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Digital technologies driving advances in precision fruit crop production

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Abstract

Precision horticulture represents a paradigm shift in fruit crop management by enabling site specific, data driven interventions that address the spatial and temporal variability inherent to perennial orchard systems. Uniform management practices are increasingly ineffective for fruit crops such as mango, apple, citrus, grape and banana, where heterogeneity in canopy structure, soil properties, and microclimate strongly influences productivity and resource use efficiency. Recent advances in digital agriculture particularly unmanned aerial vehicles (UAVs), Internet of Things (IoT) sensor networks, artificial intelligence (AI), machine learning (ML) and integrated decision support systems (DSS) have substantially expanded the scope and scalability of precision fruit farming.

UAV-based remote sensing has emerged as a core technology due to its ability to generate high-resolution multispectral, hyperspectral, and thermal imagery for near real-time orchard diagnostics. Techniques such as vegetation index mapping (NDVI and NDRE), canopy vigour assessment, thermal stress detection, and 3D canopy reconstruction support precision irrigation in apple and grape, while AI-based image analytics enable early pest and disease detection in mango and citrus. These aerial insights, combined with IoT-based soil moisture, nutrient, and microclimate sensors, enable closed loop decision systems for optimized fertigation and yield forecasting.

This review synthesizes recent advances in digital technologies driving precision fruit crop production, with emphasis on UAV enabled and AI driven applications. The case studies illustrate effective adoption across diverse agro-climatic regions. Collectively, the convergence of drones, AI, and IoT is redefining orchard management and positioning precision horticulture as a key pillar of climate-smart, resource efficient and sustainable fruit production.

Keywords: Precision farming, GIS, GPS, UAV, IoT

Introduction

Fruit crop production plays a critical role in global food and nutritional security, income diversification and rural livelihoods particularly in developing countries such as India. However, orchard based systems face increasing challenges due to climate variability, declining natural resources, rising labour and input costs, and the need for sustainable intensification (FAO, 2022; Singh *et al*., 2021) [18, 31]. Unlike annual field crops, fruit crops exhibit complex canopy architecture, long production cycles and pronounced spatial variability in soil fertility, water availability and pest pressure, making uniform management strategies agronomically inefficient and economically suboptimal (Zhang *et al*., 2002; Gebbers & Adamchuk, 2010) [20, 66].

Precision farming has therefore emerged as a transformative strategy aimed at optimizing input use through spatially explicit, data-driven management (Pierce & Nowak, 1999; Mulla, 2013) [39, 46]. In fruit crops, precision horticulture enables targeted interventions for irrigation, fertilization, canopy management and pest control, leading to improved productivity, resource use efficiency, and environmental sustainability (Shibusawa, 2016; Liakos *et al.,* 2018) [34, 53].

The rapid evolution of digital technologies including UAVs, ground-based IoT sensors, AI and ML algorithms, cloud computing and decision support platforms has significantly accelerated the adoption of precision horticultural practices (Wolfert *et al*., 2017; Kamilaris *et al*., 2018) [26, 63]. Among these technologies, UAVs have gained prominence owing to their ability to acquire ultra-high-resolution spatial-temporal data at low operational cost and with exceptional flexibility (Bendig *et al*., 2015; Zhang & Kovacs, 2012) [10, 65].

UAV-mounted multispectral, hyperspectral, RGB, and thermal sensors enable precise assessment of canopy vigour, plant water status, nutrient deficiencies, disease incidence, and yield variability in fruit crops such as mango, apple, citrus, grape, and banana (Torres-Sánchez *et al*., 2014; Zarco-Tejada *et al.,* 2018) [64]. When combined with AI and ML frameworks, drone-derived datasets support automated stress detection, predictive modelling, and intelligent decision-making shifting orchard management from reactive to predictive and adaptive systems (Chlingaryan *et al*., 2018; Liakos *et al.,* 2018) [15, 34].

In India, digital precision farming is particularly relevant due to fragmented landholdings, heterogeneous agro-ecologies, and water scarcity. Recent policies, expanding agri-tech startups, and public–private partnerships show UAVs are practical for orchard monitoring, precision spraying and yield estimation (Jat *et al*., 2019; Ramesh & Rajkumar, 2022; ICAR, 2023) [25, 48, 56]. Despite these advances, a consolidated review focusing on drone-enabled precision fruit crop management within an Indian context remains limited.

Development Stages Of Precision Farming In Fruit Crops

The implementation of precision farming in fruit orchards follows a structured, multi-stage workflow that converts raw digital data into actionable management interventions.

According to Pierce & Nowak (1999) and Gebbers & Adamchuk (2010) [20, 46], this process consists of four linked steps: abstract, reconnaissance, decision and execution.

a. Abstract Stage: Digital Data Acquisition

The abstract stage involves the generation of raw spatial and temporal datasets using digital sensing technologies. Data collection for fruit crops involves UAV remote sensing, IoT sensors for soil and microclimate, canopy sensors nearby and weather stations. Data at this stage consist of numerical signals such as spectral reflectance values, soil moisture readings, canopy temperature, and ambient meteorological parameters which lack intrinsic agronomic meaning until further analysis (McBratney *et al.*, 2005; Zhang & Kovacs, 2012) [65].

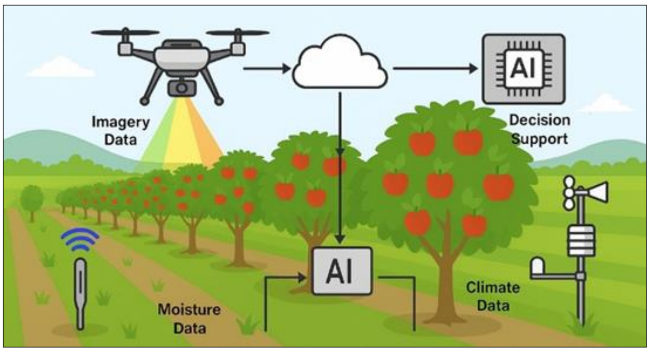

Fig 1: Digital data acquisition in precision fruit orchards using UAV-mounted multispectral sensors, IoT-based soil moisture probes, and automated weather stations

b. Reconnaissance Stage: Spatial Interpretation and Variability Mapping

During the reconnaissance phase, raw data from sensors are converted into understandable information. This involves geospatial analysis, image calibration, vegetation index generation (e.g., NDVI, NDRE, CWSI) and spatial classification to identify variability patterns within orchards. UAV imagery enables high-resolution delineation of zones exhibiting differences in canopy vigour, water stress, nutrient status, or disease severity (Mulla, 2013; Gebbers & Adamchuk, 2010) [20, 39]. This stage assigns agronomic relevance to digital observations and supports early detection of biotic and abiotic stresses in fruit crops.

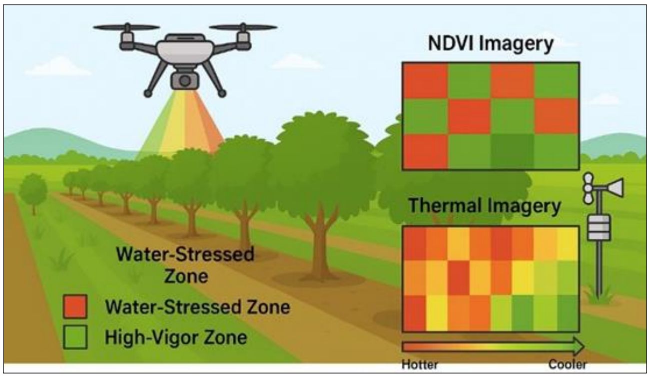

Fig 2: Orchard variability mapping using drone-derived NDVI and thermal imagery to identify water-stressed and high-vigour zones

c. Decision Stage: AI-Driven Analytics and Decision Support

The decision stage focuses on converting spatial information into site-specific management recommendations. AI- and ML-based models integrated within decision support systems analyse UAV and IoT datasets to generate prescriptions for irrigation scheduling, fertigation rates, pest and disease interventions and yield forecasting. Algorithms such as convolutional neural networks (CNNs), random forests, and support vector machines enable automated anomaly detection and predictive analytics (Wolfert *et al.*, 2017; Kamilaris *et al.*, 2018) [26, 63]. This stage bridges the gap between data interpretation and practical orchard management by translating digital intelligence into scientifically grounded recommendations.

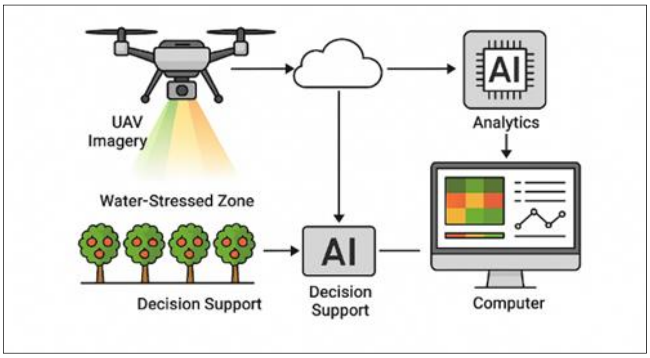

Fig 3: Integration of UAV imagery with AI-based analytics and decision support systems for precision orchard management

d. Execution Stage: Precision Intervention and Field Implementation

The execution stage involves the on-field implementation of management decisions through precise and timely actions. These include variable-rate irrigation and fertigation, drone-based precision spraying, targeted pruning and site-specific disease control. While earlier stages are computational, the execution stage requires operational expertise, farmer engagement, and contextual adaptation to ensure successful outcomes (Pierce & Nowak, 1999; Pathak *et al.*, 2018) [44, 46].

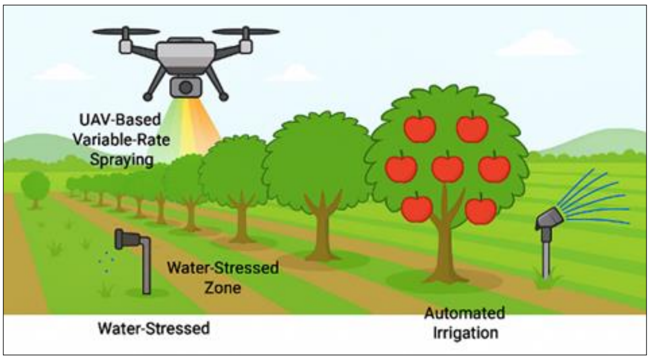

Fig 4: Execution of precision interventions in fruit orchards using UAV based variable-rate spraying and automated irrigation systems

Conceptual or Technological Framework For Digital And Precision Orchard Management

a. Unmanned Aerial Vehicles (UAVs): Drones equipped with multispectral, hyperspectral or thermal cameras provide high-resolution aerial imagery for fruit orchards. In apple and grape orchards, UAV-based remote sensing has been used to monitor canopy health, detect water or nutrient stress and assess growth variability across large areas efficiently (Bendig *et al*., 2015; Zhang *et al*., 2021) [10, 67].

b. Internet of Things (IoT) Sensor Networks: Distributed field sensors continuously monitor soil moisture, temperature, humidity, and nutrient levels in orchards. In citrus and mango orchards, these real-time data support precision irrigation, fertigation, and pest management, improving resource use efficiency and crop uniformity (Gomez-Candon *et al*., 2020 [22]; Li *et al.,* 2022).

c. Artificial Intelligence (AI) and Machine Learning (ML): AI/ML algorithms analyse complex datasets from UAVs and IoT sensors to detect canopy stress, predict disease outbreaks, and generate actionable insights. For example, in mango and citrus orchards, ML-based image analytics enable early detection of pests and diseases, facilitating timely intervention (Singh *et al*., 2021; Tiwari *et al.,* 2022) [31, 60].

d. Integrated Decision Support Systems (DSS): DSS integrate UAV imagery, IoT sensor data, weather forecasts, and AI/ML outputs to provide orchard managers with site specific recommendations. In apple and grape production, DSS guides variable-rate fertilization, optimized irrigation and precision pest control, enhancing yield, fruit quality, and sustainability (Costa *et al.,* 2020; Bramley & Hamilton, 2004) [5, 11].

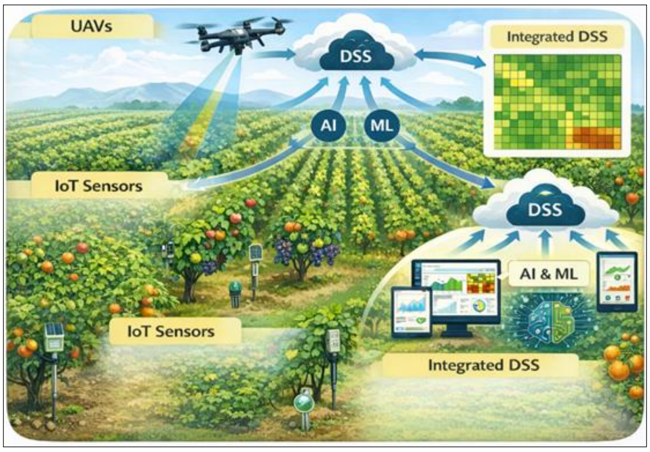

Fig 5: Integration of UAVs, IoT Sensors and AI-Based Decision Support Systems in Precision Fruit Farming

Components Of Precision Farming In Fruit Crop

1. Remote Sensing (UAV / Satellite Based)

Remote sensing plays a central role in precision horticulture by providing high resolution spatial and temporal information on canopy vigour, plant water status, nutrient deficiencies, and disease incidence in perennial orchards. Recent studies show that UAV-based multispectral and thermal imagery enables early stress detection and precise delineation of orchard management zones, thereby enhancing monitoring efficiency and supporting site specific interventions (Zhang *et al.,* 2021; Popescu *et al*., 2023; Zarco-Tejada *et al.,* 2018) [47, 64, 67]. For example, multispectral vegetation indices (NDVI, NDRE) have been successfully applied in apple and grape orchards to assess canopy vigour and guide precision irrigation and fertigation, while thermal UAV sensing has proven highly effective for detecting water stress in citrus, apple, and grape by identifying canopy temperature anomalies linked to reduced transpiration (Ahmad *et al*., 2021; Awais *et al.,* 2023) [1, 4]. In mango orchards, UAV imagery combined with spatial analysis supports early identification of stress affected zones and targeted management, demonstrating the value of remote sensing for improving resource-use efficiency and yield stability in fruit crop production systems.

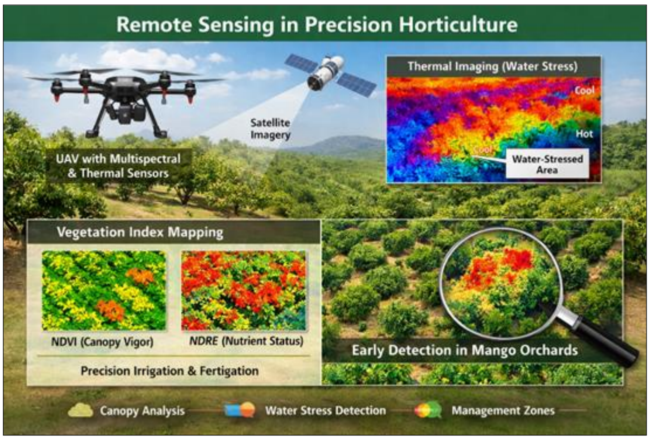

Fig 6: Remote sensing-based orchard monitoring using multispectral and thermal imagery in mango orchard

2. Geographical Information System (GIS)

A Geographical Information System (GIS) forms the analytical backbone of precision horticulture by integrating spatial data on soil, crop, weather and field history to manage within orchard variability. In India, GIS has been effectively applied in perennial fruit crops to support site-specific management and improve resource use efficiency.

Fig 7: Architecture and operational workflow of Geographic Information System (GIS) for precision farming

In mango orchards of Maharashtra and Karnataka, GIS-based soil fertility and yield variability mapping have been used to delineate management zones for precision nutrient and water management (Rao *et al.,* 2015 [50]; ICAR–IIHR, 2018). Grape vineyards in Maharashtra utilize GIS integrated with weather and soil moisture data to support precision irrigation scheduling and spatial disease risk assessment for downy mildew and powdery mildew (Patil *et al*., 2016; Narvekar *et al.,* 2019) [43, 45]. In apple-growing regions of Himachal Pradesh and Jammu & Kashmir, GIS applications include site suitability analysis based on elevation, slope, and temperature, as well as spatial yield variability and frost risk mapping (Sharma *et al*., 2014; Rana *et al.,* 2017) [49, 52].

Similarly, citrus orchards in Madhya Pradesh and Andhra Pradesh employ GIS-based canopy vigour and disease incidence mapping to enable targeted nutrient and pest management (Singh *et al.,* 2018) [44]. In banana plantations of Tamil Nadu, GIS supported GPS guided variable-rate fertilizer application has improved nutrient-use efficiency and yield uniformity (Thiyagarajan *et al*., 2016) [59].

3. Diagnosis and Recommendation Integrated System (DRIS) in Fruit Crops

The Diagnosis and Recommendation Integrated System (DRIS) is a holistic approach for optimizing mineral nutrition in crops by evaluating nutrient balance rather than absolute concentrations. It integrates plant tissue analysis, soil composition, environmental parameters and management practices to identify nutrient limitations and prioritize corrections in order of their impact on yield (Walworth & Sumner, 1987; Chen *et al.,* 2022) [13, 61]. DRIS uses nutrient ratios to interpret leaf or tissue analysis, enabling diagnosis at any stage of crop development.

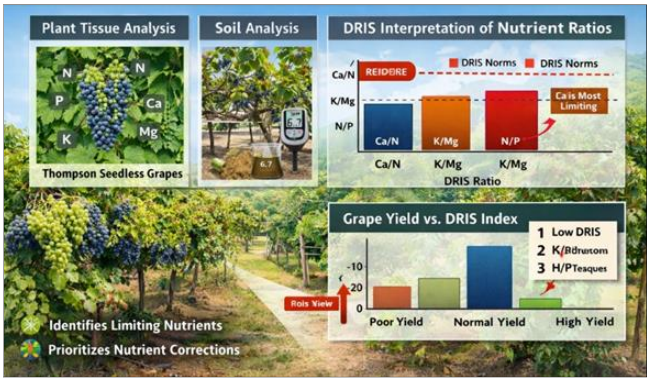

Fig 8: Schematic representation of the Diagnosis and Recommendation Integrated System (DRIS) applied in grapevine orchards

In horticultural applications, DRIS has been successfully applied to 'Thompson Seedless' grape vineyards in India, identifying calcium and nitrogen imbalances that limited yield and guiding targeted fertilization for improved productivity (Chelvan *et al.,* 1984; Kumar *et al.,* 2021) [12, 31]. Recent studies demonstrate its effectiveness in apple, citrus, and mango orchards, where DRIS-based nutrient management enhances fruit quality, optimizes input use, and supports sustainable production (Mishra *et al.,* 2020; Singh *et al.,* 2023) [38, 56]. Integrating DRIS with spatial analysis and precision tools allows site-specific nutrient interventions, making it a valuable component of modern precision horticulture.

4. Global Positioning System (GPS) in Precision Horticulture

The Global Positioning System (GPS), increasingly enhanced with RTK-GPS accuracy, is a core enabling technology in precision horticulture, providing high-resolution geospatial positioning for site-specific orchard management (Gebbers & Adamchuk, 2010; Shibusawa, 2016) [20, 53]. Integration of GPS with GIS platforms, UAV-derived maps and AI-enabled decision support systems (DSS) allows precise navigation and control of farm machinery for variable-rate irrigation, fertigation and pesticide application, thereby improving resource-use efficiency and reducing environmental impacts (Bramley & Hamilton, 2004; Costa *et al.,* 2020) [11, 16].

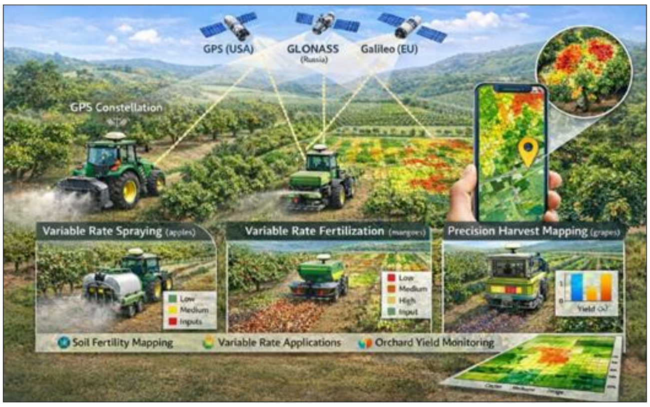

Fig 9: Schematic representation of GPS applications in fruit orchards. The infographic illustrates variable-rate spraying in apples, variable-rate fertilization in mangoes, and precision harvest mapping in grapes, guided by GPS satellite constellations (GPS, GLONASS, Galileo)

In apple and grape orchards, GPS-guided sprayers and fertigation units adjust inputs according to spatial variability in canopy vigour and soil fertility, while in mango and citrus orchards, GPS-based tree georeferencing supports targeted irrigation, mechanized pruning, and localized pest management (Pierce & Nowak, 1999; Zhang *et al.,* 2002) [46, 66]. When combined with UAV remote sensing and digital orchard mapping, GPS enables spatially explicit management decisions that enhance yield uniformity, fruit quality and sustainability in modern fruit production systems (Zhang & Kovacs, 2012) [65].

5. Variable Rate Technology (VRT) in Fruit Crops

Variable Rate Technology (VRT) enables site-specific management of inputs in orchards by integrating existing field machinery with electronic control units (ECU), onboard GPS, and sensors to adjust application rates according to spatial variability. Spray booms and spinning-disc applicators equipped with ECU and GPS allow patch-specific spraying of pesticides, while sensor driven systems adjust fertilizer application based on soil fertility or canopy vigour. In vineyards, VRT-guided nutrient management reduces variability in vine growth and enhances grape quality by applying fertilizers only where deficiencies are detected (Bramley & Hamilton, 2004; Costa *et al*., 2020) [11, 16]. Similarly, in apple and mango orchards, VRT combined with canopy vigour maps derived from UAV imagery allows precision spraying and site-specific fertigation, improving input-use efficiency and fruit uniformity (Zhang *et al.,* 2021; Popescu *et al.,* 2023) [47, 67]. By linking GPS, sensors, and automated control, VRT transforms conventional orchard machinery into precision tools, supporting sustainable and resource efficient fruit production.

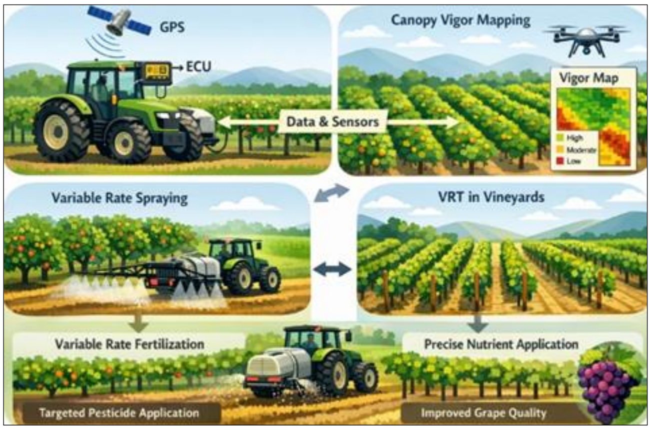

Fig 10: Variable Rate Technology (VRT) application for precision spraying and fertilization

6. Yield Monitoring in Precision Horticulture

Accurate spatial information on crop yield is a critical prerequisite for site-specific management in precision agriculture and precision horticulture. Yield mapping enables detailed analysis and evaluation of productivity variability across an orchard. While mechanized crops facilitate straightforward yield monitoring using sensors mounted on harvesters, similar technologies are increasingly adapted for tree crops. For example, in apple orchards, Li *et al.* (2020) developed a sensor equipped harvester capable of recording real time fruit weight and count, producing high resolution yield maps. Such yield monitoring systems allow orchard managers to identify low- and high yield zones, optimize input application and enhance overall productivity by integrating yield data with soil, canopy and nutrient variability.

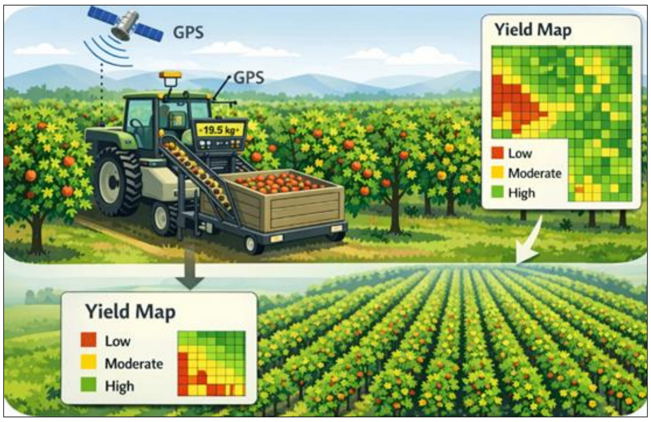

Fig 11: Sensor equipped harvester integrated with GPS for real time fruit yield monitoring and spatial yield mapping in an apple orchard, highlighting low, moderate, and high-yield zones (Li *et al.,* 2020)

7. Yield Mapping in Fruit Crops

Yield serves as the ultimate integrative indicator of spatial variability in agronomic parameters across a field or orchard. Mapping yield and analysing its correlation with spatial and temporal variability in factors such as soil fertility, canopy vigour and irrigation patterns is crucial for devising optimized management strategies for the subsequent season. In mechanized fruit crops, yield mapping can be achieved using advanced sensor technologies. For instance, in grape orchards, Tomasi *et al.* (2022) demonstrated the use of load cells integrated with harvesting conveyors to measure fruit weight in real time or arrays of ultrasonic sensors mounted above the grape discharge chute to estimate harvested fruit volume and tonnage. Such high-resolution yield maps enable precise identification of low and high yield zones, facilitating data driven interventions for precision viticulture and improved resource use efficiency

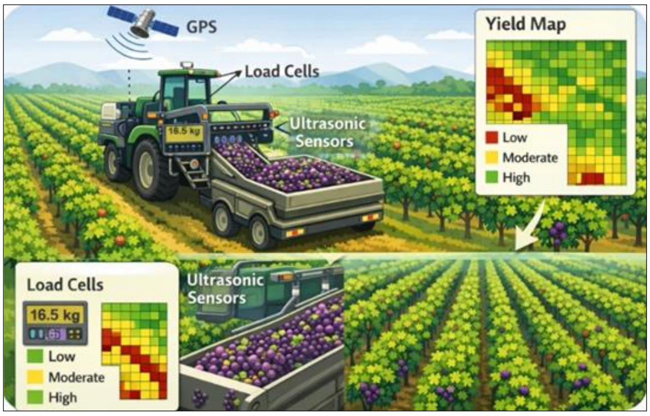

Fig 12: Sensor-equipped harvester integrated with GPS, load cells, and ultrasonic sensors for real-time yield monitoring and spatial mapping in grape orchards, highlighting low, moderate, and high-yield zones (Tomasi *et al*., 2022)

Applications of Precision Farming

a. Waste Management in Fruit Crops

Fruit crops often undergo spoilage during harvesting, handling, storage, marketing and processing, leading to significant wastage. Efficient management of this waste not only preserves essential nutrients but also reduces production costs and minimizes environmental pollution hazards (Singh & Singh, 1998). Recycling fruit waste is crucial for developing value-added products. For instance, mango seed kernel, rich in carbohydrates, fats, proteins, and minerals, can be used for extracting essential oil for soap and cosmetic manufacturing (Maini, 2004). Similarly, orange seeds provide fat and mineral matter, while apple pomace can replace fodder at 10.2 kg/day per animal without affecting health or milk yield (Singh *et al., 2007).* Citrus peels, particularly from *Galgal*, yield high-quality pectin suitable for jelly production (Maini, 2004). Additionally, fruit waste can be diverted for biogas generation and organic manure, though acidic nature requires neutralization with lime slurry for efficient fermentation (Singh *et al.,* 2005). These strategies not only enhance resource utilization but also support sustainable fruit processing industries.

b. Protected Cultivation

Protected cultivation involves greenhouses, polyhouses, shade net houses and tunnels, which are framed structures covered with transparent or semi-transparent materials to modify the microclimate and enable off-season fruit production. This technology regulates temperature, radiation, humidity and wind speed, improving growth, yield and fruit quality in crops such as banana, mango, grape, pomegranate, strawberry and lime. In banana ('Dwarf Cavendish'), Gubbuk and Pekmezci (2004) [23] reported a higher pseudostem circumference under protected cultivation (78.3 cm) compared with open field conditions (68.5 cm). In grape, Jaing *et al*. (2009) observed that plastic row covers increased air temperature while reducing solar radiation and wind speed. Similarly, Medany *et al*. (2009) found that white shade net covers in mango (cv. Keitt) reduced maximum temperatures by about 2 °C through radiation interception, thereby alleviating heat stress. Overall, protected cultivation enhances climate resilience and productivity in high value fruit crops.

c. Irrigation Management

Irrigation is a critical platform for sustainable intensification in fruit crops, enabling precise management of water and nutrients at the root-zone level. The widespread adoption of micro-irrigation systems, particularly drip and mini-sprinkler irrigation, has significantly improved water-use efficiency, reduced groundwater over-exploitation, and enhanced yield and fruit quality in crops such as banana, apple, grape, citrus, mango, and pomegranate (Narayanamoorthy, 1996, 1997 [40, 41]; Kumar *et al*., 2005; Shashidhara *et al.,* 2007).

Drip fertigation, which synchronizes irrigation with nutrient application, has proven especially effective in banana and apple, improving fertilizer-use efficiency and profitability even at reduced fertilizer doses (Bar Yosef, 1999; Narayanamoorthy, 2003; Attia *et al.,* 2018) [3, 7, 42]. Recent advances further integrate IoT-enabled soil and plant sensors, automated valves and AI-based decision support systems (DSS) to optimize irrigation timing and quantity in real time, thereby enhancing water productivity, yield stability, and climate resilience in perennial fruit orchards (Fereres & Soriano, 2007 [19]; FAO, 2017; Osroosh *et al*., 2016; Liakos *et al*., 2018) [34]. Collectively, these technologies position precision irrigation as a cornerstone of smart and sustainable horticulture.

d. Surface covered cultivation using recent technologies in precision fruit farming

Surface-covered cultivation is a key component of precision fruit farming that integrates advanced mulching materials and soil solarization technologies to improve soil microclimate, water-use efficiency, and disease management. Recent technological advancements include the use of biodegradable and photo selective mulch films, infrared-transmitting (IRT) polyethylene sheets, and sensor-assisted mulch selection, which regulate soil temperature, conserve moisture, suppress weeds, and enhance soil biological activity while reducing environmental pollution (Kasirajan & Ngouajio, 2012; Steinmetz *et al*., 2016; Bandopadhyay *et al*., 2018) [6, 27, 58]. Smart mulching systems, integrated with soil-moisture and temperature sensors and IoT-based decision support tools, enable site-specific and time-bound mulch deployment in perennial fruit orchards. Soil solarization, an eco-friendly thermal soil disinfestation technique, has been further optimized by high-transmissivity plastic films, solarization-bio fumigation combinations, and mechanized mulch laying, enhancing control of soil-borne pathogens, nematodes, and weeds (Katan, 2017). In mango orchards, polyethylene-based solarization effectively reduced the primary inoculum of *Lasiodiplodia theobromae* in nursery beds and planting pits (Khanzada *et al*., 2009) [29]. Collectively, these technologies support climate-smart, residue-free, and resource efficient soil management in modern fruit production systems.

e. Canopy Management Strategies in Precision and High-Density Fruit Orchards

Canopy management is a cornerstone of high-density (HDP) and meadow/ultra-high density planting (UHDP) systems, aiming to optimize light interception, photosynthetic efficiency, yield, and fruit quality through precise control of tree architecture. Recent advances integrate dwarfing rootstocks and interstocks, mechanized and sensor guided pruning, and UAV and LiDAR-based 3D canopy modelling to enable site-specific canopy regulation in intensive orchards. Dwarfing rootstocks such as M.9 and M.27 in apple and Vellaikulumban in mango have facilitated compact canopies suitable for HDP while improving precocity and yield efficiency (Kurian *et al.,* 1996; Robinson *et al.,* 2011) [32, 51].

In HDP systems of mango, guava, litchi, and papaya, regulated pruning and training systems maximize light distribution and operational efficiency (Nath *et al*., 2007; Lal et al.). Meadow orchard systems, particularly in guava, rely on ultra-high planting densities combined with severe mechanized pruning, resembling hedge or grassland architecture, achieving high productivity per unit area (Singh, 2008) [55]. Emerging AI-enabled decision support systems (DSS) now integrate real-time canopy geometry, vigour indices and phenological data to optimize pruning intensity and timing, positioning advanced canopy management as a key component of smart and precision horticulture.

Integrated Pest Management (Ipm)

Integrated Pest Management (IPM) in fruit crops is a holistic, ecology-based strategy that integrates biological, cultural, behavioural, host-plant resistance and need-based chemical control measures to achieve economically viable, environmentally safe and socially acceptable pest regulation. Recent advances in IPM incorporate IoT-based pest monitoring sensors, pheromone-trap automation, UAV-assisted surveillance, AI-driven image diagnostics, and decision support systems (DSS) to enable early pest detection and site-specific interventions. In apple and grape orchards, sensor-linked pheromone traps and degree-day models have improved monitoring of codling moth and grape berry moth, reducing insecticide use (Witzgall *et al.,* 2010; Knight & Light, 2013) [30, 62].

In mango and citrus, AI-enabled image analysis and remote sensing have facilitated early identification of pests such as fruit flies and citrus psyllid, supporting timely biological and behavioural control (Bebber *et al*., 2013; Liakos *et al*., 2018) [9, 34]. The integration of biological control agents, mating disruption and precision pesticide application via DSS has significantly enhanced pest suppression while conserving natural enemies, positioning advanced IPM as a cornerstone of smart and sustainable fruit production systems.

Integrated Nutrient Management (Inm)

Integrated Nutrient Management (INM) is an advanced, sustainability-oriented strategy that integrates organic nutrient sources, inorganic fertilizers, biofertilizers, and recycled residues with precision delivery technologies to enhance nutrient use efficiency, soil health and long-term productivity in fruit crops. Recent advances in INM incorporate IoT-enabled soil and plant nutrient sensors, precision drip fertigation, variable-rate fertilizer application, and AI-based decision support systems (DSS) to synchronize nutrient supply with crop demand in space and time (Liakos *et al.*, 2018; Balafoutis *et al.*, 2020) [5, 34].

In fruit crops such as banana, mango, apple, citrus and grape, the integration of organic amendments with sensor guided fertigation has improved yield, fruit quality, soil organic carbon, and nitrogen and potassium use efficiency while reducing nutrient losses and environmental impacts (Bar-Yosef, 2020; Attia *et al.*, 2018 [6, 8]; Reddy *et al.*, 2019). Emerging digital INM frameworks, combining real time diagnostics, predictive nutrient models and automation, position INM as a core component of smart, climate-resilient and environmentally benign fruit production systems (Wolfert *et al.*, 2017; Chivenge *et al.,* 2021) [14, 63].

Micropropagation In Fruit Crops

Micropropagation is an advanced plant propagation technique that enables the rapid multiplication of genetically uniform and disease free planting material from small explants under controlled *in vitro* conditions. Recent technological advances include the use of temporary immersion bioreactors (TIBs), automated culture systems, molecular indexing and AI-assisted culture optimization, which enhance multiplication efficiency, clonal fidelity and scalability. Techniques such as meristem, shoot-tip, embryo, and somatic embryogenesis cultures are widely applied in fruit crops including banana, date palm, pineapple, strawberry, citrus, pomegranate and fig. Large-scale bioreactor-based systems in banana and date palm have significantly reduced production costs while ensuring virus-free plants, positioning micropropagation as a key technology in precision and commercial horticulture (George *et al.*, 2008; Al-Khayri *et al.*, 2021; Hesami *et al.,* 2022) [2, 21, 24].

Strategies for Precision Farming in Fruit Crops

The effective adoption of precision farming (PF) in fruit crops requires coordinated public private sector support and a structured implementation framework encompassing exploration (data acquisition), analysis (variability assessment) and execution (site-specific intervention). Precision farming is founded on the principle of “heterogeneity within homogeneity,” wherein spatial and temporal variability in orchards is quantified to optimize input use efficiency (Khanna *et al.,* 1997; Maheswari *et al.,* 2008) [28, 35]. Recent advances integrate remote sensing and UAV imagery, IoT-based soil and plant sensors, AI-driven analytics, GPS guided equipment, variable-rate irrigation and fertigation, and decision support systems (DSS) to enable real-time, site-specific management in fruit crops such as mango, banana, grape, citrus, and apple (Wolfert *et al.*, 2017; Liakos *et al.*, 2018) [34, 63].

In India, despite challenges such as land fragmentation, limited access to precision infrastructure, high capital costs and skill constraints, farmers have shown strong adoption of enabling technologies like micro irrigation and protected cultivation, which serve as foundational entry points for PF implementation. Government initiatives such as the National Horticulture Mission (NHM) and allied programs have accelerated adoption by supporting technology dissemination, post-harvest infrastructure, and market integration, thereby providing growers with decision-ready, spatially explicit management tools that enhance productivity, profitability, and sustainability in fruit based production systems.

Conclusion

Precision farming has emerged as a powerful approach for sustainable intensification of fruit-crop production through the integration of digital and site-specific technologies. Innovations such as UAV-based remote sensing, IoT enabled sensors, AI-driven decision support systems, precision irrigation and fertigation, advanced canopy and nutrient management, IPM, micropropagation, and protected cultivation have significantly enhanced productivity, fruit quality and resource-use efficiency in crops like mango, banana, apple, grape, citrus and guava. While adoption in developing economies such as India is constrained by land fragmentation, cost and technological access, strong policy support particularly through the National Horticulture Mission and farmer acceptance of micro-irrigation and protected cultivation provide a strong foundation for scaling precision technologies. Future success will depend on affordable digital tools, capacity building and robust public private partnerships to ensure economically viable and environmentally sustainable fruit production systems.

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