International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(1): 478-484
www.biochemjournal.com
Received: 13-11-2025
Accepted: 16-12-2025

Dr. Priyanka Solanki
Assistant Professor, Department of Social Science, College of Horticulture and Forestry, Jhalawar, Agriculture University, Kota, Rajasthan, India

B Maheshwari
Teaching Associate, Department of Soil Science and Agricultural Chemistry, MJPTBCWREIS, B. Sc. (Hons.) Agricultural College, Karimnagar, Telangana, India

Shivam Kumar Rajpoot
Ph.D. Research Scholar, Division of Fruit Crops, ICAR-Indian Institute of Horticultural Research, Bengaluru, Karnataka, India

Satyarath Sonkar
Ph.D. Scholar, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Preeti Kumari
Ph.D. Scholar, Department of Fruit Science, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India

Saurabh Kumar Singh
Ph.D. Scholar, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Manasranjan Parida
Ph.D. Scholar, Department of Horticulture (Vegetable Science), PG College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

Mohit Pal
Ph.D. Scholar, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Corresponding Author:
Shivam Kumar Rajpoot
Ph.D. Research Scholar, Division of Fruit Crops, ICAR-Indian Institute of Horticultural Research, Bengaluru, Karnataka, India

Advanced biotechnological and precision-farming techniques in modern fruit production

Priyanka Solanki, B Maheshwari, Shivam Kumar Rajpoot, Satyarath Sonkar, Preeti Kumari, Saurabh Kumar Singh, Manasranjan Parida and Mohit Pal

DOI: https://www.doi.org/10.33545/26174693.2026.v10.i1Sf.7000

Abstract
Fruit crop production has undergone substantial transformation due to the integration of modern biotechnology and precision farming approaches. With the global population projected to reach nearly ten billion by 2050, ensuring food and nutritional security has become a major challenge. Fruit crops play a crucial role in human nutrition and economic development as important sources of vitamins, minerals, dietary fiber, and income. Advanced biotechnological tools such as micropropagation, tissue culture, pollen culture, somaclonal variation, marker-assisted selection, genetic transformation, molecular markers, and genome editing technologies have significantly improved the efficiency of fruit crop improvement programmes. These techniques enable rapid multiplication of disease-free planting material, early and accurate selection of desirable traits, enhancement of genetic variability, and development of cultivars with improved yield, quality, stress tolerance, and shelf life, particularly in perennial fruit crops with long juvenile phases. Alongside biotechnology, precision farming has emerged as a knowledge-driven and technology-intensive system aimed at optimizing resource use and enhancing sustainability. The integration of GPS, GIS, remote sensing, computing systems, and data analytics allows site-specific management of water, nutrients, and agrochemicals, leading to improved productivity and environmental protection. Despite proven benefits, adoption of precision farming in India remains limited due to socio-economic constraints, small landholdings, lack of awareness, infrastructure gaps, and shortage of skilled manpower. Overall, the synergistic application of biotechnology and precision agriculture offers a holistic pathway for sustainable fruit production, improved orchard efficiency, and long-term food security.

Keywords: Biotechnology, precision farming, fruit crop improvement, genome editing, sustainable horticulture, food security

Introduction
The enhancement and the growing of fruit crops have been significantly transformed through advanced biotechnological interventions. Modern biotechnology has brought major changes to fruit production by providing advanced methods to address long-term challenges in agriculture (Bhusari1 *et al*., 2025) [4]. With the global population expected to reach nearly ten billion by 2050, alongside increasing pressures from there is a strong and immediate requirement for novel strategies to ensure food security. Fruit crops, which contribute significantly to human nourishment and economic development, are directly affected by these challenges (Ahuja *et al*., 2019) [1]. Fruits, specialized organs of angiosperms (Li *et al*., 2020) [22], are an important source of dietary fiber, vitamins, and minerals, contributing significantly to global nutrition and health (Giovannoni *et al*., 2017) [14]. The scope of germplasm improvement programs often includes a wide array of trees, shrubs as well as non-woody perennials. These production of fruit crops primarily involves the cultivation of perennial plants that yield fruits with economic significance (Brennan and Millam, 2003) [8].
Biotechnology involves a range of advanced tools and techniques, such as genetic engineering, genome editing tools, marker-assisted selection methods and tissue culture approaches, which can greatly improve the efficiency and effectiveness of fruit crop breeding and production (Batista *et al*., 2020) [3]. The ripening of fleshy fruits is typically accompanied by inducing structural, biochemical, and physiological transformations, including alterations in appearance, texture, flavor, and aroma, which transform immature fruits into more

appealing and palatable forms, thereby enhancing their attractiveness to seed-dispersing animals (Giovannoni *et al*., 2017) [14].

Precision farming is regarded as a highly scientific and contemporary method for achieving sustainable agriculture, emerging as a significant approach in the late 20th century. This strategy incorporates cutting-edge technologies and agronomic concepts to address spatial and temporal differences within horticultural systems, aiming to improve crop productivity and environmental sustainability. At its core, precision farming focuses on optimizing resource use through location-specific, technologically advanced practices.

Hi-tech horticulture incorporates a wide range of techniques, including micro-irrigation, fertigation, protected or greenhouse cultivation, soil- and leaf-based nutrient "management practices, mulching techniques for conserving soil moisture on-site, micropropagation methods, germplasm research, genetically engineered crops, biological fertilizers, vermicomposting systems, high-density orchard planting, farm mechanization, soilless cultivation methods, biological pest regulation, and the production of green food products.

The integration of these technologies, coordinated to maximize output within a defined time frame, constitutes precision farming, which is primarily knowledge-driven (Bisen *et al*., 2024) [5].

A considerable volume of information covering multiple agricultural aspects is already available (Mondal *et al*., 2011) [23]. Despite this, the *comprehensive adoption* of precision farming at the farmer's level has remained limited. This limited uptake is largely the result of inadequate awareness regarding its potential to enhance productivity and improve crop quality while minimizing input usage. Additionally, there has been an absence of strong, organized efforts from institutions or agencies in the past to actively promote or popularize this technology.

Biotechnological approaches for enhancing fruit crops

1. Micropropagation

Micropropagation techniques are now applicable to nearly all fruit crops. The application of meristem culture has enabled the propagation of virus-free planting material in many horticultural species. Strawberry was among the earliest fruit crops for which a reliable micropropagation protocol was developed (Sharma and Singh, 1999) [31]. Plants produced through *in vitro* methods exhibit greater uniformity, generate a higher number of runners, show improved field survival, and provide up to 24% higher fruit yield compared to conventionally propagated plants (Kikas *et al*., 2006) [18]. Banana is widely propagated on a commercial scale using tissue culture. The sustainability of the banana industry in the country heavily depends on the management of the BBTV disease, and the most effective approach is the development of disease-free plants through *in vitro* propagation to replace infected plantations. Several fruit crops still rely on sexual propagation, and some are dioecious, bearing male and female flowers on separate plants. From a commercial standpoint, producing more female plants since they are the fruit-bearing individuals is highly desirable, and this can be efficiently achieved through tissue culture methodologies. Additionally, grafting tiny shoot tips taken from superior mother plants onto decapitated rootstock seedlings under sterile conditions has been successfully standardized (Kikas *et al*., 2006) [18].

2. Tissue culture

Tissue culture refers to the growth of plant cells, tissues, or organs *in vitro* under sterile, controlled environmental conditions. This method is especially important in fruit crop production because it enables the generation of pathogen-free planting material, supports the preservation of rare or threatened species, and aids in carrying out genetic improvements. Through the cultivation of explants small pieces of plant tissue on nutrient-rich media, it is possible to regenerate complete plants from just a single cell or tissue fragment. This technique plays a crucial role in producing uniform, superior-quality fruit plants, thereby ensuring stable crop performance and consistent yield and quality (Azad *et al*., 2017) [2].

3. Pollen Culture

Pollen culture is primarily used for producing haploid and homozygous diploid plants, offering a rapid method for developing pure lines. Since breeding programs often generate a higher number of tetraploid plants, culturing their anthers may provide an effective approach for obtaining valuable diploid types. Hofer (2005) [17] reported the successful regeneration of androgenic embryos in apple (*Malus* × *domestica* Borkh.) using both anther culture and microspore culture techniques.

4. Somaclonal Variation

Somaclonal variation is regarded as a valuable source of new plant genotypes for breeding programs, and progress in tissue culture methodologies has introduced new opportunities for their use in viticulture. Improvements in *in vitro* culture techniques have enabled the successful regeneration of numerous horticultural species, as standardized. Micropropagation methods for mass multiplication are now established for numerous crops. Nevertheless, plant tissue culture can induce genetic alterations known as somaclonal variations which may arise from gene mutations or modifications in epigenetic markers. The presence of minor somaclonal variations poses a limitation for both *in vitro* clonal propagation and germplasm conservation. Despite this drawback, somaclonal variation offers breeders an additional approach for generating genetic diversity quickly and without the need for highly advanced technology, particularly in horticultural crops that are challenging to improve or possess a narrow genetic base. Moreover, somaclonal variations contribute positively to enhancing variability and improving resistance to various stresses (Larkin and Scowcroft, 1981) [21].

Table 1: Sustained performance of selected somaclonal lines in resisting diseases and pests when evaluated under natural field conditions.

Fruit crop/cultivar	Somaclonal variant line	Resistant/tolerant to	Performance under field conditions	Reference
Apple	-	*Erwinia amylovora* Strain T)	Has 60% reduced symptoms when compared with the parental cultivar.	Donovan *et al.*, 1994 [10]
Banana	CIEN BTA-03	Yellow and black Sigatoka	Demonstrated stable performance during five years of field trials.	Gimenez *et al.*, 2008 [13]
Peach	S19-1 and S-156 (Sunhigh) S122-1 (Redhaven) S122-1	Bacterial leaf spot (*Pseudomonas syringae*)	*HR after 3 yrs in field HR resistance compared to Redheaven	Hammerschlag *et. al.*, 1994 [16].
Lemon	Genotypes FS 01 and FS 11	*Phoma tracheiphilla*	Has a tolerance capacity matching that of Monachello (T)	Gentile *et al.*, 1998 [12]

5. Marker assisted selection

The application of molecular markers significantly speeds up the selection process in fruit crops, especially those with long juvenile phases or when the target trait is governed by recessive genes, as well as in cases where multiple genes contribute to disease resistance. At present, markers associated with resistance to Dagger nematode (*Xiphinema index*) as well as Pierce's disease is routinely employed at the University of California as part of grapevine rootstock improvement programs (Xu *et al*., 2008) [38]. However, the effectiveness of the widely used scab-resistance gene *Vf* in apple has diminished because new pathogen strains have appeared capable of overcoming this resistance (Gygax *et al*., 2004) [15].

6. Genetic transformation

The procedure through which transgenes are introduced, incorporated, and expressed within host cells is referred to as genetic transformation. This technology enables the development of plants with enhanced resistance to biotic stresses such as citrus decline, Citrus Tristeza Virus (CTV), greening disease and papaya ring spot virus. It also supports the creation of varieties with improved tolerance to abiotic stresses like salinity, flooding, and drought. Additionally, genetic transformation can help reduce the juvenile period of fruit crops and improve various quality traits, including extended shelf life and the production of edible vaccines.

7. Molecular marker

A molecular marker refers to a distinct DNA fragment that can be easily identified and whose pattern of inheritance can be accurately tracked. Since phenotype does not always perfectly reflect genotype, being influenced by both genetic makeup and environmental factors, two plants may appear identical yet possess different genotypes. Molecular markers play a crucial role in fruit crops for assessing genetic diversity, estimating genetic distance between cultivars, conducting phylogenetic studies, identifying quantitative trait loci, and facilitating marker-assisted selection. They are also highly useful for determining the sex of dioecious plants at an early stage. In crops like date palm, the genetic mechanisms governing sex differentiation are still not fully understood, and the sex of a plant is revealed only when it flowers, typically after about five years. In contrast, molecular testing (when available and feasible) enables rapid and dependable sex identification in young seedlings. To develop such diagnostic tools, genomic DNA from 45 individual date palm plants (25 female and 20 male) from various cultivars was analyzed using PCR (Polymerase Chain Reaction) amplification with 100 RAPD (Random Amplified Polymorphic DNA) and as well as 104 ISSR (Inter Simple Sequence Repeat) markers (Dhawan *et al*., 2013) [9]. Similarly, in papaya, RAPD markers have been effectively utilized to distinguish female and hermaphrodite plants (Dwivedi *et al*., 2014) [11].

8. Genome Editing

The CRISPR system represents a sophisticated adaptive immune defense found in bacteria and archaea, enabling them to protect themselves for protection from invading viruses (bacteriophages) and foreign plasmid DNA (Sternberg *et al*., 2016) [32]. Over the past decade, one of the most significant breakthroughs in plant science has been the capability to precisely alter the plant genome (Zhang *et al*., 2021) [39]. Among the various genome-editing platforms, CRISPR/Cas9, TALENs (Transcription Activator-Like Effector Nucleases), and ZFNs (Zinc Finger Nucleases) are the most commonly used molecular tools. While ZFNs and TALENs have been successfully applied for targeted DNA editing, CRISPR/Cas9 has emerged as the preferred method due to its efficiency and simplicity. This technique employs RNA-guided nucleases that bind to specific nucleotide sequences within target genes, making it a powerful and widely adopted approach for modifying plant genomes (Puchta *et al*., 2022) [30].

For example, in fruit crops such as citrus, CRISPR technology has been applied to alter genes associated with stomatal functioning and water-use regulation, leading to enhanced drought resilience while maintaining fruit yield and quality (Bohra *et al*., 2016) [6].

One significant achievement is the creation of Bacterial canker of citrus, resistant Wanjincheng orange plants by completely removing the EBEPthA4 sequence from both alleles of the *CsLOB1* gene, which resulted in a highly favourable improvement (Wang *et al*., 2018) [37].

CRISPR/Cas9-based editing of the *MdDIPM4* gene in apple has led to decreased vulnerability to the fire blight pathogen *Erwinia amylovora* (Tripathi *et al*., 2019) [35]. Similarly, the deletion of the *WRKY52* gene in grapevines enhanced their resistance to *Botrytis cinerea* (Pompili *et al*., 2020) [29]. In bananas, one of the major post-harvest challenges is their short shelf life, which was improved by using CRISPR/Cas9 to modify the *MA-ACO1* gene (Tripathi *et al*., 2019) [35]. Along with advancing CRISPR applications to optimize its advantages, it is crucial to address public acceptance to minimize potential risks (Tian *et al*., 2019) [34].

Precision Farming

1. Major Components and Drivers of Precision Farming

a) **Computing Systems and Internet Connectivity:** Computers and the Internet form the essential foundation for making precision farming feasible, as they serve as the primary tools for accessing, processing, and collecting information.

Computers and the Internet are among the most essential elements in facilitating precision farming, as they serve as the primary tools for data collection, processing, and management. These digital technologies enable the aggregation and analysis of vast amounts of agricultural information, making informed decision-making and efficient farm management possible.

b) **Global Positioning System (GPS) based location tracking system:** The main use of Global Positioning System in agriculture lies in yield mapping and in regulating site-specific applications of fertilizers or pesticides at variable rates.
Global Positioning System technology is essential for accurately determining field locations, which allows for the assessment of spatial variability and the site-specific application of agricultural inputs. When operating in differential mode, GPS systems can provide location accuracy within approximately one meter, enabling precise management of crops and resources.

c) **Geographical Information System (GIS):** A Geographic Information System is an organized framework that includes computer hardware, specialized software, spatial datasets as well as skilled operators, developed to successfully collect, store, modify, process, interpret, and present location-based information. Often regarded as the "brain" of precision farming, GIS supports agriculture in two key ways. First, it enables the integration of GIS data, including soil characteristics, crop performance, weather conditions, and field history, into simulation models for better decision-making. Second, it assists the engineering aspect of precision agriculture by aiding in the design of implements and GPS-guided machinery, such as variable rate applicators, ensuring accurate and site-specific management of agricultural inputs.

d) **Remote Sensing (data collection through satellites and drones):** Remote sensing offers significant potential for precision farming due to its ability to monitor spatial variability over time with high resolution. Imagery used in precision agriculture can be collected through satellite-based sensors or CIR (Color Infrared) digital cameras mounted on small aircraft, providing detailed and timely information for effective crop and field management.

2. Phases in Precision Farming Implementation

The foundational steps in precision farming involve assessing, managing, and evaluating variability. Among these, evaluating field variability is the crucial first step, as effective management cannot occur without a clear understanding of existing differences. Spatial variability within a field can be identified and mapped using various approaches, including field surveys, interpolation of sampled points, analysis of high-resolution aerial or satellite imagery, and modelling techniques to predict spatial patterns (Nabi *et al*., 2017) [24].

a) **Assessment of Precision Farming:** The fundamental truth about the profitability of precision agriculture lies not in the technology itself, but in the effective use of data. Precision farming is frequently highlighted for its potential to improve environmental quality. Benefits such as reduced pesticide application, enhanced nutrient use efficiency, optimized input usage, and improved soil productivity are often cited as possible environmental advantages. The implementation of precision agriculture is made possible through enabling technologies, guided by agronomic principles and decision-making rules, and becomes economically viable due to increased production efficiency or added value. The concept of technology transfer may imply that precision agriculture occurs merely by acquiring and utilizing these technologies. However, precision agriculture involves not only the use of technologies but also the application of agronomic strategies to manage spatial and temporal variability in fields. Much of the focus in technology transfer has shifted toward effective engagement with farmers. Challenges related to operator expertise, infrastructure distribution, and technology compatibility with specific farm conditions are expected to evolve significantly as precision agriculture continues to advance (Pierce and Peter, 1999) [28].

b) **Optimizing Site-Specific Variability:** When the variability within a field is properly evaluated, farmers need to adjust agronomic inputs according to the specific site conditions by following localized management guidelines and using precise control tools. The effectiveness of precision farming largely depends on how accurately soil fertility, pest pressures, crop growth in relation to biotic and abiotic factors, and water resources are optimized, as well as how effectively corrective measures are implemented based on the variations detected in the field.

c) **Evaluating of Field Variability:** Assessing field variability is the essential initial step in precision farming, as it is evident that effective management is impossible without adequate knowledge of field conditions. Spatial variations within the field can be charted through various techniques, including field surveying, interpolating data from point samples, analyzing high-resolution aerial and satellite imagery, and using modeling approaches to predict spatial patterns.

3. Soil Resource and Nutrient Optimization

The world's natural resources are steadily declining while the human population continues to grow, accompanied by rising levels of environmental pollution affecting water, soil, and air. This issue is especially pronounced in developing countries like India. As the population continues to rise, the need for food and fibre will become even greater, while the supply of land and water resources keeps diminishing.
Consequently, precision farming has become a critical necessity. Several factors influence enhanced crop growth and productivity, including the choice of crop varieties, irrigation methods and water quantity, techniques of fertilizer application, the application of agrochemicals to manage pests, the influence of rootstocks, the practice of moistening the root zone, adopting high-density planting systems, considering environmental factors, and implementing automated irrigation technologies (Pérez-Ruiz *et al*., 2012) [27].

4. Scope of Precision Agriculture in India

Even though precision farming has been successfully adopted in several technologically advanced countries, its application in India remains restricted. The factors that hinder the expansion of site-specific farming practices in India include:

1. The fragmented and small-sized landholdings restrict the practical application of precision farming.
2. The socio-economic conditions of Indian farmers act as a barrier to adopting advanced technologies.
3. There is a scarcity of documented success cases or cost-benefit analyses related to precision farming in India.
4. A significant knowledge and technology gap exists, along with the diverse and heterogeneous cropping patterns practiced across the country.
5. Imperfect or poorly functioning markets also limit the growth of precision agriculture.
6. There is a shortage of skilled local professionals capable of supporting and guiding precision farming operations.
7. Reliable, high-quality, and affordable data needed for precise decision-making are often unavailable.

5. Propagation of Genuine Planting Material for maintaining crop quality and uniformity

Development a healthy mother tree block with the preferred traits of selected varieties plays a crucial role in determining the overall productivity of a mango plantation. Hence, high-yielding clones of popular commercial cultivars should be chosen for establishing these mother blocks. It is also essential to adopt region-specific, standardized propagation techniques to produce high-quality planting material required for expanding mango cultivation. Additionally, the use of salt-tolerant rootstock such as 13-1 should be explored for areas with problematic soils in India.

6. The effective utilization of water to maximize crop growth and yield while minimizing waste

Various factors that influence the irrigation response such as soil characteristics, seasonal conditions, regional climate, growth stage of the tree, and the variety grown must be considered when preparing irrigation schedules. To ensure efficient use of water, drip irrigation is increasingly being adopted in mango cultivation.

7. Providing crops with the appropriate and proportionate supply of essential nutrients for optimal growth and productivity

Research on leaf-sampling methods indicates that collecting 30-40 healthy, fully developed leaves that are 6-7 months old from the middle portion of shoots—covering nearly all heights and directions of the canopy—provides an accurate assessment of the tree's nutrient status. Critical threshold levels for nutrients such as Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Sulfur, Iron, Manganese, Zinc and Copper need to be established.

Along with balanced fertilizers, applying organic manure is vital for maintaining soil fertility, which greatly influences tree vigor and yield. Because mango trees have an extensive root system, are perennial, and show variable fruiting patterns and rootstock effects, relying solely on soil testing for fertilizer recommendations is inadequate. Therefore, both soil and leaf analyses should be used together to determine the ideal nutrient requirements (Bongiovanni & Deboer, 2004) [7].

8. Planting at a High-Density

In the Indian mango industry, low productivity is partly attributed to the wide spacing traditionally used in orchards, where trees are planted 10 to 12 meters apart both within and between rows. The canopies of such trees often require more than a decade to occupy the allotted space in the orchard. This challenge can be addressed by adopting high-density planting systems. Managing the tree canopy particularly controlling its size, has become essential for lowering production costs while enhancing fruit yield and quality.

9. Strategies to regulate and minimize the fluctuations in crop yield caused by Irregular bearing

Irregular bearing is widely observed in most commercial mango varieties and is largely attributed to the natural conflict between vegetative growth and flowering. To address this issue, strategies aimed at regulating vegetative development and managing flowering can be implemented.

10. To Enhance their Productivity and Vigour of Rejuvenation of Unproductive Orchards

One of the major causes of low mango production is the presence of numerous old orchards, many of which fall within the age range of 30-62 years or more. These orchards have either become unproductive or show a significant reduction in yield. This decline is mainly due to dense and overlapping branches with sparse foliage, which restricts adequate light from reaching the inner shoots of the canopy. As a result, such orchards become economically unviable. However, severe pruning can help rejuvenate and restore the productivity of these trees.

11. Strategies and practices aimed at controlling pests and diseases in fruit crops

Proper management of insect pests and diseases is essential, as they affect almost every stage of a plant's growth and development. Therefore, it is essential to implement Integrated Pest Management (IPM) strategies for proper and sustainable pest control.

12. Injury or harm to crops caused by mechanical handling or equipment during cultivation and harvesting

Mechanized operations and handling can cause physical injury to crops and may create additional structural or mechanical stress on plant tissues. Recently, significant progress has been made in understanding how tissue architecture, types of intercellular connections, and cell wall properties influence the elasticity and failure patterns of vegetative tissues. Although the characteristics of these crops are shaped by both cultivation and storage conditions, they are also influenced by genetics. In some cases, evidence suggests that genetic factors contribute to tissue strength and product form. This knowledge can support the development of crop varieties that better withstand mechanical pressure during harvest and possess desirable texture and firmness qualities for consumers or processors (Tennes *et al*., 1988) [33].

13. Adoption of precision agriculture techniques in the cultivation of major fruit crops.

a) **Mango:** The applying of black polythene mulch combined with drip irrigation was found to conserve soil moisture, suppress weed emergence, and enhance fruit yield and quality in an experiment conducted at the Horticultural Farm, Precision Farming Development Center, Department of Horticulture, IGKV, Chhattisgarh during the 2009-2010 season. The study revealed that water-use efficiency was lower under the basin irrigation method that utilized a V volume of water, whereas it was significantly higher under drip irrigation using 0.6 V water volume together with plastic mulch (Panigrahi *et al*., 2010) [26].

b) **Apple:** Wireless sensor network (WSN) is being used as one of the components used for precision farming throughout several areas worldwide for different objectives e.g. disease forecasting in apple, its identification and thus taking precautions according to the prediction (Nabi *et al*., 2022) [25].

c) **Grape:** Together with the Harvest Master system, a yield-monitoring device for commercial grape harvesters was created in 1996 to facilitate a long-term research program that began in 1997. This project investigated how mechanical pruning and thinning influence grape yield and quality in the Yakima Valley region of Washington. A 10-acre block of Concord grapes was subjected to five different pruning treatments. After pruning, sub-sample counts were taken to estimate the number of flower buds and clusters per vine. The cluster numbers per vine, along with estimated cluster weights recorded in late June, were used to calculate the level of mechanical thinning required and to predict potential yield. Mechanical thinning was carried out in early July. Yield maps helped identify differences caused by pruning and thinning methods as well as variations due to vineyard location. Information on fruit quality, yield, yield components, and vegetative growth was documented (Wample *et al*., 1999) [36].

d) **Banana:** In India, banana is one of the few crops for which sophisticated and precision-based agricultural methods have been successfully applied, yielding notable advantages. The integration of superior varieties adapted for processing and export markets, micropropagation methods, optimized planting geometry, drip irrigation, fertigation, mulching, green-manure incorporation, recycling of banana by-products, organic farming practices, and maintaining plantation hygiene via integrated pest and disease management combined with post-harvest processing like puree production, dissemination of technology, farmer training, and participatory demonstrations has played a vital role in significantly enhancing productivity.

e) **Indian gooseberry:** Indian gooseberry is native to the Indian subcontinent. Advanced precision-farming methods to enhance its production consist of choosing superior varieties, multiplying authentic planting material, employing proper planting techniques, applying training and pruning, using manures and fertilizers, managing water efficiently, applying mulch, controlling pests and diseases, and implementing effective harvesting and post-harvest handling practices.

14. Difficulties faced in the adoption and practical application of precision farming techniques

1. Several agricultural fields are divided into small, irregular plots, which prevents the use of even basic mechanized tools.
2. Technologies such as GIS and GPS are still inaccessible to most farmers, including those with higher incomes.
3. Cultural practices and traditional beliefs combined with the economic limitations of farmers in developing countries reduce the adoption of advanced farming methods.
4. Limited availability of soil testing and other analytical facilities also restricts progress.
5. The current post-harvest infrastructure and marketing channels are inadequate and unable to effectively store or transport agricultural produce.
6. The high price of advanced machinery and equipment further discourages adoption.
7. The presence of small landholdings also poses a major constraint.
8. There is a shortage of successful case studies that could motivate farmers.
9. Diverse cropping patterns and imperfections in the market system hinder improvement.
10. Challenges related to land tenure, poor infrastructure, and institutional barriers also limit adoption.
11. A lack of skilled local technical personnel restricts the implementation of modern practices.
12. There remain significant gaps in knowledge and technical know-how.
13. The accessibility of data, the reliability of the information collected, and the expenses involved in obtaining and managing such data are critical considerations.

References

1. Ahuja I, Kissen R. Transcriptional regulation of fruit ripening by MADS-box transcription factors. Critical Reviews in Plant Sciences. 2019;38(3):178-192.
2. Azad MOK, Kim IS, Park CH, Park CH. Fruit crop production. Boca Raton: CRC Press; 2017. p.162.
3. Batista DS, Lazzarotto F, Henriques AT. Biotechnology as a tool for banana improvement. Biotechnology Research and Innovation. 2020;4(1):87-99.
4. Bhusari RM, Patil SD, Dhemre JK, Shinde C. Advances in biotechnological intervention in fruit crops: a review. 2025;25(1):441-450.
5. Bisen A, Jain V, Singh J. Strategic approaches of precision farming technology for improvement of fruit production. International Journal of Agricultural Invention. 2024;9(2):221-226.
6. Bohra A, Jha UC, Adhimoolam P, Bisht D, Singh NP, Singh D, *et al*. Genomics and molecular breeding in lesser explored pulse crops: current trends and future opportunities. Biotechnology Advances. 2016;34(7):1395-1418.
7. Bongiovanni R, Deboer J. Precision agriculture and sustainability. Precision Agriculture. 2004;5:359-387.
8. Brennan RM, Millam S. Fruits of temperate climates: improvement and maintenance of fruit germplasm. In: Encyclopedia of Food Sciences and Nutrition. 2nd ed. 2003. p.2774-2780.
9. Dhawan C, Kharb P, Sharma R. Development of male specific SCAR marker in date palm (*Phoenix dactylifera* L.). Tree Genetics and Genomes. 2013;9:1143-1150.
10. Donovan AM, Morgan R, Valobra-Piagnani C, Ridout MS, James DJ, Garrett CE. Assessment of somaclonal variation in apple. I. Resistance to the fire blight pathogen, *Erwinia amylovora*. Journal of Horticultural Science. 1994;69(1):105-113.

11. Dwivedi S, Pandey P, Shamin MD, Srivastva D, Singh KN. Identification of female and hermaphrodite specific marker and diversity assessments in papaya (*Carica papaya*) cultivars. Indian Journal of Agricultural Biochemistry. 2014;27(2):129-132.
12. Gentile A, Deng ZN, Tribulato E, Vardi A, Albanese G, Grimaldi V, *et al*. Evaluation of lemon somaclones for tolerance to mal secco disease by artificial inoculation. In: First International Citrus Biotechnology Symposium. 1998;535:259-263.
13. Giménez C, De García E, Haddad O. Genetic and resistance stability to Black Sigatoka disease during micropopagation of *Musa* CIEN BTA-03 somaclonal variant. Phyton. 2008;77:65.
14. Giovannoni J, Nguyen C, Ampofo B, Zhong S, Fei Z. The epigenome and transcriptional dynamics of fruit ripening. Annual Review of Plant Biology. 2017;68(1):61-84.
15. Gygax M, Gianfranceschi L, Liebhard R, Kellerhals M, Gessler C, Patocchi A. Molecular markers linked to the apple scab resistance gene Vbj derived from *Malus baccata* jackii. Theoretical and Applied Genetics. 2004;109(8):1702-1709.
16. Hammerschlag F, Ritchie D, Werner D, Hashmil G, Krusberg L, Meyer R, *et al*. In vitro selection of disease resistance in fruit trees. In: Genetic Improvement of Horticultural Crops by Biotechnology. 1994;392:19-26.
17. Hofer M. Regeneration of androgenic embryos in apple (*Malus* × *domestica* Brokh.) via anther and microspore culture. Acta Physiologiae Plantarum. 2005;27(4):709-716.
18. Kikas A, Libek A, Vasar V. Influence of micropropagation on the production of strawberry runner plants, yield and quality. Acta Horticulturae. 2006;708:241-244.
19. Lakhiar IA, Gao J, Syed TN, Chandio FA, Buttar NA. Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. Journal of Plant Interactions. 2018;13(1):338-352.
20. Lakso AN, Robinson TL. Principles of orchard systems management optimizing supply, demand and partitioning in apple trees. In: VI International Symposium on Integrated Canopy, Rootstock, Environmental Physiology in Orchard Systems. 1996;451:405-416.
21. Larkin PJ, Scowcroft WR. Somaclonal variation a novel source of variability from cell cultures for plant improvement. Theoretical and Applied Genetics. 1981;60(4):197-214.
22. Li S, Zhu B, Pirrello J, Xu C, Zhang B, Bouzayen M, *et al*. Roles of RIN and ethylene in tomato fruit ripening and ripening-associated traits. New Phytologist. 2020;226(2):460-475.
23. Mondal P, Mondal P, Basu M, Bhadoria PBS. Critical review of precision agriculture technologies and its scope of adoption in India. 2011. p.49-68.
24. Nabi A, Afroza B, Mushtaq F, Malik A. Precision farming in vegetables. Journal of Pharmacognosy and Phytochemistry. 2017;6:370-375.
25. Nabi F, Jamwal S, Padmanbh K. Wireless sensor network in precision farming for forecasting and monitoring of apple disease: a survey. International Journal of Information Technology. 2022;14(2):769-780.
26. Panigrahi HK, Agrawal N, Agrawal R, Dubey S, Tiwari SP. Effect of drip irrigation and polythene mulch on the fruit yield and quality parameters of mango (*Mangifera indica* L.). Journal of Horticultural Sciences. 2010;5(2):140-143.
27. Pérez-Ruiz M, Slaughter DC, Gliever J, Upadhyaya SK. Automatic GPS-based intra-row weed knife control system for transplanted row crops. Computers and Electronics in Agriculture. 2012;80:41-49.
28. Pierce FJ, Nowak P. Aspects of precision agriculture. Advances in Agronomy. 1999;67:1-85.
29. Pompili V, Dalla Costa L, Piazza S, Pindo M, Malnoy M. Reduced fire blight susceptibility in apple cultivars using a high-efficiency CRISPR/Cas9-FLP/FRT-based gene editing system. Plant Biotechnology Journal. 2020;18(3):845-858.
30. Puchta H, Jiang J, Wang K, Zhao Y. Updates on gene editing and its applications. Plant Physiology. 2022;188:1725-1730.
31. Sharma RR, Singh SK. Strawberry cultivation—a highly remunerative farming enterprise. Agro India. 1999;3(2):29-31.
32. Sternberg SH, Richter H, Charpentier E, Qimron U. Adaptation in CRISPR-Cas systems. Molecular Cell. 2016;61:797-808.
33. Tennes BR, Zapp HR, Brown GK, Ehlert SH. Self-contained impact detection device: calibration and accuracy. Transactions of the ASAE. 1988;31(6):1869-1874.
34. Tian T, Shu B, Liu L, Zhou X. Droplet-digital Cas13a assay enables direct single-molecule microRNA quantification. bioRxiv. 2019;748939.
35. Tripathi JN, Ntui VO, Ron M, Muiruri SK, Britt A, Tripathi L. CRISPR/Cas9 editing of endogenous banana streak virus in the B genome of *Musa* spp. overcomes a major challenge in banana breeding. Communications Biology. 2019;2(1):46.
36. Wample RL, Mills L, Davenport JR. Use of precision farming practices in grape production. In: Proceedings of the Fourth International Conference on Precision Agriculture. 1999. p.897-905.
37. Wang M, Wang S, Liang Z, Shi W, Gao C, Xia G. From genetic stock to genome editing: gene exploitation in wheat. Trends in Biotechnology. 2018;36(2):160-172.
38. Xu K, Riaz S, Roncoroni NC, Jin Y, Hu R, Zhou R, *et al*. Genetic and QTL analysis of resistance to *Xiphinema index* in a grapevine crop. Theoretical and Applied Genetics. 2008;116:305-311.
39. Zhang P, Du H, Wang J, Pu Y, Yang C, Yan R, *et al*. Multiplex CRISPR/Cas9-mediated metabolic engineering increases soybean isoflavone content and resistance to soybean mosaic virus. Plant Biotechnology Journal. 2020;18(6):1384-1395.