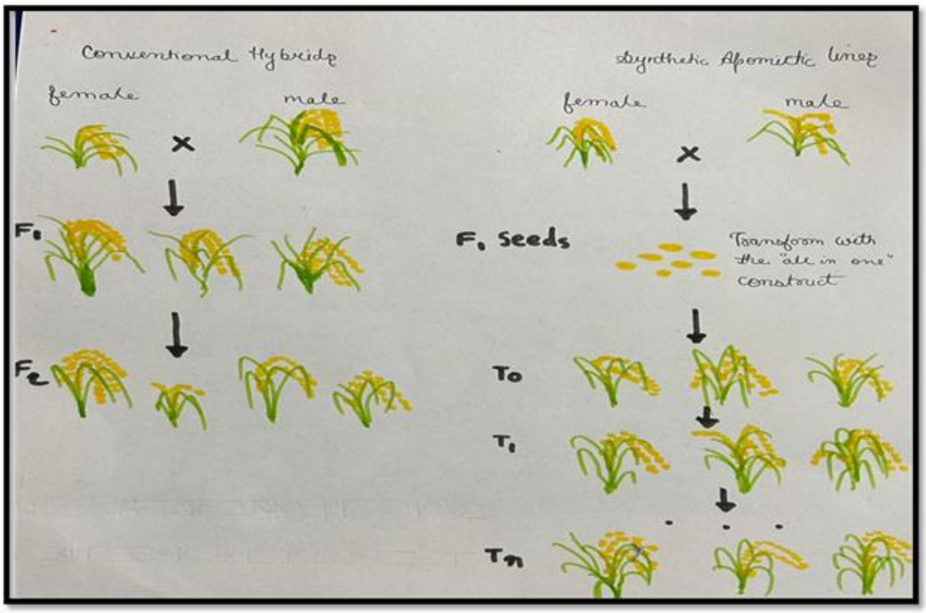

Figure 2: Fixing hybrid vigour in apomixis

Types of Apomixis

1. Adventitive Embryony

Adventive embryony is a kind of asexual reproduction in plants, where new embryos grow directly from parts of the ovule like the nucellus or integuments, without the need for fertilization. This means seeds can form without the joining of male and female gametes. Since there's no fertilization, the new plants are genetically identical to the parent plant. This process is a type of apomixis, which allows plants to make seeds without sexual reproduction. This method is useful in stable environments where the same genetic traits can help plants thrive. It also allows quick and consistent reproduction, especially when conditions for sexual reproduction (like pollination) are not ideal. Examples of plants showing adventive embryony are Citrus (like oranges and lemons), Opuntia (a type of cactus) and Mango etc.

2. Gametophytic Apomixis

Diplospory- In diplospory, a type of gametophytic apomixis, the embryo sac forms directly from the megaspore mother cell without undergoing normal meiosis. As a result, the embryo sac remains diploid and contains a diploid egg cell that develops into an embryo. This process is found in plants like *Tripsacum*, *Erigeron*, and *Taraxacum officinale*.

Apospory is another form of gametophytic apomixis where the embryo sac develops from somatic cells of the ovule, not from the megaspore mother cell. These somatic cells, called aposporous initial cells. This type of apomixis occurs in species such as *Panicum*, *Poa*, *Pennisetum*, and *Hieracium*.

3. Apogamy

Apogamy is a form of asexual reproduction in plants in which the sporophyte develops from the gametophyte without fertilization. Instead of forming through the union of male and female gametes, the embryo arises directly from the vegetative cells of the gametophyte. As a result, the new plant is a genetic clone of the parent.

4. Parthenocarpy

Parthenocarpy is a phenomenon in which fruits develop without the fertilization of ovules, typically leading to the production of seedless or nearly seedless fruits. Some common fruits that naturally show this process include pineapple, banana, cucumber, grape, orange, grapefruit, and breadfruit.

a. Natural parthenocarpy happens on its own in certain plant species, without the need for fertilization. In these cases, the ovary of the flower grows into a fruit without any pollination or fusion between male and female reproductive cells. This leads to fruits that have no seeds or only a few seeds. Examples of plants that naturally produce parthenocarpic fruits include bananas, pineapples, figs, and certain kinds of oranges and grapes. One major benefit of natural parthenocarpy is that it doesn't rely on pollinators. This means the plant can still produce fruits even in places where pollinators are limited or environmental conditions are not suitable for pollination.

b. Artificial parthenocarpy refers to the process of fruit development without fertilization through human intervention. This technique is commonly used in agriculture to produce seedless fruits that are in high demand commercially. Plant hormones like auxins and gibberellins are applied to simulate the natural signals that typically result from fertilization, prompting the ovary to develop into fruit. In addition, advances in genetic engineering have made it possible to cultivate seedless fruits without the need for external hormone applications. Parthenocarpy can also be achieved by manipulating environmental factors such as temperature or through mechanical handling of flowers.

5. Parthenogenesis

Parthenogenesis is a reproductive process in which an embryo forms from an unfertilized egg, eliminating the need for fertilization (Heesch *et al.,* 2021). While often classified as a type of asexual reproduction, it is sometimes more accurately viewed as a partial form of sexual reproduction, since it involves the development of offspring from gametes.

Sexual Reproduction

Sexual reproduction involves fusion of male and female gametes to form a zygote, which develops into an embryo. The main requirement for sexual reproduction is the development of male and female gametes through meiosis.

Events for reproduction in plants:

1. Sporogenesis: Production of megaspores and microspores in ovule and anther, respectively.

a. Microsporogenesis- Microsporogenesis refers to the process of microspore formation within the anther. It begins when diploid microspore mother cells (2n) undergo meiosis, resulting in a tetrad of four haploid microspores (n). These microspores are initially enclosed in a protective callose wall. As the microspore mother cells mature, they gradually lose water, and the callose wall dissolves. This breakdown of the callose releases the individual microspores, which eventually develop into pollen grain.

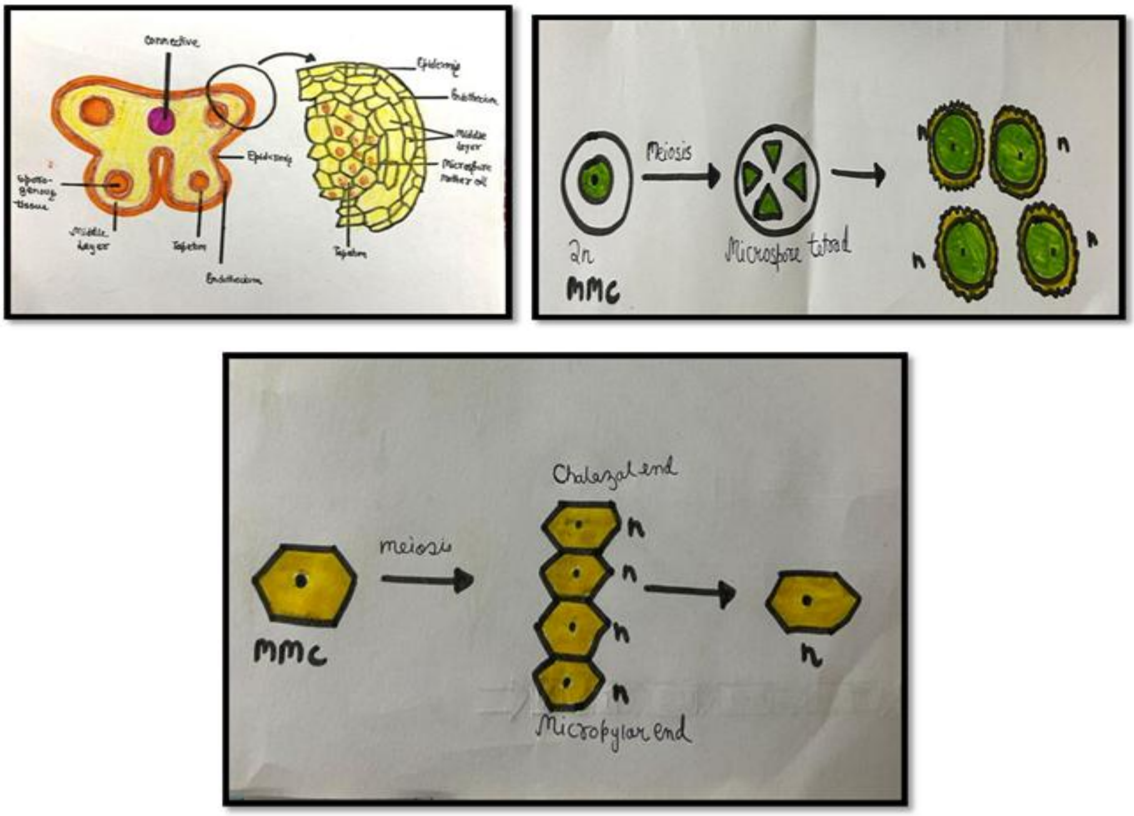

Figure 3: Microsporogenesis in flowering plants

b. Megasporogenesis- Megasporogenesis is the process of megaspore formation within the ovule. It begins when a single cell from the nucellus, located near the micropylar region, differentiates into the megaspore mother cell (MMC). This diploid MMC undergoes meiosis to produce four haploid cells. Of these, only the one positioned toward the chalazal end remains functional, while the other three, located toward the micropylar end, degenerate.

2. Gametogenesis: Production of male and female gametes in microspores and megaspores.

a. Microgametogenesis:

Microgametogenesis is the process through which male gametes (sperm cells) are formed from microspores. As the pollen matures, the nucleus of each microspore undergoes a mitotic division, resulting in two distinct nuclei: a generative nucleus and a vegetative (or tube) nucleus. Pollen is typically released from the anther at this binucleate stage. Upon reaching the stigma of a compatible flower—a process called pollination—the pollen grain germinates, and a pollen tube begins to grow through the style toward the ovary. The generative nucleus then undergoes another mitotic division within the pollen tube, forming two male gametes (sperm cells). Together, the pollen grain and the growing pollen tube constitute the male gametophyte. Eventually, the pollen *tube* penetrates the ovule via a small opening called the micropyle and releases the two sperm cells into the embryo sac for fertilization.

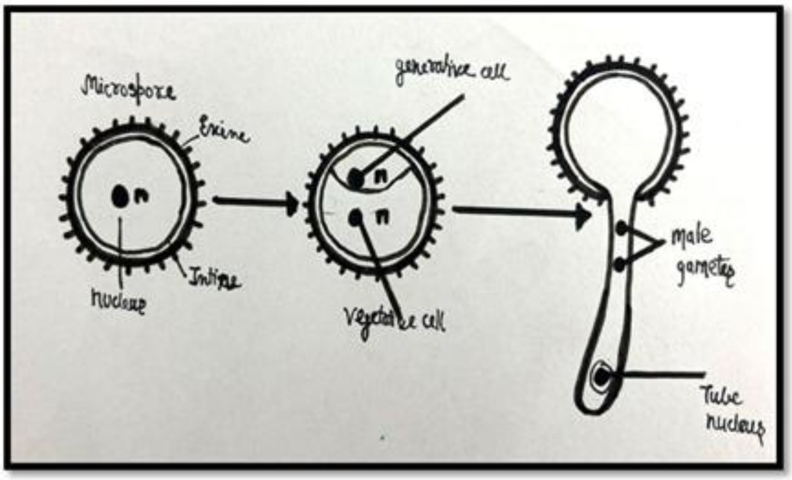

Figure 4: Microgametogenesis in flowering plants

b. Megagametogenesis:

Megagametogenesis is the developmental process through which the functional megaspore transforms into a mature female gametophyte, commonly known as the embryo sac. In most angiosperms, the nucleus of this functional megaspore undergoes three successive mitotic divisions, giving rise to eight haploid nuclei. These nuclei are then organized in a distinct spatial pattern within the developing embryo sac. At the micropylar end, three nuclei are positioned — one becomes the egg cell, while the other two differentiate into synergids that assist in fertilization.

At the chalazal end, another group of three nuclei forms the antipodal cells. The remaining two nuclei migrate toward the center of the sac and fuse to form a single diploid secondary nucleus, also called the central cell.

Consequently, the mature embryo sac typically comprises:

- One egg cell

- Two synergids
- Three antipodal cells
- One central cell (containing a diploid secondary nucleus formed by the fusion of two polar nuclei).

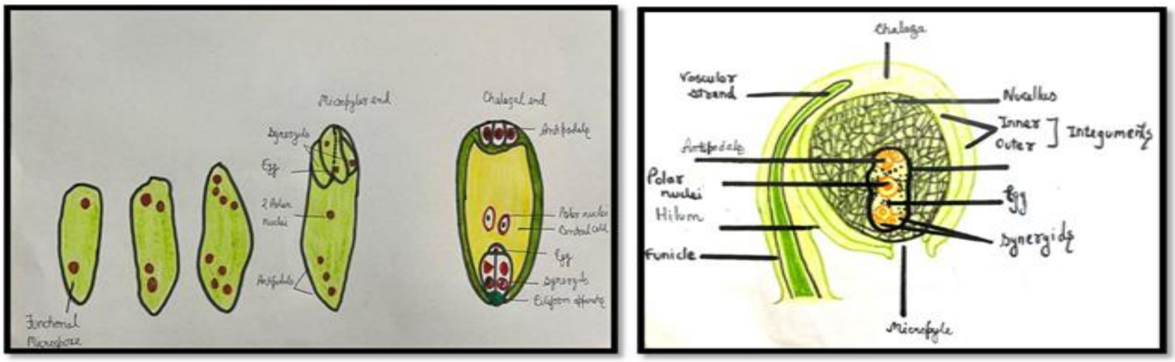

Figure 5: Development of Embryosac in flowering plants

Fertilization:

In angiosperms, fertilization begins when compatible pollen grains land on the stigma of the carpel and ends with the fusion of male and female gametes within the embryo sac. Since the male gametes cannot directly reach the egg cell, the pollen grain germinates on the stigma to form a pollen tube. This tube grows through the style, reaches the ovary, and penetrates the ovule to access the embryo sac. Once inside, the pollen tube releases two male gametes. One gamete fuse with the egg cell to form a zygote (a process called syngamy), while the other fuses with the two polar nuclei to form the primary endosperm nucleus (a process known as triple fusion). Because two separate fertilization events occur within the same embryo sac, this process is called double fertilization, a unique and defining feature of angiosperms.

In the embryo sac of flowering plants, two distinct fusion events take place during fertilization—a process known as double fertilization. The first fusion, called syngamy, involves the fusion of one male gamete with the egg cell, resulting in the formation of a zygote, which is the first cell of the future sporophyte (embryo). The second event, known as triple fusion, occurs when the other male gamete fuses with two polar nuclei in the central cell, forming a triploid (3n) nucleus called the primary endosperm nucleus. This nucleus develops into the endosperm, a nutritive tissue that supports the growth of the developing embryo. Double fertilization is a very unique phenomenon in angiosperms and discovered for the first time by S.G. Nawaschin (1898) in Lilium and Fritillaria species.

Significance of Sexual Reproduction:

Sexual reproduction enables the mixing of genetic material from two or more parent organisms, resulting in hybrid offspring. Through the process of genetic recombination, it generates a wide range of unique genotypes. This diversity is crucial for introducing genetic variation via hybridization. In fact, the foundation of most plant breeding techniques relies heavily on the mechanisms of sexual reproduction.

Pollination:

Pollination is the initial step in the reproductive cycle of higher plants, involving the movement of pollen from the anther to the stigma of the same or a different flower. It occurs after the development of reproductive organs and related structures. Two types of Pollination: Self pollination (Autogamy & Geitonogamy) and cross- pollination (Abiotic and biotic agents).

Self Pollination: When pollen from the anther lands on the stigma of the same flower, the process is known as self-pollination or autogamy. Eg. Chickpea, Pea, wheat etc.

Geitonogamy: "When pollen from one flower is transferred to the stigma of another flower on the same plant, it is still considered self-pollination. Eg. in maize

Cross Pollination: Cross-pollination involves the transfer of pollen from the anther of one flower to the stigma of a genetically distinct flower. This process relies on external agents for successful pollen transfer. Eg. Cauliflower, carrot etc.

Agencies of Pollination:

1. Abiotic

a) Wind (Anemophily): The process by which pollen is dispersed by the wind is known as anemophily or wind pollination (Vijayaraghavan *et al.,* 1998), Anemophily pollinates around 12% of plants worldwide, including major agricultural species like wheat, rye, barley, and oats as well as cereal crops like rice and corn. Because anemophilous pollen grains are light, smooth, and non-sticky, air currents may carry them. Long, well-exposed stamens are used by anemophilous plants to collect and disperse pollen. In addition to being exposed to wind currents, these stamens contain a big, fluffy stigma that makes it simple to catch flying pollen grains.

b) Water (Hydrophily): A somewhat rare type of pollination is hydrophily, in which pollen is dispersed by water movement, especially in rivers and streams. Two types of hydrophilous species are distinguished: (i) those that spread their pollen throughout the water's surface. For instance, pollen grains or the male flower of Vallisneria are discharged onto the water's surface and passively carried away by water currents; some of them finally make their way to the female flower (ii) others that disperse them below the surface. For instance, sea grasses, where the pollen grains are discharged into the water while the female flower stays submerged. Aquatic plants are often those that are pollinated by water. They generate a lot of pollen grains since most of them are lost in the water flow and only a small percentage make it to the stigma. The female flower's stigmas are often huge and feathery to capture the pollen grains, and they are typically above the water. Underwater pollen is heavier than water, but surface pollen is lighter. Once fully grown, the male bloom separates from the plant and hovers above the water.

2. Biotic

a) Insects (Entomophily): Entomophily, often known as insect pollination, is a type of pollination in which insects disperse plant pollen, particularly from blooming plants but not exclusively from other types of plants. Insect-pollinated flowers usually promote themselves with vivid colours, occasionally with noticeable patterns (honey guides) that provide pollen and nectar rewards; they may also have a pleasing fragrance that occasionally resembles insect pheromones. For their job, pollinators like bees have developed adaptations including lapping or sucking mouthparts to absorb nectar and, in certain species, pollen baskets on their hind legs. In order to benefit both groups, this necessitated the coevolution of blooming plants and insects in the creation of pollination mechanisms by the flowers and pollination behaviour by the insects.

b) Birds (Ornithophily): Ornithophilly is the term for pollination by birds. At least 10,000 plant species—mostly in the temperate southern hemisphere and the tropics—have it. The southwestern region of Australia is home to the greatest number of bird-pollinated species. Hummingbirds, spiderhunters, drongos, orioles, sunbirds, honeycreepers, and sugarbirds are a few of the birds that aid in flower pollination. The characteristics characterize flowers that specialised for pollination by birds are Large, tubular flowers with recurred petals that resemble tubes, funnels, or cups.

The petals are brilliantly coloured, such as red, yellow, or orange; they are unscented (birds have poor senses of smell); they are open during the day; they should be a prolific nectar producer with deeply buried nectar; and they offer robust support for perching.

c) Bats (Chiropterophily): Mango, banana, durian, and guava are among the more than 500 plant species that depend on bats to pollinate their blossoms. In contrast to bees, which are mostly drawn to brilliant, daytime blooms, bat-pollinated plants frequently feature pale nighttime blossoms. Some bats have developed especially to reach the nectar at the bottom of these blooms, which are frequently big and bell-shaped. This is precisely why the banana bat, which is found exclusively on the Pacific coast of Mexico, and the tube-lipped nectar bat of Ecuador have incredibly long tongues. The tongue of the tube-lipped nectar bat is more than 1.5 times as long as its body.

d) Snails (Malcophily): Malacophily is the term used to describe snail and slug pollination. Not many people are aware of or think of snails as pollinators. However, snails serve as pollinators for plants in the sweet potato family on wet days. Lamellaxis gracilis is a species of snail that exhibits malacophily.

e) Ants (Myrmecophily): Ants (Hymenoptera: Formicidae) are known to visit flowers primarily for nectar, and while they can carry pollen, their effectiveness as pollinators is limited.

f) Snakes (Ophiophily): Pollination by snakes is Ophiophily, it is found in Sandals and Michelia.

g) Entomophily: The pollen grains are transferred to a mature through the agency of insects like moths, butterflies, wasps, bees, beetles, etc. e.g. Toria, sarson, raya, kashmal, safeda, punna etc.

Mechanism Promoting Self-Pollination

1. **Cleistogamy:** Cleistogamous flowers stay closed for their entire lifespan and undergo self-pollination. This process, referred to as cleistogamy, is a form of autogamy, where the fusion of gametes occurs within the same individual. Since these flowers do not open, they do not rely on external agents like wind, water, or insects for pollination. Instead, they develop seeds through an internal mechanism. In such flowers, both the anther and stigma are typically small in size. Cleistogamous pollination is commonly observed in members of the grass family, including species like pansies, peas, and peanuts. However, a significant limitation of this type of pollination is the lack of genetic variation, as the reproductive structures involved share the same genetic makeup. As a result, the seeds produced have limited genetic diversity.
2. **Chasmogamy:** In such cases, the flowers remain closed until pollination has occurred. As a result, only limited cross-pollination can happen after the flowers open. Crops like wheat, barley, and rice are common examples of this process.
3. **Homogamy:** Homogamy refers to the state in which a flower's anthers (male reproductive parts) and stigmas (female reproductive parts) mature simultaneously. This timing is essential for self-pollination, as it enables the plant to fertilize itself without relying on pollen from another plant.
4. **Papilionaceous corolla:** In plants belonging to the Fabaceae (Papilionaceae) family, the flower petals are arranged so that the anthers are enclosed within a boat-shaped structure called the keel, formed by the two lower petals. This special arrangement helps in self-pollination by keeping the reproductive parts close together.

Mechanism Promoting Cross-Pollination

1. Dicliny (Unisexuality): In diclinous plants, male (staminate) and female (pistillate) flowers are found separately—either on different plants (dioecious), like papaya, or on the same plant but in different flowers (monoecious), like maize. This separation of helps to minimize the chances of self-fertilization, and encourages cross-pollination.

2. Dichogamy: This mechanism refers to the different timing of maturity between stamens and pistils within the same flower, which helps promote cross-pollination. It is classified into two types: Protandry: Stamens mature before the pistils (e.g., maize, sugar beet). Protogyny: Pistils mature before the stamens (e.g., bajra).

3. Self- Incompatibility: Self-incompatibility (SI) is a genetic system in some plants that prevents them from being fertilized by their own pollen. This helps to promote cross-pollination and increases genetic diversity. By recognizing and rejecting their own pollen, plants ensure mixing of genes, which is important for maintaining variation within a species.

4. Herkogamy- It is the presence of any physical barriers, like presence of wax layer in stigma that affects the receptivity of stigma and it acts as a barrier to self- fertilization. **Example-** Calotropis, pentangular stigma is positioned above the level of anthers.

5. Heterostyly- The variability in length of style in a flower is known as Heterostyly. Example – Primrose (Primula vulgaris) shows distyly. It has two types of flowers *i.e.* Pin-eyed (Long style and short stamen) and Thrum-eyed (Short style and long stamen). This stops the pollen from reaching the stigma and pollinating it.

The Vital Role of Pollinators in Agriculture

Pollinators play an important role in the reproductive cycle of flowering plants, significantly influencing the formation of fruits, vegetables, and numerous agricultural crops. This process, which depends on biological agents such as animals and other pollinating vectors, is vital for successful fertilization, seed formation, and ultimately, the productivity of cultivated plants. Over 75% of globally grown crop species depend on animal-mediated pollination, which affects more than one-third of the food and drink consumed around the world. The contribution of pollinators extends beyond just food crops—they are also essential for the production of medicinal plants and other plant-based goods. Their influence is especially important in determining fruit set, quality, and the overall yield across a wide range of crops, including fruits, vegetables, seed spices, and industrial crops like cotton, soybean, sesame, and mustard.

Involvement of Pollinators in Fruit Production

Mango- In many mango-producing countries around the world, insect pollinators play a vital role in the successful cultivation of the fruit. Research has shown that introducing bee colonies into mango orchards significantly enhances fruit set, with open (uncaged) flower clusters achieving a 41% fruit set rate, in contrast to just 0.7% in enclosed (caged) clusters (Fajardo *et al.,* 2008). The primary insect pollinators involved in mango production include species such as *Melipona* and *Syrphus* (Singh, 1988).

Guava- Guava, a fruit native to tropical regions, grows best in warm environments. Honey bees are considered the most effective pollinators for guava, significantly improving both fruit set and quality (Rajagopal & Eswarappa, 2005). They are responsible for approximately 20% to 40% of the total pollination activity.

Artificial Pollination to Enhance Seed Setting

Artificial pollination, also referred to as, assisted pollination, is a process where pollen is manually transferred from the anther (male part) of a flower to the stigma (female part) by human. This technique is used to ensure fertilization, leading to the formation of fruits or seeds, especially in cases where natural pollinators are absent or ineffective.

Methods of Artificial Pollination

Artificial pollination involves different techniques that are used to manually or mechanically move pollen between flowers. These methods are often used when natural pollinators are lacking or to support natural pollination. Below is an overview of some common approaches.

Mechanical Pollination

Hand-pollination, also known as mechanical pollination, is a method used when natural pollination is limited or not desirable. In this technique, pollen is manually transferred from the stamen (male part) of one flower to the pistil (female part) of another. The flower from which pollen is taken is called the pollen donor or pollen parent, while the flower receiving the pollen is referred to as the seed parent. This process is usually carried out using a cotton swab or a small brush. In some cases, the petals of a male flower are removed, and the flower is gently brushed against the stigma of a female flower. For bisexual flowers, such as tomatoes, gently shaking the flower can help release pollen and achieve pollination. Hand-pollination is commonly used when natural pollinators are unavailable, to control cross-pollination between different plant varieties, or to assist in breeding programs (McLaughlin (2010). It is importance in developing specific hybrids and maintaining genetic control during cultivation (Rai and Rai, 2006).

Drone Pollination

Drone pollination technology involves using unmanned aerial vehicles (UAVs) to carry and spread pollen onto flowering plants. These drones are fitted with special tools, such as small brushes or air blowers, to gently transfer pollen from one flower to another. In greenhouse settings, this method gives growers more control over the pollination process. In outdoor farming, drones serve as a helpful alternative when there are too few bees or other natural pollinators. For crops that rely heavily on cross-pollination, drone assistance can greatly improve yield and help prevent crop losses.

The Decline of Natural Pollination

In recent years, the number of natural pollinators—especially bees—has been decreasing. Factors such as climate change, large-scale single-crop farming (monoculture), the spread of diseases, and heavy pesticide use have all played a role in this decline. In some areas, entire bee colonies have vanished, forcing farmers to look for other ways to pollinate their crops.

Pollination is a critical part of food production, not just an added benefit. Around 75% of the world's food crops depend, at least partly, on pollinators. Without bees, the production of important crops like apples and almonds can be severely affected. This is where drone pollination can help—not to replace bees, but to support the pollination process when natural pollinators are not available.

Working Process

Pollination drones come in various designs, but they all serve the same purpose: to transport pollen and deliver it precisely to receptive flowers. Some models use gentle brushes to imitate the way bees naturally transfer pollen, while others rely on air bursts or static electricity to direct the pollen onto the flower. More advanced drones are equipped with computer vision technology that helps identify flowers and determine the ideal timing for pollination. This improves accuracy and reduces the risk of harming the plants. These drones can be programmed to follow GPS-guided paths through fields, orchards, or greenhouses. In some experimental setups, groups of smaller drones work together as a team to complete pollination over large areas quickly and efficient.

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AI IN AGRICULTURE FOR VIDARBHA'S SMALL FARMERS

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Abstract:

Vidarbha, an agrarian region in eastern Maharashtra, is dominated by small and marginal farmers cultivating 2–3-acre landholdings and facing persistent challenges such as climatic instability, pest infestations, high input costs, and market volatility. Artificial Intelligence (AI) offers transformative solutions that can enhance productivity, reduce risk, and improve livelihood security without requiring major capital investments. This chapter provides a crop-specific analysis of AI applications for cotton, soybean, orange orchards, and rice, the major agricultural systems in Vidarbha. Key innovations discussed include AI-based pest prediction and drone scouting for cotton, optimized sowing windows and disease recognition in soybean, smart irrigation and citrus greening detection in Nagpur mandarin orchards, and water-level prediction and targeted weed control in rice cultivation. Evidence indicates that AI-driven advisories significantly cut input expenditure, improve yield reliability, and strengthen farmers' bargaining power through market prediction and produce grading systems. The chapter further highlights the collaborative role of government and agricultural universities in scaling AI adoption through rural connectivity, local-language advisory platforms, subsidized digital tools, AI training programs, and region-specific data models. Overall, AI-enabled farming can accelerate Vidarbha's agricultural resilience by empowering smallholders with data-driven decision support and accessible smart-farming tools, ensuring long-term sustainability and socioeconomic upliftment.

Keywords: Artificial Intelligence (AI); Smallholder Farmers; Vidarbha; Pest and Disease Forecasting; Drone Monitoring; Market Advisory Systems; Sustainable Agriculture

1. Introduction:

Vidarbha, located in eastern Maharashtra, is an agriculturally important but economically vulnerable region, where most farmers are smallholders cultivating small and marginal landholdings. A majority of farmers operate on small and marginal landholdings of only 2-3 acres, which limits their ability to invest in mechanisation or high-cost technologies [1]. The region's agriculture is heavily dependent on the monsoon, and its crop mix, primarily cotton, soybean, oranges, and rice, is exposed to climatic instability, pest pressures, and market fluctuations [2]. Because small farms rely directly on seasonal outcomes, a single failure due to pest attack, erratic rainfall, or unforeseen weather events can severely affect a family's livelihood [3].

In this context, Artificial Intelligence (AI) provides a unique opportunity to improve productivity, reduce risks, and enhance decision-making for small farmers [4]. AI tools do not always require large land or costly machinery; instead, many solutions work through smartphones, local drones, low-cost sensors, and village-level data platforms [5]. Thus, AI can become a powerful equaliser, allowing small farmers to access advanced advisory systems previously accessible only to large landowners [3].

2. AI Applications in Vidarbha by Crop

2.1 Cotton Farming (Yavatmal-Akola-Amravati Belt)

Cotton is the backbone of Vidarbha's agriculture, but it is also one of the riskiest crops due to pests like pink bollworm and whitefly [6]. AI can help mitigate these risks significantly by enabling more precise monitoring and control [4].

AI-Based Pest Prediction and Detection: AI systems analyse satellite patterns, weather trends, and pheromone trap data to predict pest outbreaks several days before they occur [4]. This early warning gives farmers valuable time to prepare and take preventive measures. For a small 2–3 acre cotton farmer, such timely alerts can prevent devastating crop losses and help reduce dependency on excessive pesticide sprays [6].

Precision Spray Timing: Traditional spraying often happens without considering weather or pest lifecycle, leading to wastage and poor results. AI platforms can combine humidity, wind speed, temperature, and rainfall predictions to suggest the most effective day and time to spray pesticides [2]. This ensures maximum impact of each spray, reduces input costs, and prevents chemical residues from being washed away due to sudden showers [4].

Drone Scouting for Cotton Stress: Drones equipped with high-resolution cameras can scan cotton fields quickly and efficiently. AI then analyses these images to detect crop stress, nutrient deficiency, or early signs of pest infestation [5]. For small farmers who cannot manually inspect their crops daily or hire labour, drone scouting becomes an affordable way, especially through FPOs, to catch problems before they escalate [6].

Soil and Fertilizer Recommendation Models: AI models process soil data from health cards and historical yield patterns to generate crop-specific fertilizer recommendations [7]. These personalised advisories help farmers avoid overuse or misuse of fertilizers, thus saving money while maintaining soil health. For small cotton growers, optimizing fertilizer use directly improves profitability [2].

AI-Based Cotton Price Prediction: Cotton markets are highly volatile, and many small farmers are forced to sell soon after harvest due to immediate cash needs. AI models can forecast price trends based on historical mandi data and current market conditions [3]. This enables farmers to decide whether to sell immediately or store their produce for a better price, improving their bargaining power and income [1].

2.2 Soybean Farming (Akola-Amravati-Wardha Zone)

Soybean is extremely sensitive to rainfall patterns, so good sowing and disease management are crucial [2].

AI-Driven Sowing Window Alerts: AI combines long-term weather forecasts and soil moisture patterns to recommend the ideal sowing window [4]. This advice helps farmers avoid sowing just before heavy rains that can wash away seeds. By preventing re-sowing, a major cause of debt among small farmers, AI saves time, money, and effort [1].

Disease Recognition and Early Intervention: Mobile apps using AI can identify diseases such as mosaic virus and rust simply through leaf photos [8]. Knowing the disease early allows farmers to apply the right pesticide at the right time, avoiding unnecessary spraying and minimizing yield loss. This is especially important for small farmers who cannot afford repeated crop failures [6].

Waterlogging Prediction: Heavy rains often cause waterlogging in soybean fields, which can destroy the crop within days. AI models use rainfall predictions and soil drainage data to warn farmers about potential waterlogging risks [4]. This gives time to create drainage channels or avoid applying fertilizers that may be wasted or cause further damage [2].

Harvest Prediction & Pod-Shatter Risk Alerts: AI tools estimate the ideal harvest time by analysing pod maturity, weather trends, and plant moisture levels [4]. Because soybean pods are prone to shattering under sudden rain or high heat, such predictive alerts help farmers harvest before major losses occur [3].

2.3 Oranges (Nagpur-Wardha-Amravati Citrus Belt)

Vidarbha's oranges are world-famous, but the crop requires continuous monitoring and timely management [3].

Citrus Greening (HLB) Detection: HLB is one of the most destructive diseases in citrus. AI-powered image analysis can detect subtle early symptoms, such as leaf discoloration or irregular patterns, that farmers may miss [5]. Early detection helps prevent the spread of disease to other trees and extends orchard productivity [4].

Smart Irrigation for Orchards: IoT sensors installed at different soil depths help monitor moisture and evaporation rates. AI interprets this data and recommends precise irrigation schedules, preventing both under- and over-watering [5]. This is crucial for small orchard owners with limited borewell capacity who must manage water usage carefully throughout the season [2].

AI-Based Fruit Counting and Yield Estimation: AI uses drone or smartphone images to estimate how many fruits are on each tree [5]. This information allows farmers to prepare harvesting labour, plan post-harvest handling, and negotiate prices with traders more confidently. Accurate yield estimation strengthens farmers' position in the value chain [3].

Heatwave Stress Alerts: AI models analyse upcoming temperature spikes and warn farmers to irrigate or shade vulnerable trees [4]. These preventative measures protect fruit size and quality during Vidarbha's frequent heatwaves [2].

2.4 Rice (Bhandara-Gondia-Chandrapur-Gadchiroli)

Rice cultivation in Vidarbha relies heavily on water availability and weed control [2].

Water Management Models: AI-based models help farmers maintain optimal water levels in paddies by predicting evaporation and rainfall patterns [4]. This helps save water and electricity by reducing unnecessary pump usage, an important factor for farmers with small holdings and limited irrigation resources [5].

AI Weed Detection and Targeted Spraying: Computer-vision-enabled sprayers can identify weed patches and apply herbicide only where needed [4]. Unlike manual weeding, which is labour-intensive and costly, AI-driven targeted spraying helps small farmers reduce expenses and improve crop growth [6].

Yield Estimation at Flowering Stage: AI analyses satellite data and plant canopy conditions to estimate rice yield well before harvest [4]. Such information helps farmers prepare post-harvest logistics, decide storage requirements, and negotiate with buyers more effectively [1].

Disease Forecasting: AI models can predict outbreaks of rice blast or brown plant hopper based on humidity, temperature, and wind patterns [4]. For small farmers with limited resources, preventive management guided by such predictions can save an entire season's income [3].

3. Expanded Benefits for Small Farmers (2-3 Acres)

Reduced Input Cost: AI reduces unnecessary use of pesticides, fertilizers, and water by informing farmers exactly when and where these inputs are needed [2]. This leads to significant savings, especially for small farmers who have limited capital and cannot afford wastage [5].

Higher Productivity: Accurate sowing windows, targeted disease control, and optimal irrigation collectively improve crop yields [4]. Because small farmers depend heavily on maximizing production from limited land, even modest yield improvements can have a meaningful impact on household income [1].

Improved Risk Management: AI-generated weather alerts, pest outbreak forecasts, and market predictions help farmers plan better [4]. This reduces uncertainties related to rainfall failure, sudden pest attacks, or price crashes, factors that often expose small farmers to financial stress [6].

Better Market Access: AI-enabled grading systems can classify produce such as oranges or cotton by size and quality [3]. This helps farmers sell at premium prices and reduces exploitation by middlemen. Digital marketing platforms also connect smallholders directly to buyers, improving their profit margins [1].

4. What the Government Can Do?

Strengthen Digital and Rural Connectivity: Government-led expansion of 4G/5G networks in rural Vidarbha is essential. Reliable connectivity ensures that farmers can access AI tools, weather advisories, and market platforms without disruption, even in remote villages [6].

Subsidize Low-Cost Sensors and Drones: To make AI affordable, the government can offer subsidies for soil moisture sensors, weather units, and agricultural drones [5]. These devices, when owned or operated by Farmer Producer Organizations (FPOs), become accessible to clusters of small farmers at a low per-acre cost [2].

Establish Village-Level AI Service Centers: Government-funded AI resource centres can provide services like drone spraying, soil analysis, and disease diagnosis [3]. By centralizing such services, farmers need not invest individually, making advanced technology accessible to even the smallest landholders [1].

Promote AI Integration with Crop Insurance: AI-based satellite yield estimation can speed up insurance claim settlements by providing objective proof of crop loss [4]. Faster claim processing increases trust in insurance schemes and provides timely relief to farmers [1].

Develop AI-Enabled Pest Surveillance Networks: Installing digital pheromone traps across Vidarbha and linking them to district-level AI dashboards can help predict pest outbreaks earlier [4]. This region-wide surveillance is especially critical for cotton farmers vulnerable to bollworm infestations [6].

Local-Language AI Apps: Government can fund development of Marathi-based, voice-enabled AI apps that help farmers with disease diagnosis, fertilizer planning, and weather warnings [9]. This ensures inclusivity for farmers who may not be comfortable with English interfaces [8].

Mandatory AI Training through KVKs: Krishi Vigyan Kendras (KVKs) should incorporate AI modules into their regular training programs [2]. This includes hands-on demonstrations of mobile apps, sensors, and drones, making technology adoption easier and faster [1].

5. What Agricultural Universities Can Do?

Develop Crop-Specific AI Models: Agricultural universities can create AI models tailored specifically for Vidarbha's climate, soil, and crop varieties, which improve the accuracy of recommendations for small farmers [2].

Create Regional AI Datasets: Universities can build extensive datasets of crop diseases, pest images, soil parameters, and yield patterns [3]. By making this data available to researchers and startups, they accelerate the development of localized AI tools [7].

Establish Drone Training Schools: Training rural youth in drone operation and data interpretation can create new livelihood opportunities [5]. These trained operators can offer drone services to local farmers through FPOs, enabling community-based technology access [6].

Launch Diploma Courses in AI and Agri-Tech: Short-term diploma programs or certificate courses can equip students and farmers with practical skills in AI-based farming [2]. This builds technical capability within the region itself [3].

On-Farm AI Experimentation Plots: Universities can set up demonstration plots that showcase AI-driven irrigation, disease monitoring, and drone spraying, helping farmers to see real-world benefits [4].

Research on Low-Cost AI Solutions: Universities can design low-cost sensors, offline-capable AI apps, and frugal-tech drone attachments suitable for small and fragmented farms [5]. These innovations ensure affordability and practicality [7].

Collaboration with Government and Private Sector: By partnering with government agencies, startups, and FPOs, universities can bridge the gap between academic research and real-world adoption [6]. Joint demonstrations, village campaigns, and farmer workshops can accelerate technology dissemination [1].

Conclusion:

AI has the potential to revolutionize agriculture in Vidarbha by empowering small farmers with tools that improve productivity, reduce risks, and enhance profitability [4]. Whether through predicting pest outbreaks in cotton, optimizing sowing windows for soybean, managing irrigation for oranges, or improving water efficiency in rice, AI offers practical solutions to long-standing agricultural challenges [2].

For this transformation to be successful, coordinated efforts are needed. Government must provide infrastructure, subsidies, and training platforms, while agricultural universities must develop localized AI solutions and build human capital [3]. Together, these initiatives can create a resilient, sustainable, and technology-driven agricultural ecosystem that benefits every small farmer in Vidarbha [1].

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ADVANCES IN SEED PRIMING FOR ABIOTIC STRESS TOLERANCE IN SOYBEAN

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Abstract:

Seed priming has emerged as an effective and economical technique to enhance germination, seedling vigour, and abiotic stress tolerance in soybean (*Glycine max* L.). Advances in osmopriming, hormone priming, biopriming, and nanopriming have shown significant improvements in metabolic activation, membrane repair, antioxidant responses, and stress signalling pathways. These approaches enhance tolerance to drought, salinity, cold, and heavy metal stress by improving osmotic balance, ionic homeostasis, ROS regulation, and nutrient uptake. With increasing climatic variability, priming represents a sustainable, climate-smart approach for improving soybean establishment and productivity. However, optimization across genotypes and environment-specific protocols remains necessary for large-scale adoption.

1. Introduction:

Soybean (*Glycine max* L.) is a major annual legume crop belonging to the family Leguminosae and is believed to have originated in East Asia. Globally recognized as the "Wonder Crop" and the "Gold of the Century," soybean is valued for its rich nutritional composition, containing approximately 40% protein, 30% carbohydrates, 20% oil, 9% water, and 5% ash (Anonymous, 2005). Soybean cultivation expanded to India around the 10th century AD through China, and currently, India ranks fifth in global production after the USA, Brazil, Argentina, and China (FAO, 2023). Despite covering nearly 10% of the global acreage, India contributes only 4% to world soybean production, with a productivity level of 1.1 t/ha far below the global average of 2.2 t/ha (FAO, 2022). Major soybean-producing states include Madhya Pradesh, Maharashtra, and Rajasthan (ICAR-IISR, 2021; SOPA, 2023).

Productivity constraints in soybean are largely attributed to abiotic stresses, particularly drought, which can cause yield reductions of up to 40% (Fahad *et al.,* 2017). Drought often induces osmotic stress, inhibiting seed germination and early seedling establishment (Pei *et al.,* 2010;

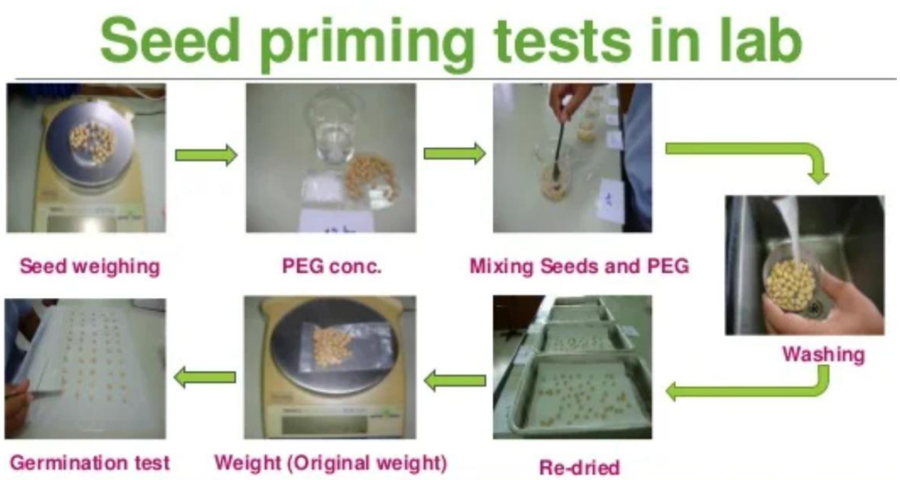
Jisha *et al.,* 2013). Plants combat such stress by accumulating osmolytes and activating enzymatic and non-enzymatic antioxidant defense systems (Das and Roychoudhury, 2014).

Seed germination and establishment are critical for yield stability, especially under low-moisture environments. Seed priming**,** a controlled hydration technique, has emerged as an effective, low-cost strategy to enhance germination rate, uniformity, and stress tolerance (Singh, 2015). While advanced tools such as molecular breeding, genome editing, and transgenic approaches offer precision drought resilience, they are expensive, time-consuming, and limited in field adoption. In contrast, seed priming is simple, scalable, and sustainable (Lal, 2018). Various priming methods including hydro-priming, osmo-priming, chemical, hormonal, biological, have been shown to improve soybean germination and drought resilience (Li and Liu, 2016; Waqas *et al.,* 2019). Studies further confirm that primed soybean seeds show faster emergence and improved yield under stress conditions (Arif *et al.,* 2008). Recent advancements highlight chemical priming as a promising approach in enhancing abiotic stress resilience (Savvides *et al.,* 2016).

2. Historical perspective and definitions

Seed priming has evolved from a traditional, experience-based practice to a scientifically established pre-sowing technology. Historically, evidence suggests that ancient civilizations, including those in Mesopotamia, China, and Egypt, soaked seeds in water before sowing to improve germination and field establishment, even though the scientific principles behind the practice were not understood at the time (Heydecker & Coolbear, 1977).

The modern scientific framework of seed priming emerged during the 1970s. Heydecker and colleagues introduced the term and standardized the process by defining controlled hydration techniques that activate the early stages of germination without allowing radicle protrusion (Heydecker *et al.,* 1973). This concept laid the foundation for the development of various scientifically validated priming methods.

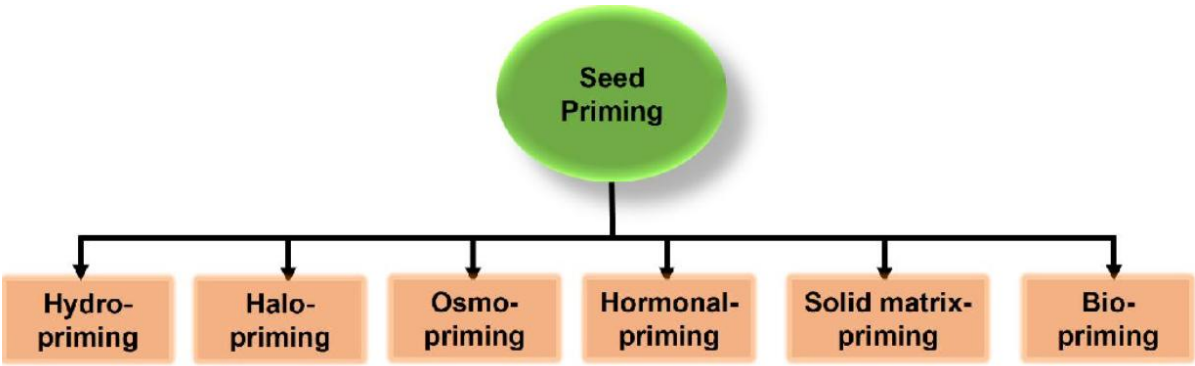


Seed priming is now broadly defined as a pre-sowing technique involving partial hydration of seeds to a point where key metabolic activities such as membrane repair, enzyme activation, hormonal modulation, and antioxidant accumulation are initiated, yet germination does not proceed to completion. Following priming, seeds may be dried back to their initial moisture level for storage or direct sowing (Varier *et al.,* 2010).

In soybean (*Glycine max* L.), seed priming has gained increasing significance due to its proven ability to enhance germination speed, seedling vigor, and field emergence, particularly under environmental stress conditions. Early findings by Ghassemi-Golezani *et al.,* (2011) showed that primed soybean seeds performed better in semi-arid regions with higher emergence and improved yield stability. Subsequent research confirmed that methods such as hydropriming, osmopriming, halopriming, and biopriming improve metabolic readiness and tolerance to drought, salinity, and temperature extremes (Kuzjur & Lal, 2015; Farooq *et al.,* 2019).

Advancements in recent years have expanded priming research toward microbial and nano-enabled priming, which enhance early growth, stress resilience, nutrient uptake efficiency, and nodulation in soybean (Prasad *et al.,* 2020; Rajput *et al.,* 2021). Thus, seed priming has progressed from ancient water-soaking practices to a low-cost, scalable, and climate-smart technology, especially valuable for soybean production in stress-prone environments.

3. Types of seed priming used in soybean



3.1 Hydropriming

Hydropriming is a pre-sowing seed treatment in which soybean seeds are soaked in clean or distilled water under controlled conditions and later dried back to their original moisture level before sowing. This controlled hydration activates initial metabolic processes such as membrane repair, enzyme activation, and hormonal regulation without permitting radicle emergence, improving germination readiness (Kujur & Lal, 2015). Typically, soybean seeds are hydroprimed for 6–12 hours at 20–25°C, followed by shade drying to 10–12% moisture.

Advancements in Soybean:

Hydropriming has demonstrated enhanced germination speed, uniform emergence, seedling vigour, and membrane stability, particularly under water-limited or saline environments (Miladinov *et al.,* 2015). Field studies reported improved nodulation, biomass accumulation, and final yield in both irrigated and rainfed soybean systems (Chavan *et al.,* 2014; Shete *et al.,* 2018). Recent advancements include nutrient- and microbe-assisted hydropriming, which further improve photosynthetic efficiency, seed vigor, and stress tolerance, making the technique a scalable and climate-resilient strategy for sustainable soybean production (Tamindžić *et al.,* 2024).

3.2 Osmopriming

Osmopriming is a pre-sowing seed enhancement technique in which soybean seeds are partially hydrated using controlled osmotic solutions such as PEG-6000, KNO_3, KH_2PO_4, or NaCl. The osmotic agent regulates water absorption, preventing imbibition injury while initiating early metabolic processes including enzyme activation, membrane repair, and osmotic adjustment without allowing radicle emergence (Kujur & Lal, 2015; Miladinov *et al.,* 2015). After treatment, seeds are dried back to their original moisture content for storage or sowing.

Osmopriming has shown significant improvement in germination rate, vigour, and early seedling growth in soybean, especially under drought and salinity stress (Kujur & Lal, 2015). Field studies reported improved nodulation, seedling establishment, and yield under rainfed and saline conditions (Chavan *et al.,* 2014; Shete *et al.,* 2018). Recent innovations, such as micronutrient- and microbe-assisted osmopriming, further enhance photosynthetic efficiency and stress tolerance, making it a climate-smart strategy for resilient soybean production (Tamindžić *et al.,* 2024).

3.3 Halopriming

Halopriming is a controlled pre-sowing seed treatment where soybean seeds are soaked in dilute salt solutions such as NaCl, $CaCl_2$, or KCl to induce partial hydration and activate early metabolic events without allowing radicle protrusion. The salt solution regulates water uptake while triggering osmotic adjustment, ion balance, and stress-responsive pathways, thereby preparing the seed for rapid and uniform germination under stress conditions (Farooq *et al.,* 2019). After treatment, seeds are dried back to their original moisture level for storage or sowing.

Advancements in Soybean:

Halopriming has been shown to improve germination speed, membrane stability, seedling vigour, and salt tolerance in soybean by enhancing antioxidant activity and ion homeostasis (Miladinov *et al.,* 2015). Field evaluations also reported better establishment, early vigor, and yield under saline and drought-affected environments (Shete *et al.,* 2018). Recent advancements demonstrate that combining halopriming with micronutrients or beneficial microbial inoculants further enhances photosynthetic efficiency, root development, and stress resilience, making halopriming a promising strategy for climate-smart soybean production (Tamindžić *et al.,* 2024).

3.4 Hormopriming

Hormopriming is a seed-priming method in which soybean seeds are treated with low concentrations of plant growth regulators such as gibberellic acid (GA_3), salicylic acid (SA), indole-3-acetic acid (IAA), indole-3-butyric acid (IBA), abscisic acid (ABA), brassinosteroids, or cytokinins before sowing. This controlled hydration activates key physiological and biochemical pathways involved in enzyme synthesis, cellular signaling, and reserve mobilization without allowing radicle emergence. The process improves germination speed, metabolic readiness, and seedling vigor by regulating hormonal balance and early developmental processes.

Advances in Soybean Hormopriming

Recent research shows that hormopriming significantly improves soybean germination, vigor index, and biomass compared to non-primed seeds (Khanal, 2024). Studies by Miladinov *et al.,* (2015) and Tamindžić *et al.,* (2024) revealed that GA_3- and SA-primed seeds enhance antioxidant defense systems (SOD, CAT, APX), maintain membrane stability, and improve tolerance to drought and salinity. Advanced approaches involving combined hormopriming with osmopriming or biopriming show synergistic improvement in nutrient uptake, stress resilience, and field performance, making it an emerging strategy for climate-smart soybean cultivation.

3.5 Biopriming

Biopriming is a biological seed enhancement technique in which soybean seeds are treated with beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), *Trichoderma spp., Bacillus spp.,* Rhizobium, or mycorrhizal fungi during controlled hydration. The process promotes early microbial colonization on the seed surface and activates metabolic and defense pathways without permitting radicle emergence. Biopriming enhances nutrient uptake, phytohormone regulation, and enzymatic activity, resulting in faster germination, improved root architecture, and stronger early establishment.

Advances in Soybean Biopriming

Recent advancements show that biopriming significantly improves seed vigor, seedling growth, and field emergence by enhancing nitrogen fixation and stress tolerance (Miladinov *et al.,* 2015). Studies by Shete *et al.,* (2018) and Tamindžić *et al.,* (2024) reported that soybean seeds primed with PGPR or Trichoderma exhibited higher antioxidant activity, better membrane integrity, and improved tolerance to salinity and drought. Modern approaches combining biopriming with osmopriming or micronutrient priming have demonstrated synergistic effects on nodulation efficiency, chlorophyll content, and yield, making biopriming a promising eco-friendly strategy for sustainable and climate-resilient soybean production.

3.6 Nanopriming

Nanopriming is an advanced seed-priming approach in which soybean seeds are treated with nanoparticles such as zinc oxide (ZnO), silver (Ag), silicon dioxide (SiO_2), iron oxide (Fe_2O_3), or carbon-based nanomaterials during controlled hydration. These nanoparticles penetrate seed tissues at nanoscale, enhancing water uptake, enzymatic activation, and cellular metabolism without allowing visible radicle emergence. Nanopriming also stimulates hormonal signaling, antioxidant defense, and nutrient mobilization, resulting in improved germination rate, uniformity, and early seedling vigor.

Advances in Soybean Nanopriming

Recent studies indicate that nanopriming improves germination speed, vigor index, and root–shoot growth compared to traditional priming methods (Miladinov *et al.,* 2015). Khanal (2024) and Tamindžić *et al.,* (2024) reported that ZnO- and SiO_2-nanoprimed soybean seeds showed enhanced antioxidant activity, better osmotic adjustment, and improved tolerance to drought and salinity stress. Emerging research shows that combining nanopriming with biopriming or osmopriming results in synergistic benefits including improved nutrient uptake, chlorophyll content, and yield potential. These advancements highlight nanopriming as a novel, efficient, and future-ready technology for sustainable and climate-resilient soybean production.

4. Physiological and biochemical mechanisms

Seed priming initiates a suite of processes that contribute to faster and more uniform germination:

4.1 Repair of DNA and Membranes

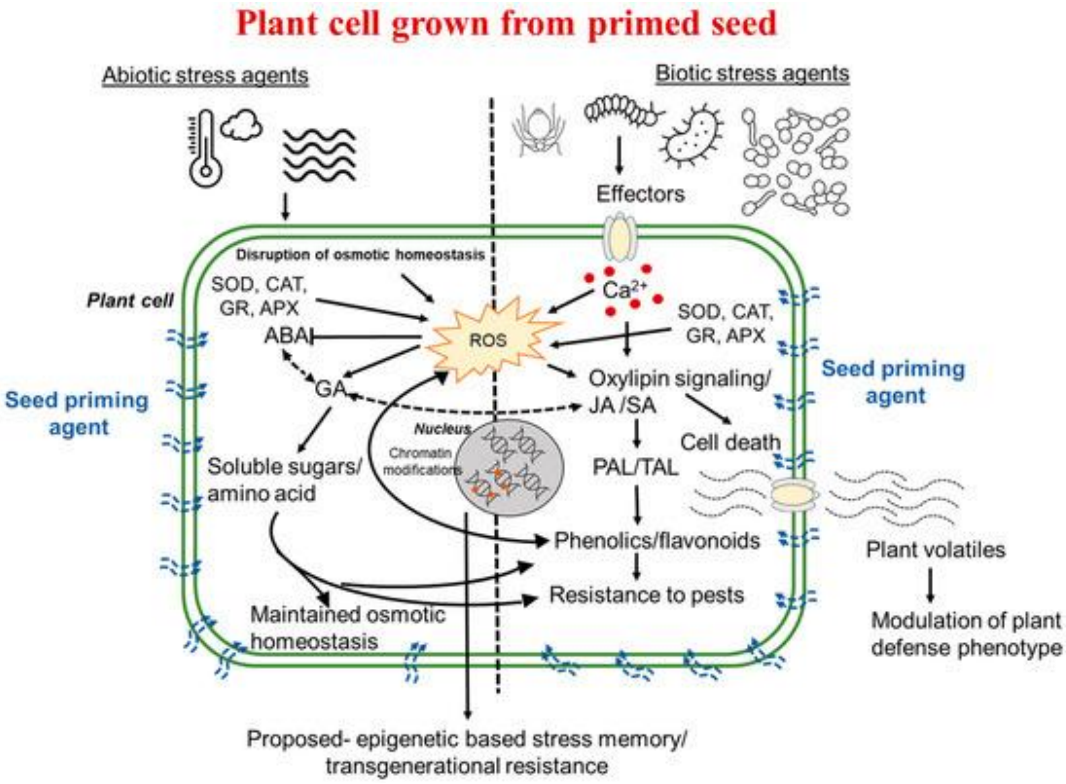
During priming, partial hydration activates DNA repair enzymes and membrane restructuring, correcting storage-induced deterioration and improving cell stability. This "pre-germinative metabolism" enhances seed vigour and viability (Varier *et al.,* 2010; Paparella *et al.,* 2015; Macovei *et al.,* 2022).

4.2 Mobilization of Stored Reserves

Seed priming enhances activation of hydrolytic enzymes including α-amylase, proteases, and lipases, enabling rapid breakdown and utilization of starch, protein, and lipid reserves during germination. This improves energy release and promotes faster radicle emergence (Farooq *et al.,* 2006; Ashraf & Foolad, 2005).

4.3 Enhanced Antioxidant Capacity

Priming increases activities of antioxidant enzymes such as SOD, CAT, POD, and APX, reducing ROS-induced oxidative damage and lipid peroxidation during imbibition. This antioxidant strengthening improves seed survival and uniform emergence (Jisha *et al.,* 2013; Kubala *et al.,* 2015).



4.4 ROS Signalling Optimization

Priming modulates ROS accumulation, maintaining controlled levels where ROS act as signalling molecules rather than causing cellular damage. This controlled oxidative burst regulates germination, hormonal pathways, and radicle protrusion (Bailly, 2004; El-Mahrouk *et al.,* 2019; Gupta *et al.,* 2022).

4.5 Hormonal Balance Shift

Seed priming alters endogenous hormonal regulation, decreasing ABA concentration or sensitivity while enhancing GA activity, which improves germination speed and seedling uniformity. Hormonal recalibration supports radicle emergence and metabolic activation (Song *et al.,* 2018; Lutts *et al.,* 2016; Paparella *et al.,* 2015).

4.6 Membrane and Metabolic Reconditioning

Priming improves membrane fluidity, mitochondrial activity, ATP synthesis, respiratory metabolism, and enzyme activation before radicle emergence. These metabolic changes accelerate germination and promote vigorous seedling growth (Bewley *et al.,* 2013; Paparella *et al.,* 2015; Farooq *et al.,* 2019).

5. Effects on germination, seedling vigour and stand establishment

Primed soybean seeds typically show:

- Higher and faster germination percentage
- Reduced mean germination time (MGT)
- Greater seedling vigour index
- Improved root and shoot growth at early stages
- More uniform stand establishment under suboptimal temperatures, salinity, and moisture stress
- Specific outcomes are dependent on genotype, seed lot quality, priming agent, and protocol.

6. Role of Seed Priming in Stress Tolerance in Soybean

6.1 Drought and Osmotic Stress

In soybean, major advances in drought resilience through seed priming include osmopriming using PEG and osmoprotectants such as glycine betaine or proline, which improve osmotic adjustment, enhance root growth and stimulate antioxidant enzymes like SOD, CAT and APX (Farooq *et al.,* 2019; Jaybhaye *et al.,* 2024). Recent transcriptomic studies show that PEG-primed seeds develop a temporary "stress memory," allowing faster activation of defence pathways during later drought exposure (Saha *et al.,* 2022). Hormone-based priming, including GA_3 and SA, has also been reported to enhance germination speed, water uptake efficiency and early vigour under drought in soybean (Lei *et al.,* 2021).

6.2 Salinity Stress

Advances in salinity tolerance via seed priming in soybean demonstrate success using halopriming with KCl, $CaCl_2$ or NaCl, which improves ionic homeostasis by maintaining a favourable K^+/Na^+ ratio and reducing membrane electrolyte leakage (Biswas, 2023; Hmissi *et al.,* 2023). Priming with silicon or antioxidants such as ascorbate and glutathione further enhances salt tolerance by protecting membrane lipids and increasing antioxidant enzyme activity (Khan *et al.,* 2022). Recent controlled-environment trials reveal that Ca^{2+}-based halopriming often provides stronger cellular protection and ion selectivity than NaCl alone, improving seedling vigour and chlorophyll stability under saline conditions (Singh *et al.,* 2024).

6.3 Cold Stress

Cold priming has emerged as an effective strategy for improving soybean germination under low temperatures by enhancing metabolic reactivation and reducing imbibitional chilling injury (Suo *et al.,* 2022). Primed seeds show increased activity of hydrolytic and antioxidant enzymes, improved membrane stability and faster radicle emergence in cold soil (Li *et al.,* 2025). Metabolomic analyses reveal enhanced accumulation of osmoprotectants, TCA cycle intermediates and stress-responsive proteins in cold-primed soybean, which support better germination uniformity and early seedling establishment under early-season planting conditions (Guo & Zhang, 2024).

6.4 Heavy Metals and Oxidative Stress

Recent progress using seed priming to mitigate heavy-metal toxicity in soybean highlights biopriming with beneficial microbes such as Bacillus and Bradyrhizobium, which reduce metal uptake and improve antioxidant responses (Amir *et al.,* 2024). Antioxidant priming using ascorbate or glutathione minimizes oxidative injury by enhancing ROS-scavenging capacity (Vyas *et al.,* 2024). Nanopriming using low-dose ZnO or TiO_2 nanoparticles has shown further promise by improving membrane stability, photosynthetic activity and metal sequestration in roots, though safety and environmental assessments remain ongoing (Jia *et al.,* 2025).

7. Factors influencing priming efficacy

- Seed lot quality and viability
- Genotype (cultivar-specific responses)
- Priming agent type and concentration
- Duration and temperature of priming
- Drying rate and final moisture content
- Storage time after priming (some benefits decline over time)

8. Limitations, risks and knowledge gaps

- **Seed storage after priming**: Some primed seeds may lose benefits over extended storage; stability protocols require optimization.
- **Pathogen proliferation**: Prolonged wet treatments can promote fungal/bacterial growth unless controlled.
- **Nanoparticle safety and environmental fate**: Long-term ecological and food-safety studies are limited.
- **Genotype specificity**: Not all cultivars respond similarly; breeding for priming-responsiveness is underexplored.
- **Lack of standardized protocols**: Wide variability in methods across studies makes cross-comparison difficult.

9. Integration with modern technologies

- **Molecular markers**: Identifying markers for priming responsiveness could enable breeding programs.

- **Seed coatings and controlled-release systems**: Combine priming benefits with protection and nutrition delivery.
- **Precision agriculture**: Use seed priming as one component in integrated stress management (paired with soil moisture sensors, sowing date optimization).
- **High-throughput phenotyping**: To screen genotype × priming interactions rapidly.

Conclusions:

Seed priming is a versatile, cost-effective approach to improve soybean establishment and stress resilience. Advances in priming agents, mechanistic insights, and integration with microbial and nanotechnologies have expanded its potential. However, careful optimization, safety evaluation, and genotype-specific testing are essential for reliable field outcomes.

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PRECISION AND DIGITAL AGRICULTURE: TECHNOLOGIES FOR SMART AND SUSTAINABLE FARMING

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Abstract:

Agriculture is undergoing a major transformation driven by technological innovation, data analytics and automation. Precision Agriculture and Digital Agriculture together form the foundation of modern smart farming systems aimed at improving productivity, sustainability and resource-use efficiency. Precision agriculture focuses on managing spatial and temporal variability within fields through site-specific input application, supported by tools such as GPS, GIS, remote sensing, Variable Rate Technology (VRT) and advanced sensors. Digital agriculture expands this framework by integrating big data, IoT-based monitoring, drones, cloud computing, robotics and artificial intelligence across the entire agricultural value chain. These technologies enable real-time data collection, predictive analytics, automated decision-making and transparent supply chains. Applications include soil mapping, moisture-based irrigation, pest and disease detection, livestock monitoring, automated farm machinery and blockchain-enabled traceability. The benefits of these systems include reduced input costs, higher yields, improved environmental sustainability and enhanced farm profitability. However, challenges remain, especially in developing countries, where small landholdings, high technology costs, limited technical expertise and inadequate data availability hinder large-scale adoption. Despite these limitations, future prospects are promising, with emerging innovations such as autonomous farms, digital twins, 5G-enabled sensor networks and climate-smart agriculture. Overall, precision and digital agriculture offer scalable solutions for achieving sustainable food production, efficient resource management and resilience in the face of climate change.

Keywords: Digital Agriculture, Variable Rate Technology (VRT), Remote Sensing, Smart Farming, Artificial Intelligence, Robotics, Site-Specific Management, Climate-Smart Agriculture.

Introduction:

Agriculture is entering a new era driven by data, automation and advanced technologies. Rising population, decreasing arable land, climate change, water scarcity, and the need for environmentally responsible farming have created urgent pressure to move beyond traditional methods. The 21st century demands farming systems that are more precise, productive, profitable, sustainable, and resource-efficient.

Precision Agriculture and Digital Agriculture represent two interconnected revolutions that are transforming global farming practices. Precision agriculture focuses on site-specific management, ensuring that the right input is applied at the right place, in the right amount, and at the right time. Digital agriculture expands this concept by integrating data-driven tools, smart devices, automation, big data analytics, remote sensing, drones, IoT, AI, robotics, and cloud platforms across the entire agricultural value chain. Together, they help farmers make informed decisions, reduce wastage, increase productivity, and minimize environmental degradation. As nations strive toward climate-smart, sustainable farming systems, precision and digital agriculture provide the technological backbone required for future food security.

In the past years, it was assumed that the fields for crop production were more or less uniform. The application of uniform levels of fertilizer over the field resulted in non-optimal fertilizer levels over the entire field. An overdose of inputs only meant an extra cost without any additional profit while degrading the quality of soil as well as surface waters. Even in the orchards, the condition of trees was very different from place to place which resulted in uneven fruit quality at harvest time. These problems have been realized over many years but the technical tools available to the growers are unable to cope with the heterogeneity in the growing conditions.

Precision farming is a technique that combines information and communication technology in the management of a farm system. It acts as an approach where inputs are being utilised in precise amounts to augment the average yield when compared to traditional cultivation practices.

According to the National Research Council, 1997, precision farming is the application of modern information technologies to provide, process and analyse multisource data of high spatial and temporal resolution for decision making and operations in the management of crop production.

This technique is being utilised to identify, analyse and manage variability arising in the fields while optimising profitability, sustainability and protecting land resources. One of the fundamental components of adopting precision farming is its ability to measure the spatial variation in the soil system and assess the influence on crop variability for the application of appropriate management strategies.

Precision farming, also known as precision agriculture, satellite farming or site-specific crop management (SSCM) is basically a farm management concept based on observation and measurement, and responding to inter and intra field variations in crops.

Steps in Precision Farming

Precision farming is concerned with the differences in crop or soil qualities that occur within a field, and these variations are frequently observed and mapped. Assessing, managing, and evaluating variability are the basic steps that contribute to the concept of precision farming, and they are described as:

Assessing Variability

Assessing variability is the first crucial step in precision farming as it is obvious that one cannot control what one does not understand. Crop performance and yield are influenced by a variety of processes and properties that vary over time and space. There are techniques for analysing temporal variation, however reporting both spatial and temporal variation at the same time is uncommon, and the theory of these types of operations is still in its infancy. Surveying, interpolation of point samples, use of high-resolution aerial and satellite data, and modelling to determine spatial patterns can all be used to map the spatial variability in the field. Precision agriculture's future and success will be determined by the decreased cost and ease of quantifying variability with high-resolution sensors.

Managing Variability

Farmers must adapt agronomic inputs to known conditions utilising site-specific management suggestions and accurate control equipment once variance has been adequately measured. Precision farming's effectiveness is determined by how accurately soil fertility, pest infestation, and crop management are managed in relation to biotic and abiotic variables as well as the precision with which remedial actions are implemented in light of the observed variability in the field. Since all areas of a field are not similarly infested with pests, the variability of weed, insect, and disease infestation can be observed and mapped, and remedial measures can be adopted to the differences discovered in different portions of a field. Similarly, water availability in the field can be monitored, and variable rate irrigation can be used to apply irrigation.

Evaluation of Precision Farming

Economic viability, environmental preservation, and feasibility of precision agriculture's technology transfer are three significant evaluating criteria. The economic assessment focuses on whether the documented agronomic benefits are translated into something worth through market

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mechanisms. Precision farming is being studied during environment evaluations to see if it may improve the soil, water, and overall ecological sustainability of our agricultural systems. The final and most crucial question is whether this site-specific farming technology will function on individual farms and how far it can be extended to other farmers.

Evolution of Precision and Digital Agriculture

Early Developments

The roots of precision agriculture can be traced to the 1980s when the United States introduced the first Global Positioning System (GPS) for civilian use. Farmers realized that GPS could be used to map fields and track machinery movement. In the 1990s, yield monitors on combine harvesters became common, giving farmers their first insights into intra-field variability.

Technological Expansion (2000–2010)

The early 2000s saw rapid growth in:

- Remote sensing
- GIS-based mapping
- Variable Rate Technology (VRT) for fertilizer, seed, and pesticide application
- Auto-steering tractors

Digital Agriculture Era (2010 Onwards)

From 2010 onwards, the agricultural sector witnessed explosive integration:

- Cloud computing
- Mobile-based advisory systems
- AI and machine learning
- Drone-based crop monitoring
- IoT-based automated irrigation
- Robotics and automation
- Blockchain for supply chain management

This marked the transition to Digital Agriculture, enabling real-time decision-making, predictive analytics and integrated farm management systems.

Concept of Precision Agriculture

Precision agriculture (PA) is an advanced farming management system that utilizes information technology to ensure that crops and soil receive what they need for optimum health and productivity.

Definition

"Precision agriculture is the management of spatial and temporal variability to improve productivity, sustainability, and environmental protection."

Core Philosophy

- Every part of a field is unique.
- Inputs should be adjusted according to variability.
- Data-driven decisions lead to efficiency and sustainability.

Key Goals

1. Increase resource-use efficiency
2. Improve soil health
3. Reduce environmental pollution
4. Enhance crop yields
5. Reduce production costs
6. Support climate-resilient agriculture

Digital Agriculture: Concept and Scope

Digital agriculture goes beyond precision agriculture. It refers to the integration of digital tools, data ecosystems, and communication networks across the entire agricultural value chain.

Key Components

1. **Data Collection Technologies:** Sensors, drones, satellites, machinery logs
2. **Data Storage:** Cloud platforms and local servers
3. **Data Analytics:** AI, ML, predictive modelling
4. **Decision Support Systems:** Mobile-based advisory, dashboards
5. **Digital Marketplaces:** E-commerce systems for inputs and outputs
6. **Automation and Robotics:** Smart machinery and autonomous systems

Characteristics

- Real-time data flow
- Predictive analytics
- Automated decision-making
- Connected farms
- Traceable supply chains

Importance for Future Agriculture

- Helps adapt to climate change
- Improves input-use efficiency
- Enables transparency and safety in food chains
- Boosts farmer profitability

Major Technologies used in Precision and Digital Agriculture

The synergy of multiple technologies drives precision and digital agriculture. Below are key tools and their applications.

Global Positioning System (GPS) and GNSS

GPS and GNSS allow:

- Accurate field mapping
- Controlled traffic farming
- Auto-steering tractors
- Guidance systems for sprayers and seeders
- Creating prescription maps

Accuracy improves significantly when combined with RTK (Real-Time Kinematic) positioning, bringing precision within 2–3 cm.

Geographic Information Systems (GIS)

GIS integrates spatial information and helps create:

- Soil nutrient maps
- Yield maps
- Water flow and drainage maps
- Topographical maps
- Management zones

GIS is essential for VRT recommendations.

Remote Sensing

Remote sensing uses satellite and aerial imagery for:

- Disease and pest detection
- Monitoring crop stress
- Estimating biomass and canopy cover
- Yield prediction
- Mapping soil moisture

Internet of Things (IoT) in Agriculture

IoT enables real-time monitoring and automation through connected devices.

Soil Sensors

- Moisture
- pH
- Electrical conductivity (EC)
- Nitrogen sensors

Climate Sensors

- Temperature
- Humidity
- Rainfall
- Wind speed

Livestock Sensors

- Body temperature
- Movement tracking
- Health monitoring

Water and Irrigation Sensors

- Smart valves
- Flow meters
- Pressure sensors

Drone Technology

Drones provide:

- High-resolution field images
- Aerial spraying
- Crop height estimation
- Weed mapping
- Livestock surveillance

Advantages:

- Faster data collection
- Less labour requirement
- Access to difficult terrain

Artificial Intelligence (AI) and Machine Learning (ML)

AI helps transform data into actionable insights.

Applications:

- Disease and pest diagnosis from leaf images
- Predicting yield
- Detecting nutrient deficiencies
- Climate risk forecasting
- Recommending fertilizer and irrigation schedules
- Smart sorting and grading

Robotics and Automation

Robotics support repetitive and labour-intensive tasks.

Examples:

- Autonomous tractors
- Robotic harvesters
- Laser-guided weeders
- Drone sprayers
- Milking robots

Automation helps overcome labour shortages and improves accuracy.

Variable Rate Technology (VRT)

Types:

1. **Map-based VRT:** Uses prescription maps
2. **Sensor-based VRT:** Sensors detect real-time needs

Applications:

- Fertilizer application
- Seed rate adjustment
- Pesticide spraying
- Irrigation

Benefits: lower input use but higher productivity.

Farm Management Information Systems (FMIS)

FMIS combine:

- Crop planning
- Input inventories
- Machinery logs
- Financial management
- Field histories

Cloud-based apps allow farmers to make smart decisions anytime.

Blockchain in Agriculture

Blockchain ensures:

- Food traceability
- Tamper-proof records
- Transparency in supply chain
- Fair market transactions

Used for high-value crops like coffee, spices, fruits, and organic products.

Components of a Precision Agriculture System

1. Data Collection: Sensors, drones, satellites, machinery.

2. Data Storage: Cloud platforms, servers.

3. Data Processing: Statistical analysis, GIS, AI.

4. Decision Support Systems: Apps, dashboards, advisory tools.

5. Field Application: VRT applicators, autonomous equipment.

6. Monitoring and Feedback: Updates and continuous improvement.

APPLICATIONS

Soil Management

- Soil mapping
- Variable rate lime and fertilizer application
- Moisture-based irrigation scheduling

Crop Management

- Optimized seed depth and spacing
- Automated weeding
- Disease detection via AI
- Drone-based field scouting

Water Management

- Smart drip irrigation
- Automated sprinkler systems
- Water stress monitoring via remote sensing

Livestock Management

- Wearable technology for health tracking
- Automated feeding systems
- Robotic milking
- Behavior monitoring

Machinery and Resource Management

- Fuel efficiency optimization
- Automated machinery diagnostics
- Controlled traffic farming

Supply Chain Management

- Sorting and grading automation
- Cold chain temperature logging
- Blockchain-based product traceability

Benefits of Precision and Digital Agriculture

Economic Benefits

- Higher yield
- Reduced fertilizer and pesticide cost
- Improved labour efficiency
- Better market access

Environmental Benefits

- Reduced chemical runoff
- Sustainable soil health
- Less groundwater depletion

Resource Conservation

- Saves water, seeds, fertilizers
- Reduces wastage

Social Benefits

- Better livelihood opportunities
- Less drudgery
- Improved farm safety

Limitations of precision farming

The following are some of the constraints that different scientists have highlighted as limiting the possibilities for site-specific farming in India:

- Small size of land holdings.
- Socio-economic status of Indian farmers.
- Lack of success stories or cost-benefit analysis done on precision farming.
- Gaps in knowledge and technology
- Cropping system heterogeneity in India.
- Lack of market perfection.
- Paucity of technical expertise in the area.
- Data is scarce, both in terms of quality and cost.

Out of the following, small size of operational land holding and the cost of precision farming systems are two main issues for implementing precision agriculture in our nation. In India, around 57.8% of operational holdings are smaller than 1 hectare. With this field size and farming being primarily subsistent, adopting precision farming techniques at the individual field level is a challenging task.

However, the field (rather simulated field) sizes are big when we examine contiguous fields with the same crop (usually under similar management approaches). For the purposes of implementation of precision farming, these contiguous fields can be treated as a single field, and many profitable horticultural crops in India provide ample opportunities for precision farming.

Future Prospects

- **AI-Enabled Autonomous Farms:** Fully automated farms capable of independent operations.
- **Digital Twins:** Virtual farm replicas for scenario testing.
- **5G-Driven Smart Farms:** Ultra-fast communication enabling millions of sensors.
- **Climate-Smart Agriculture:** Technologies to reduce climate vulnerability.
- **Quantum Computing:** For complex agricultural optimization.
- **Expansion of Agritech Startups:** Increasing access to affordable technologies.

Conclusion:

Precision farming is still a mere concept in many developing nations, and the public and private sector's strategic support is needed to promote its rapid implementation**.** However, there are at least three phases for successful adoption: exploration, analysis, and implementation.

Precision agriculture has the potential to alleviate both the economic and environmental challenges that surround modern agriculture today. Questions regarding cost-effectiveness and the most effective methods to use the technological tools we currently have remain unanswered, but the concept of "doing the right thing at the right place and time" has a strong intuitive appeal. In light of today's demanding need, concerted measures should be taken to use new technological inputs to turn the "Green Revolution " into "Evergreen Revolution ".

In the end, precision agriculture's success is primarily determined by how well and swiftly the information required to guide new technologies can be acquired. Precision farming offers a novel system-based answer to today's agricultural challenges, such as balancing productivity with environmental concerns. Precision farming is based on advanced information technology. It entails characterising and modelling variation in soil and plant species, as well as combining agricultural practices to satisfy site-specific needs. It aims to maximise economic returns while also lowering the agricultural energy input and impact on the environment.

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BALANCING CROP YIELD AND ENVIRONMENTAL HEALTH THROUGH INTEGRATED PEST MANAGEMENT

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Abstract:

Integrated Pest Management (IPM) is an approach that combines different methods to manage pests in a practical and safe way. According to several studies, IPM aims to keep pest levels below the point where they cause serious crop loss while reducing heavy dependence on chemical pesticides. Early concepts of IPM began with "supervised control," where decisions were based on regular field monitoring rather than routine spraying and later expanded to include cultural, biological, genetic, physical and selective chemical methods. Several reports show that pests destroy more than 40% of potential food production each year, making pest management essential for global food security. The reviewed materials explain that IPM supports good crop health by using practices such as crop rotation, sanitation, intercropping, resistant varieties and proper field observation. Biological control, which includes using predators, parasitoids and beneficial microorganisms is highlighted as one of the most effective parts of IPM and helps reduce pesticide use and resistance problems. Recent studies also discuss new tools that strengthen IPM, such as pheromone traps, improved monitoring systems, plant-based pesticides, nano-formulated chemicals. These advances help farmers identify pests early and take timely action. Although challenges remain such as lack of awareness, limited access to biological agents and the need for regular field scouting. IPM is consistently shown to reduce costs, protect useful insects, improve soil and water safety and support stable crop yields. Overall, the reviewed literature shows that IPM is a practical and farmer-friendly strategy that balances crop protection with environmental safety.

Keywords: Integrated Pest Management; Biological Control; Crop Protection; Sustainable Farming; Pest Monitoring.

1. Introduction:

Pests—including insects, diseases, nematodes and weeds remain one of the most serious threats to global agriculture, causing an estimated 20-40% annual loss in major crops (Oerke, 2006; Angon *et al*., 2023). For many years, farmers relied heavily on chemical pesticides to manage pests. Although pesticides offered quick and effective solutions, their excessive and repeated use led to several problems, including pest resistance, resurgence, environmental pollution, loss of biodiversity and health risks for farmers and consumers (Pimentel, 2009; Tiwari, 2024). These challenges highlighted the need for a safer, more balanced and long-term strategy for crop protection.

Integrated Pest Management (IPM) emerged in the mid-20th century as a response to these concerns. Early forms of IPM began with “supervised control,” which stressed field monitoring and economic thresholds instead of calendar-based spraying (Stern *et al*., 1959; Ehi-Eromosele *et al*., 2013). Over time, IPM evolved into a holistic approach that combines cultural, biological, mechanical, genetic and need-based chemical methods to maintain pest populations below damaging levels while minimizing risks to humans and the environment (FAO, 2012; Angon *et al*., 2023).

Biological control—using predators, parasitoids and microbial agents is now recognized as a cornerstone of IPM due to its long-term effectiveness and compatibility with ecological processes (Zhou *et al*., 2024; Tiwari, 2024). Cultural practices such as crop rotation, sanitation, resistant varieties, intercropping and proper irrigation also play essential preventive roles (Khan *et al*., 2014; Angon *et al*., 2023). When pesticides are needed, IPM encourages the use of selective, low-risk or biological products and discourages the indiscriminate use of broad-spectrum chemicals (Kogan, 1998; Ehi-Eromosele *et al*., 2013).

Modern IPM is further strengthened by new technologies such as pheromone traps, remote sensing, drones, precision agriculture, nano-formulated pesticides and artificial intelligence for detection and forecasting (Zhou *et al*., 2024; Sharma *et al*., 2022). These innovations help farmers make timely decisions and reduce unnecessary pesticide applications. Despite its proven benefits, the adoption of IPM remains uneven due to limited farmer awareness, insufficient training, lack of quality biological agents and weak policy support (Pretty *et al*., 2018; Angon *et al*., 2023). Expanding training, improving extension services and strengthening farmer–researcher partnerships are essential for the wider implementation of IPM.

Overall, IPM represents a practical, environmentally responsible and economically beneficial strategy for modern agriculture, offering a pathway to improved crop productivity while protecting ecosystem health.

2. Historical Development of IPM

Integrated Pest Management (IPM) evolved as a solution to the widespread problems caused by chemical-intensive farming. During the 1940s and 1950s, farmers increasingly adopted synthetic pesticides such as DDT because they provided quick pest control. However, repeated and indiscriminate use of these chemicals soon led to serious issues such as pest resistance, pest resurgence, loss of natural enemies and environmental contamination (Pimentel, 2009; Carson, 1962).

By the late 1950s, scientists realized that relying only on chemicals was not sustainable. This led to the concept of "supervised control," introduced by Stern *et al*. (1959), where control decisions were made based on regular field monitoring and economic thresholds instead of fixed spray schedules. This idea laid the foundation for modern IPM. During the 1970s and 1980s, IPM expanded into a broader framework combining cultural, biological, mechanical and chemical methods. Global organizations such as FAO and UNEP promoted IPM as an environmentally sound crop protection strategy (FAO, 2012). By the 1990s, IPM was adopted widely in Asia, Africa, Europe and the Americas and became an essential part of sustainable agriculture (Angon *et al*., 2023; Kogan, 1998).

Today, IPM is recognized as a dynamic, knowledge-based and eco-friendly approach that aims to balance pest control with environmental protection and economic viability.

3. Need for IPM in Modern Agriculture

Agriculture faces increasing pest pressure due to monocropping, climate change and the introduction of exotic pests. Globally, 20-40% of crop production is lost to pests each year (Oerke, 2006; Savary *et al*., 2019). Heavy dependence on pesticides has resulted in several issues.

A. Development of Pest Resistance

Many pests have developed resistance to multiple pesticides, making formerly effective chemicals useless. Resistant insects such as *Helicoverpa armigera* and whiteflies have become major threats in several crops (Tiwari, 2024; Wu & Guo, 2005).

B. Pest Resurgence

Broad-spectrum pesticides kill beneficial insects that naturally suppress pests. When natural enemies die, pest populations rebound quickly causing more damage (Angon *et al*., 2023; Georghiou, 1990).

C. Environmental Pollution

Chemical residues contaminate soil, water bodies and food commodities, harming wildlife, aquatic organisms and human health (Zhou *et al*., 2024; Aktar *et al*., 2009).

D. Decline in Biodiversity

Pollinators, predators, parasitoids and soil microbes are severely affected by continuous pesticide exposure (Potts *et al*., 2010; Sánchez-Bayo & Wyckhuys, 2019).

E. Human Health Risks

Farm workers and consumers may suffer from acute poisoning and long-term health effects due to pesticide exposure (Mostafalou & Abdollahi, 2017).

Given these issues, IPM provides a sustainable alternative that ensures pest control, crop productivity and long-term environmental health.

4. Principles of Integrated Pest Management

IPM is based on several core principles that guide decision-making and implementation strategies.

A. Accurate Pest Identification

Misidentifying pests leads to wrong control measures. Therefore, recognizing insects, diseases, weeds and beneficial organisms is the first essential step (Angon *et al*., 2023; Pedigo & Rice, 2021).

B. Regular Monitoring and Surveillance

IPM requires frequent field visits to observe pest populations, crop conditions and natural enemies. Tools such as pheromone traps, light traps, sticky traps and field scouting help track pest activity (Ehi-Eromosele *et al*., 2013; Kogan,1998).

C. Setting Economic Threshold Levels (ETLs)

Action should be taken only when pest numbers reach a level where economic loss is expected. This prevents unnecessary pesticide sprays and protects beneficial insects (Zhou *et al*., 2024; Pedigo *et al*., 1986).

D. Combining Multiple Tactics

IPM uses a combination of preventive and curative methods i.e cultural, biological, physical, genetic and chemical measures. This reduces dependence on synthetic pesticides (FAO, 2012; Kogan, 1998).

E. Preference for Eco-Friendly Tools

Selective pesticides, biopesticides and microbial formulations are prioritized. Chemicals are the last option, used with caution and only when required (Tiwari, 2024; Isman, 2006).

F. Evaluation and Adjustment

IPM is an ongoing process. Farmers evaluate results after implementation and adjust practices to improve future outcomes (Pedigo & Rice, 2021).

5. Pest Management Tactics

Effective pest management in Integrated Pest Management (IPM) relies on a combination of tactics that work together to keep pest populations below damaging levels. These tactics are chosen based on pest biology, crop stage, monitoring data and environmental considerations (Kogan, 1998; FAO, 2012).

1. Cultural Control

Cultural control involves modifying agricultural practices to reduce pest establishment, reproduction and survival.

Key practices include:

- **Crop rotation** to break pest life cycles.
- **Sanitation**, including removal of crop residues that harbor pests.
- **Adjusting sowing and harvesting dates** to avoid peak pest periods.
- **Use of resistant or tolerant varieties** (FAO, 2012).
- **Intercropping and mixed cropping** to reduce pest spread and habitat suitability.

Importance: Cultural methods serve as the foundation of IPM and are effective, economical and environmentally safe.

2. Mechanical and Physical Control

Mechanical/physical tactics suppress pests through direct physical means.

Common methods:

- **Handpicking** of visible pests.
- **Traps** such as pheromone traps, sticky traps and light traps for monitoring and control.
- **Barriers and nets** to exclude pests.
- **Tillage** to expose soil-dwelling insect stages (FAO, 2012).
- **Soil solarization** to manage soil pathogens and weed seeds.

3. Biological Control

Biological control utilizes living organisms to suppress pest populations. It is a central component of IPM globally.

Types of biological control:

- **Predators:** Ladybird beetles, lacewings, spiders (Snyder, 2019).
- **Parasitoids:** *Trichogramma* spp. for lepidopteran pests (van Lenteren, 2012).
- **Pathogens:** *Bacillus thuringiensis*, entomopathogenic fungi like *Beauveria bassiana*, NPV viruses (Sharma *et al*., 2011).
- **Conservation biological control:** Protecting habitats of natural enemies by reducing pesticide use (Gurr *et al*., 2017).
- **Augmentative release:** Laboratory-reared beneficial insects released in the field (van Lenteren, 2012).

Importance: It provides long-lasting, environmentally safe pest suppression and supports ecological balance (Angon *et al*., 2023).

4. Chemical Control

In IPM, chemical control is used **judiciously** only when pest populations exceed economic thresholds.

- Apply pesticides only after confirming pest levels through monitoring .
- Prefer **selective and low-toxicity chemicals**.
- Use **botanical pesticides** and **biopesticides** when possible.
- Rotate chemical classes to delay resistance development.
- Avoid broad-spectrum pesticides to protect natural enemies.

5. Genetic Control (Host Plant Resistance)

Genetic control relies on crop varieties that naturally resist insect pests, diseases or nematodes.

- **Antibiosis:** Plant traits adversely affect pests (Stout, 2013).
- **Antixenosis:** Plants deter pest colonization (Smith & Clement, 2012).
- **Tolerance:** Plants withstand damage better than susceptible varieties (Stout, 2013).

6. Behavioral Control (Semiochemicals)

Behavior-modifying chemicals influence pest behavior.

Techniques:

- **Pheromone traps** for monitoring and mass trapping (Witzgall et al., 2010).
- **Mating disruption** to prevent reproduction (Cardé & Minks, 1995).
- **Attract-and-kill systems** combining lures with toxicants (El-Sayed et al., 2006).

7. Regulatory Control

Regulatory tactics involve laws and government actions that prevent pest entry, spread and establishment.

Examples:

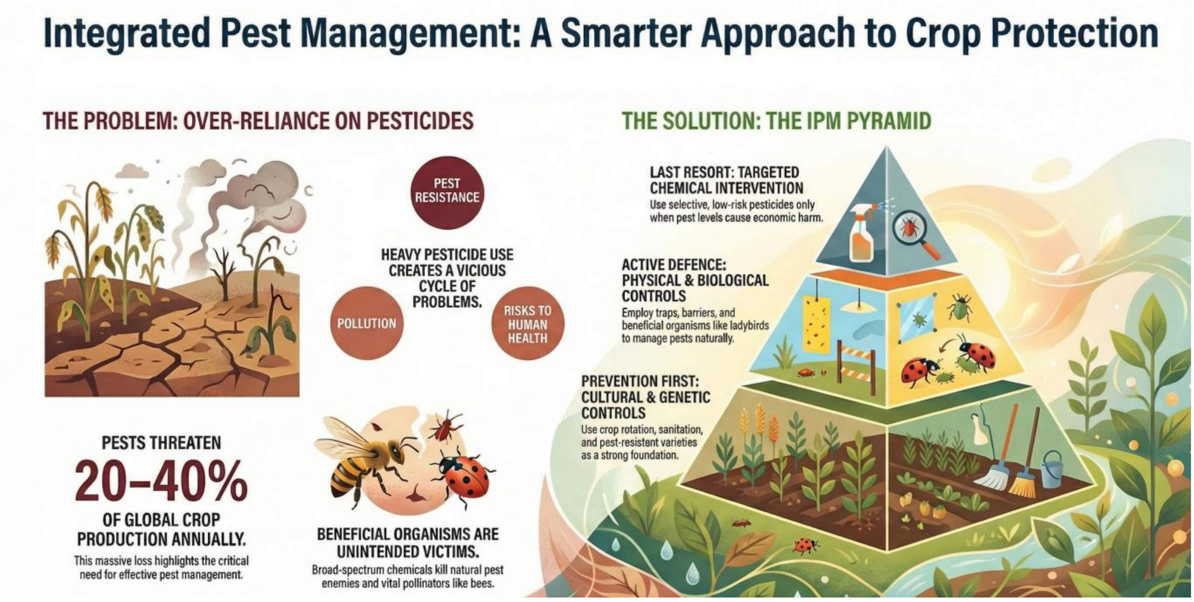
- **Quarantine regulations** to prevent introduction of invasive pests (FAO, 2012).
- **Inspection and certification** of planting materials (Kogan, 1998).
- **Area-wide pest management programs** for pests like fruit flies and bollworms (Klassen, 2005).

8. Integrated Use of Tactics

IPM emphasizes combining tactics in a compatible manner. The integration is based on:

- Pest biology
- Crop stage
- Monitoring data
- Environmental safety
- Economic thresholds

This holistic strategy reduces pesticide dependence, supports biodiversity and ensures long-term sustainability (Kogan, 1998; FAO, 2012).



6. Benefits of an IPM Programme

Integrated Pest Management (IPM) provides multiple ecological, economic and social advantages compared with conventional pest control. Because it uses a combination of tactics i.e monitoring, cultural practices, biological control, selective pesticides and resistant varieties which promotes long-term sustainability while ensuring effective pest suppression.

A. Reduction in Pesticide Use

IPM emphasizes non-chemical methods and uses pesticides only when needed and at economic thresholds. This significantly lowers the amount of pesticides applied in fields (Kogan, 1998; FAO, 2012).

Benefit: Reduced chemical burden on the environment and lower input costs.

B. Environmental Protection

Reduced pesticide applications lead to:

- Lower contamination of soil and water
- Less risk to wildlife, pollinators and natural enemies
- Better soil microbial activity (Zhou *et al.,* 2024; Aktar *et al.,* 2009)

C. Delayed Development of Pest Resistance

Because IPM encourages rotation of tactics and minimal chemical use, pests are less likely to develop resistance to pesticides (Georghiou, 1990).

D. Enhanced Biological Control

IPM protects natural enemies by reducing broad-spectrum pesticide use. This strengthens biological control and supports ecological balance (Gurr *et al.,* 2017).

E. Improved Crop Yield and Quality

Better pest management and reduced pest damage lead to higher yield and better market quality of produce (Angon *et al.,* 2023).

F. Safer Working Conditions and Food Safety

Lower pesticide exposure reduces health risks for farmers and consumers (Mostafalou & Abdollahi, 2017).

G. Economically Sustainable

Although initial adoption can require training, long-term costs reduce due to:

- Lower pesticide use
- Improved plant health
- Fewer outbreaks (Pedigo & Rice, 2021)

H. Climate and Ecosystem Resilience

IPM enhances resilience against climate-induced pest outbreaks through diversified strategies and ecosystem-based management (Pretty *et al.,* 2018).

7. Disadvantages of an IPM Programme

While IPM offers many benefits, it also has certain limitations—mostly related to knowledge, resources and implementation challenges.

A. Requires Technical Knowledge and Training

IPM demands accurate pest identification, monitoring and decision-making. Farmers often lack training and technical expertise (FAO, 2012).

Disadvantage: Harder to implement in remote or resource-poor areas.

B. Monitoring Is Time-Consuming

Regular field scouting, installing traps and record-keeping require time and labor (Pedigo & Rice, 2021).

Disadvantage: Increased workload for farmers.

C. Slower Results Compared with Chemicals

Biological and cultural methods may act slower than chemical pesticides, especially under severe pest outbreaks (Isman, 2006).

Disadvantage: Farmers may become impatient or rely back on chemicals.

D. Initial Costs and Resource Requirements

Some practices—like pheromone traps, resistant varieties, or biological agents—may have higher initial cost or limited availability (van Lenteren, 2012).

Disadvantage: Adoption may be difficult for small-scale farmers.

E. Limited Availability of Biological Agents

In many developing regions, high-quality biological control agents are not easily accessible (Gurr *et al.,* 2017).

Disadvantage: Makes implementation uneven across regions.

F. Requires Strong Coordination

IPM works best when applied area-wide, not by individual farmers alone (Klassen, 2005).

Disadvantage: Lack of community cooperation reduces effectiveness.

G. Unpredictability of Natural Enemies

Natural enemies may be affected by weather, pesticide drift, or habitat changes (Snyder, 2019).

Disadvantage: Biological control results can vary.

H. Government Support and Policy Gaps

Successful IPM requires supportive regulations, extension systems and subsidies. In many regions, these are weak (Pretty *et al.,* 2018).

Disadvantage: Slow adoption and lack of long-term support.

Conclusion:

Integrated Pest Management (IPM) provides a practical and balanced way to manage pests while reducing the problems caused by heavy pesticide use. The studies and discussions in this report show that pests continue to cause major losses in agriculture, and relying only on chemical pesticides has created issues such as resistance, pollution and harm to beneficial insects. IPM offers a better approach by encouraging farmers to use different methods together rather than depending on one single solution.

A major advantage of IPM is that it starts with correct pest identification and regular field observation. This helps farmers understand which pests are present, how serious the problem is and whether action is actually needed. By taking measures only when pests reach harmful levels, IPM prevents unnecessary pesticide use and reduces costs. Cultural methods like crop rotation, clean fields and resistant varieties help stop pests before they become a major issue. Biological methods also play an important role by using natural enemies such as predators, parasitoids or microbes to keep pest populations under control. The use of chemicals is still allowed in IPM but only when other methods are not enough. Even then, safer or selective pesticides are preferred so that useful insects and the environment are protected. New tools like pheromone traps, improved monitoring devices and simple decision-making tools also make IPM more effective and easier for farmers to use.

However, IPM does require regular observation, some technical knowledge and access to good-quality inputs. These factors can make adoption difficult for some farmers. More training, better extension services and easier availability of biological products can help address these gaps.

Overall, IPM is a sensible and long-term approach to pest management. It helps farmers protect their crops, reduce pesticide dependence, save money, and maintain a healthier environment. Strengthening IPM adoption will support more stable and sustainable agricultural production in the years ahead.

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