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A Review of Planting Systems in Apple Orchards: Principles, Practices, and Performance

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Abstract

Apple (Malus domestica Borkh.) is one of the world's most important temperate fruit crops, originally domesticated in Central Asia, and in Afghanistan it plays a vital role in rural livelihoods, nutrition, and the horticultural economy. However, production remains dominated by traditional low-density orchards, which constrain yield, fruit quality, and export competitiveness. This review synthesizes literature published between 2000 and 2024 on apple orchard planting systems, examining layout design, planting density, rootstock–scion combinations, and training methods through a review of peer-reviewed articles, technical reports, and institutional publications. Findings highlight that high-density (HDP) and ultra-high-density planting (UHDP) systems using dwarfing rootstocks such as M.9 and T337, combined with modern training techniques like Tall Spindle, Bi-Axis, and Vertical Axis, significantly improve early yield, fruit quality, and resource-use efficiency, while precision agriculture tools including RTK-GNSS planning, UAV-SLAM mapping, and sensor-based fertigation further enhance orchard performance. Despite these benefits, adoption in Afghanistan remains limited due to high establishment costs, inadequate technical expertise, and restricted access to improved planting materials. Transitioning towards modern orchard systems, supported by localized research and technological innovation, offers a sustainable pathway to increase apple productivity and strengthen competitiveness in developing regions.

Key words: Apple orchards; High-density planting; Orchard layout; Rootstock; Sustainable horticulture; Training systems

د مڼو د باغونو د کښت سیستم ته بیاکتنه: اساسات، طریقې او کړنې

رحمت گل حسن زی[1]، محمد نسیم ایوبی[1]
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لنډیز

مڼه (*Malus domestica* Borkh) د نړۍ له مهمو معتدله مېوو څخه گڼل کېږي چې په اصل کې په منځنۍ آسیا کې اهلي شوې ده. په افغانستان کې د مڼو کښت د کلیوالو خلکو د ژوند، تغذې او د باغداري اقتصادي پرمختگ لپاره حیاتي ارزښت لري. سره له دې، تولید لاهم تر دودیزو کموگڼو باغونو پورې محدود دی، چې په حاصل، د مېوو کیفیت او صادراتو په سیالي منفی اغېزې لري. دغه بیاکتنه د ۲۰۰۰ او ۲۰۲۴ کلونو تر منځ د منې د باغونو د کښت سیستمونو اړوند علمي آثار څېړي او د باغ د نقشې جوړښت، د ونو تراکم، د نیله بوټي او پیوند د ترکیبونو او د روزنې طریقو ارزونه کوي. دا څېړنه د علمي مقالو، تخنیکي راپورونو او مؤسسو د خپرونو یوې منظمې بیا کتنې له لارې ترسره شوې ده. دغه څېړنه په بېلابېلو اقلیمي ـ کرنیزو زونونو کې د باغ په هندسي جوړښت، د کښت تراکم او د روزنې په سیستمونو تمرکز کوي. د دغه بیاکتنې موندنې

څرګندوي چې د لوړ تراکم (HDP) او ډېر لوړ تراکم (UHDP) کښت سیټمونه، چې د M9 او T337 نیله بوټو او Tall Spindle، Bi-Axis، او Vertical Axis روزنې تخنیکونو په کارولو سره عملي کېږي، د حاصلاتو لوړونې، د مېوې کیفیت او د سرچینو د کارونې ورتیا په څرګند ډول ښه کوي. د کره کرنې وسایل لکه د RTK-GNSS پلان جوړونه، د UAV- SLAM نقشې اخیستنه، او د سینسر پر بنسټ سره ورکونه، لا زیات د سیستم کړنه پیاوړې کوي. سره له دې ګټو، د دغو سیستمونو منل د لوړو لومړنیو لګښتونو، تخنیکي مهارتونو د کموالي او د معیاري توکو د محدود لاسرسي له کبله محدود پاتې دي. د سیمه ییزو څېړنو او ټکنالوژۍ په حمایت سره عصري سیستمونو ته تګ، په مخ پر ودې سیمو او هیوادونو کې د مڼو د تولید د لوړولو ښه تګلاره ده.

کلیدي ټکي: د مڼو باغونه؛ لوړ تراکم کښت؛ نیله بوټي؛ د روزنې سیستمونه؛ د باغ نقشې جوړښت؛ کره کرنه؛ پایداره باغداري

Introduction

Apple (Malus domestica Borkh.), which originated in Central Asia (Kazakhstan, Kyrgyzstan, China, and Kashmir) more than 4,000 years ago, is the fourth most cultivated fruit in the world after citrus, grapes, and bananas (Akšić et al., 2022). In terms of both production volume and economic value, apples rank among the most significant temperate fruit crops globally. China produced about half of the world's 93 million metric tons of apples in 2022, with the United States, Turkey, and Poland following as major producers (FAO, 2023).

Afghanistan ranks 36th in the world for apple production, making it an important part of the horticultural industry. In 2022, the country produced over 318,000 tons of apples, accounting for roughly 0.33% of global production. This success highlights not only Afghanistan's agricultural potential but also its opportunities for economic growth and export development. With proper investment and infrastructure improvements, Afghanistan could further enhance its position in the global market (FAO, 2023). National production has grown significantly over the last five years, rising from 217,000 tons in 2018 by more than 46%. In 2019, about 27,559 hectares were planted with apples, with an average yield of 9,038 kg/ha, reflecting growing demand driven by both domestic consumption and export opportunities (ASSAM, 2019).

From 2007 to 2019, Wardak province consistently led Afghanistan in apple production, contributing around 29% of the country's total cultivated area and output (Wardak et al., 2024). Most apples are consumed domestically or exported to nearby countries such as India and Pakistan, yet the industry has considerable room for growth, particularly through value-added processing, cold storage, and improved post-harvest handling.

Over the past decade, apple orchard design and management have undergone substantial changes in response to consumer demand and the need to improve orchard profitability. The planting system—which includes rootstock–scion combinations, training and pruning techniques, tree density, and spatial arrangement—is one of the most critical factors in this transition. Although innovative planting systems have recently been introduced with limited success, conventional methods still dominate (Rehman & Mubarak, 2023). These technologies were initially adopted in more developed apple-growing regions to overcome production and quality constraints.

In traditional plantation systems, only about 270 trees per hectare are planted. However, with the increasing use of growth-controlling rootstocks, densities have risen significantly: 444 plants per hectare with semi-vigorous rootstocks like MM.111, 1,333 plants per hectare with semi-dwarfing rootstocks like MM.106, and up to 3,333 plants per hectare with dwarfing rootstocks such as M.9. Achieving high yields and high-quality fruit suitable for consumption requires appropriate planting designs and rootstock combinations (Uselis, 2020). Despite these advances, numerous edaphic, climatic, pathological, entomological, and management-related challenges continue to affect orchard systems (Bhat & Choure, 2014).

With an emphasis on their structural designs, guiding principles, and performance outcomes, this review aims to present a comprehensive synthesis of planting systems in apple orchards. With a focus on sustainability and region-specific adaptations, the paper critically analyzes recent developments, difficulties, and innovations in planting system techniques. This report attempts to direct future orchard development and research efforts toward more resilient, sustainable, and productive apple production systems by combining the results of recent studies.

Methodology

The review employed a narrative approach to collect, analyze, and synthesize literature on apple orchard planting systems. A comprehensive search across Scopus, Web of Science, Google Scholar, and Science Direct (2000–2024) used keywords such as *apple orchard planting systems, high-density planting in apples,* and *orchard performance.* Only peer-reviewed and relevant studies were included. Data on traditional, semi-dwarf, and high-density systems were extracted, focusing on principles, yield, fruit quality, and resource efficiency. A Comparative analysis assessed performance across agro-climatic conditions, with a focus on key apple-growing regions, adoption challenges, technological gaps, and extension needs. References were documented in a consistent academic format for reliability.

Result and discussion

Principle of apple orchard layout

To increase productivity and sustainability, apple orchard architecture principles place a strong emphasis on creating a system that incorporates ecosystem services and supports a diverse range of perennial plants. Traditional orchards mostly grow single-variety apples with consistent spacing, frequently using soil cultivation and pesticides to keep weeds and other pests under control, which over time can deteriorate soil health. (Hoagland et al., 2008; Yao et al., 2005). To improve soil microbial activity, nutrient cycling, and overall ecosystem function, contemporary methods influenced by forest garden systems incorporate a variety of plantings, including living mulches and organic amendments. (Hoagland et al., 2008). To minimize the need for synthetic inputs and address problems such as replant disease, which is caused by soil nutrient imbalances and pathogen accumulation, proper orchard design involves selecting suitable spacing and rootstocks while promoting ground cover diversity (Leinfelder and Merwin, 2006). By simulating natural forest ecosystems with a variety of plant layers and microbiological support, this holistic design philosophy seeks to achieve long-term system health, resilience, and productivity in addition to short-term apple yields.

Types of planting systems and canopy management

Traditional planting system in apple orchards

A single apple variety is usually planted in rows that are widely apart in traditional apple orchard planting schemes to facilitate tree growth and care. To manage weeds, pests, and diseases, these orchards frequently rely on traditional methods including soil tillage, herbicide use, and pesticide treatments. Although the primary goal of this strategy is to increase apple production, it may ultimately lead to soil degradation and harm biodiversity.

(i) **Square system:** One of the simplest and most widely used planting techniques for fruit trees is the square system, in which plants are evenly spaced within and between rows to create squares and perfect right angles (Fig. 1). The plan is made simpler by the consistent spacing, which also makes it easier to perform cross-cultural tasks like watering, weeding, and harvesting from both sides. Furthermore, due to the regular spacing, gardeners can plant quick-maturing crops, such as vegetables or bananas, between the trees, which can yield additional revenue. Orchardists prefer the square system because of its effectiveness and simplicity (Singh, 2022).

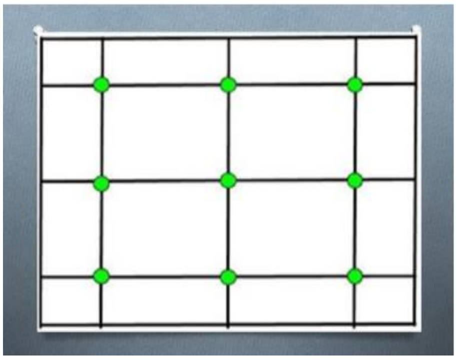

Fig. 1: Square system of planning
Source: http://www.ecofarming.rdagricul-

(ii) **Rectangular system:** The field is arranged in a rectangular plan with extra space between rows (Fig. 2). One side of the field has straight rows of trees placed at right angles to each other. A rectangle is formed by four trees linked at the base, and the distances between plants and rows are different. Similar to the square system, there are two ways to carry out intercultural activities such as irrigation and farming. Sunlight and adequate space are essential for the growth and development of plants (Singh, 2022).

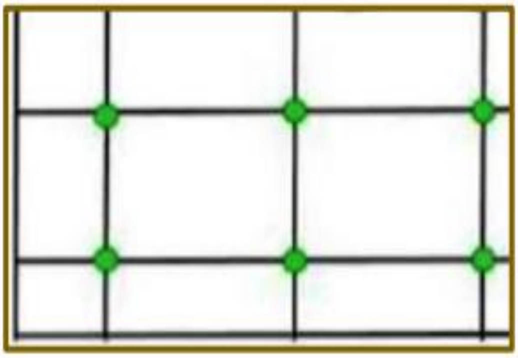

Fig. 2: Rectangular system of planning
Source: http://www.ecofarming.rdagriculture.in

(iii) **High-density planting in apples:** Between 2020 and 2024, high-density apple orchards with planting densities of up to 3,333 trees per hectare demonstrated improved agronomic and economic performance. According to a study conducted in Manang, Nepal, high-density systems demonstrated both quicker payback and greater profitability delivering a benefit-cost ratio of 3.47 by year 7, as opposed to typical plants' 0.35–1.72 ratio (Bhatta and Paudel., 2022). The vegetative growth, leaf nutrient status, and production efficiency of high-density "Super Chief" apple orchards in India that were irrigated by drip irrigation and fertigation between 2021 and 2023 demonstrated notable gains. (Sharma et al., 2024). Furthermore, additional watering or fertigation dramatically increased early tree vigor and fruit output over five years period in a study comparing irrigated and non-irrigated high-density orchards in New York (Ladon et al., 2024). All of these studies emphasize that high-density planting offers a profitable and sustainable approach to contemporary apple production when paired with focused water and nutrient management.

(iv) **Ultra-High Density Planting (UHDP) in Apple Orchards:** When planting apple orchards in ultra-high density, dwarf or semi-dwarf rootstocks, such as M.9 and T337, are frequently used in high-density configurations (e.g., 2,222 trees/ha at a 1.5 × 3 m spacing). In comparison to rainfed controls, a 2020 study on "Super Chief" apples in Kashmir revealed that employing drip irrigation with 100% Etc[1] doubled production and improved vegetative growth indicators (such as plant girth, height, and leaf area) by more than 50%, indicating the high feasibility of UHDP[2] systems (Mushtaq, 2020). Over the course of two seasons, drip-fertigation is used in dense apple plantings. In addition to improving leaf nutrient status and vegetative growth, it reported 50–60% water savings, 76% yield improvements, and 50–60% labor efficiency advantages, demonstrating how optimal water + nutrient delivery improves UHDP performance (Sharma et al., 2024). In a different field experiment conducted in New York in 2024, fertigation and irrigation were contrasted in young,

[1] ETc- Evapotranspiration conditions
[2] UHDP- Ultra high-density planting

dense plants (rootstocks M.9/B.9). Even in humid regions, fertigation and irrigation both greatly enhanced early tree growth and yield when compared to non-irrigated controls, making them profitable practices (Dominguez and Robinson, 2024).

Popular training systems

Choosing the right rootstock, cultivar, and training technique is a crucial financial choice for effective orchard management. The benefits of using new rootstocks to increase fruit harvests and enhance tree performance have been shown in numerous studies. Likewise, it has been demonstrated that training programs significantly impact the horticultural and financial performance of orchards (Gonzalez Nieto et al., 2023; Lordan et al., 2018a, b; Reig et al. 2019; Robinson et al., 2007a, b). One of the most important steps in orchard design is choosing a training system. The Tall Spindle, Central Leader, Fruiting Wall, Palmette, Slender Pyramid, Slender Axis, Slender Spindle, Solaxe, Super Spindle, Vertical Axis, V-shaped, and Y-trellis are some of the new training systems that have been created in recent decades (Reig et al., 2019; Robinson, 2003a). Specific tree training, such as tree shape, rootstock, and tree density, varies between modern orchard planting methods. This frequently leads to variations in total light interception, light distribution under the canopy, and the harmony between cropping and vegetative development (Robinson, 2003a).

(i) **Spindle bush:** Two key leader-based training techniques used in apple orchards to maximize fruit yield, canopy structure, and light distribution are the spindle bush system and the cone system (Fig. 3). With buds 75–90 cm above the ground, trees in the cone system are planted in rows 1.5–2.0 m apart and 4–4.5 m apart. In order to encourage balanced growth and prevent arching, which might result in powerful upright shoots, branches with naturally wide angles are chosen and trained to approximately 30 degrees above horizontal (Janbandhu et al., 2023). In contrast, the spindle bush method, which is commonly employed with dwarfing rootstocks such as MM106, creates a compact, conical canopy with spreading lateral branches. The impact of precise training and canopy control on productivity was demonstrated by a comparative study that revealed the more structured cone system produced significantly more fruit (160.6 t/ha vs. 111.6 t/ha) and a higher proportion of large, marketable apples over 80 mm in diameter, despite the spindle bush being easier to manage. (Gandev, 2009).

Fig. 3: Spindle Bush system
Source: (*Janbandhu et al.,* 2023).

(ii) **Super spindle:** A central leader training system, dwarfing rootstocks, and extremely tight tree spacing (20 to 40 inches apart) are characteristics of the Super Spindle Axe (SSA), a high-density apple orchard system (Fig. 4). High yields per acre and early fruiting are encouraged by this arrangement. The SSA is labor-intensive yet efficient in terms of land use and early returns because it depends on base flower buds on one-year-old shoots for fruit production and necessitates the annual renewal of almost all lateral branches. However, elements like labor expenses and rootstock selection may have an impact on its economic viability (CAB[3] International, 2003).

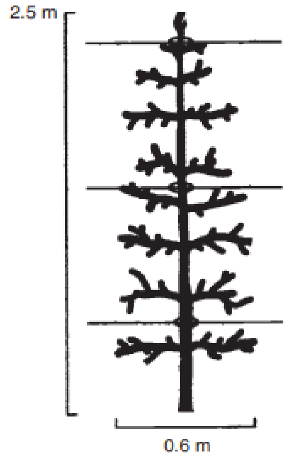

Fig. 4: Super-spindle
Source: (CAB International, 2003)

[3] CAB- Central for Agriculture and Biosciences

(iii) **Slender spindle:** The slender spindle system was developed in Northern Europe (Fig. 5). According to this approach, a wooden stake that is eight feet long and three inches in diameter must be used to support each tree. As an alternative, if each tree is supported by a high-tensile wire 8 to 9 feet above the ground, smaller diameter pegs, bamboo, conduit, or angle iron can be positioned next to it. The wire is attached to stakes that are 5 to 6 inches in diameter and 8 to 9 feet above the ground. Annual cutting into 2-year-old wood on the leader to a weak side limb controls excess vigor in the tree top and helps the tree grow into a tight conical shape. Because the lower parts of the canopy are shaded and tree tops grow too quickly, this method has not worked effectively in Virginia (Marini and Sherif, 2025).

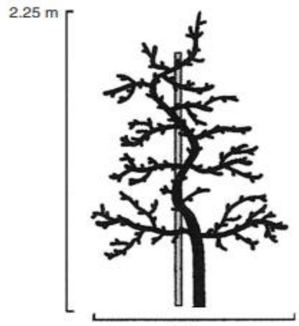

Fig. 5: Slender spindle
Source: CAB International, 2003)

(iv) **Tall spindle:** Early production, better fruit quality, and lower expenses for training, trimming, and spraying are all ways that the Tall Spindle planting strategy increases profitability (Hoying et al., 2016). Using highly feathered nursery trees enables high-density orchards using the Tall Spindle technique to achieve notable yields in the second and third years (Dominguez, 2015; Robinson, 2007) (Fig. 6). The ideal trees for these systems have 10–15 feathers and a minimum stem diameter of 15 mm (Dominguez, 2015; Reig et al., 2019). One well-liked choice for replanting orchards is the Tall Spindle system. However, the cost of each tree has a direct correlation with the investment cost (Reig et al., 2019).

Fig. 6: Tall spindle
Source:(Mir et al., 2022)

(v) **Vertical axis:** A slender, upright central leader with little lateral branching is used in this high-density orchard technique, which is frequently held aloft by a trellis to optimize air circulation and light interception (Fig. 7). In order to maximize space usage and encourage early fruit production, trees are planted tightly together, usually 2 to 3 feet apart. By increasing fruit exposure to sunshine and enhancing canopy ventilation, this technique lowers the incidence of illness. To preserve a manageable tree size and ideal fruiting structure, it works exceptionally well when paired with precision pruning methods and dwarfing rootstocks (Warmund, 2014).

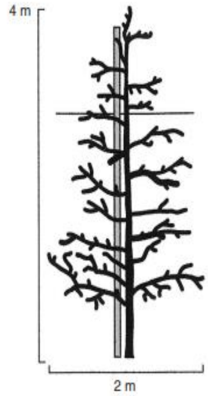

Fig. 7: Vertical axis
Source: CAB International, 2003)

(vi) **Bi-Axis:** In order to enhance light interception, boost productivity, and streamline orchard management, the bi-axis training system for apple trees (*Malus x domestica* Borkh.) is becoming a viable substitute for conventional tall spindle systems in Europe (Musacchi, 2008; Robinson et al., 2013; Dorigoni et al., 2011). This technique produces a narrow, flat canopy by training two vertical stems, each fashioned like a slender spindle, on a single rootstock (Musacchi, 2008). Better light penetration throughout the tree is made possible by this structure, which raises photosynthetic efficiency, improves flower bud development, and produces more consistent fruit colors (Yang et al., 2021). Furthermore, pruning is made easier with an emphasis on thinning and renewal cuts due to the absence of large lateral branches; it is even compatible with mechanical pruning (Dorigoni et al., 2011). In addition to showing improved fruit quality and output, bi-axis-trained trees also provided easier mechanization and labor savings. In areas like South Korea, where existing tall spindle systems (up to 5 meters) make it challenging to operate orchards efficiently, the bi-axis system is being viewed as a potential solution because of these advantages. (Robinson et al., 2013; Dorigoni et al., 2011).

Impact of planting systems on orchard performance

An orchard's planting method has a significant impact on labor efficiency, fruit quality, light distribution, pest and disease control, and production per hectare. By employing dwarfing rootstocks and sophisticated training techniques including vertical axis, slender spindle, and Tatura trellis, high- and ultra-high-density systems, enable more trees per unit space, thereby boosting productivity. By enhancing light interception and photosynthesis, these systems enhance canopy structure, leading to more consistent fruit development and improved color. Light penetration is further enhanced by new training techniques, such as centrifugal system. The hexagonal pattern with North-South row orientation is an ideal orchard layout because it maximizes solar exposure, which enhances fruit quality and tree health. Additionally, dense planting increases air circulation, which slows the spread of illnesses and pests. Effective design facilitates the integration of mechanization and the management of cultural activities. All things considered, a carefully thought-out planting method guarantees the best possible use of available space and resources, resulting in a high yield and long-term fruit production (Javaid et al., 2017).

Table 1. Comparison of high-density plantation with traditional orchard system in apple

Parameter	Traditional orcharding	HDP (Recommended)
Planting density	100-278 plants	2222-3333 plants
Training system	Centre leader, open center, modified central leader system	Tall spindle and Espalier
Precocity	Bearing starts after 6-8 years of plantation	Highly precocious (bearing starts after the second year of plantation
Productivity	Low (<20t/ha)	High (>60 t/ha)
Yield potential	Low	High
Fruit quality	Low, due to low photosynthetic photon flux density (PPFD) and less penetration and diffusion of photosynthetically active radiation (PAR)	High, due to photosynthetic photon flux density (PPFD) and more penetration and diffusion of photosynthetically active radiation (PAR)
Input use efficiency	Low	High
Disease incidence	High, this is due to dense canopy and low air circulation through the canopy	Low, which is due to a sparse canopy and more leaf area index
Mechanization	Difficult	Easy and cost-effective

Source: Mir et al., (2022)

Technological innovation

GPS-based layout design

Fruit orchards are using more GPS[4]- and GNSS[5]-based layout systems to increase planting accuracy, crop monitoring, and self-sufficient operations. Recent developments have shown how well RTK[6]-GNSS can be integrated with LiDAR[7] and IMU[8] sensors to provide real-time mapping and high-accuracy navigation in orchard settings. For instance, Wang et al., (2024) used RTK-GNSS, LiDAR, and IMU to create an integrated navigation system for an orchard-dosing robot that was aided by Kalman filtering methods and LIO-SAM[9]. Field tests demonstrated the system's accuracy and dependability in challenging orchard circumstances, with a global localization accuracy of roughly 2.2 cm and a lateral deviation kept below 10 cm. Wang et al., (2024). In order to enhance the accuracy of orchard layout and facilitate optimal planting designs, 3D mapping systems utilizing UAV-SLAM[10] in conjunction

[4] Global Positioning System
[5] Global Navigation Satellite System
[6] Real-Time Kinematic
[7] Light Detection and Ranging
[8] Inertial Measuring Unit
[9] Lidar Inertial Odometry via Smoothing and mapping
[10] Simultaneous Localization and Mapping

with RTK-GNSS have been created to produce comprehensive spatial data. An unmanned aerial vehicle (UAV) fitted with LiDAR and GNSS/IMU sensors was used by Nishiwaki et al., (2024) to collect high-density point cloud data of orchard environments. Through the use of simultaneous localization and mapping (SLAM) algorithms and RTK-GNSS georeferencing, their system generated precise 3D maps with a vertical root mean square error (RMSE) of 5.43 cm and a horizontal RMSE of 2.14 cm. Better light interception, more effective row spacing, and effective orchard management are all made possible by this accurate mapping technique. Furthermore, RTK-GNSS systems have proven to operate reliably under tree canopies; in forests and orchards, repeatability errors have been found to range from 1 to 12. The accuracy and repeatability of RTK-GNSS have been assessed in challenging circumstances by studies such as Eren et al., (2025), demonstrating its applicability for precision surveying applications under dense canopy cover. Together, these cutting-edge positioning technologies provide improved automation, effective resource management, and accurate orchard planning in fruit crop production systems.

Sensor-based planting and fertigation

By providing accurate, real-time input management, sensor-based planting and fertigation using IOT[11] technologies provide a notable advance over conventional basin approaches in citriculture. Meshram et al., (2024) conducted a two-year study on Nagpur assessing three fertigation schedules that corresponded with important phenological stages, and four sensor-regulated irrigation levels based on volumetric moisture content (VMC). The I4F1 treatment (25% VMC with optimum fertilization produced the best results, significantly increasing plant growth, canopy volume, relative leaf water content, and A-grade fruit output. Because boron and zinc were applied stage-specifically, this treatment significantly enhanced fruit quality characteristics like juice content, TSS, and TSS: acid ratio. In addition, I4F1 preserved 65–87% more nutrients and 20–30% more water than traditional techniques. These results validate that, in citrus production, combining sensor-based planting and fertigation ensures increased water productivity, improved nutrient-use efficiency, and enhanced fruit quality.

Challenges and limitations

By facilitating early yields, maximizing land use, and improving resource efficiency, High-Density Planting (HDP) raises orchard productivity and profitability. It promotes sustainable growth, reduces labor costs through simplified management, and supports modern methods such as drip irrigation (Subedi et al., 2020). High initial expenses, a shorter orchard lifespan, the need for specialized maintenance, limited space for intercropping, and increased insect risks are some of the challenges HDP faces. Adoption is further impeded by mechanization challenges, limited rootstock supply, and a lack of technical expertise (Subedi et al., 2020). Better marketing and technical assistance are needed in Himachal Pradesh, as farmers face challenges including high input costs, disease control issues, inadequate guidance, volatile markets, and environmental problems such as hail (Singh et al., 2023).

Conclusion

1. **Summary of Key Findings:**

In order to increase apple orchard productivity, sustainability, and profitability, this review highlights the importance of planting strategies. High-density planting (HDP) and ultra-high-density planting (UHDP) systems have been shown to produce noticeably higher yields, better fruit quality, and increased input use efficiency, even if traditional systems with low planting densities are still widely used. When paired with dwarfing rootstocks, training techniques including Tall Spindle, Vertical Axis,

[11] Internet of things

and Bi-Axis maximize canopy structure, light penetration, and space utilization. Furthermore, technological advancements such as sensor-regulated fertigation, UAV-SLAM, and GPS/GNSS-based layout mapping have enabled precise, data-driven orchard management. However, significant obstacles still exist, including high initial costs, the need for trained labor, and limited access to rootstocks and modern machinery.

2. Recommendations for Future Orchard Design:

To design productive and sustainable orchards:

- ❖ Adopt HDP/UHDP systems using dwarfing or semi-dwarfing rootstock based on regional conditions.
- ❖ Choose modern training systems (e.g., Tall Spindle, Vertical Axis) to improve fruit quality and reduce labor costs.
- ❖ Implement precision agriculture tools**,** such as RTK-GNSS, LiDAR, and soil moisture sensors, to enhance layout accuracy, irrigation control, and fertigation.
- ❖ Optimize row orientation (preferably North–South) and planting geometry (square or hexagonal) for better sunlight interception and mechanization.
- ❖ Incorporate diverse ground cover and sustainable practices to reduce synthetic inputs and enhance long-term soil health and orchard resilience.

3. Research Gaps and Future Directions:

There are several areas where further investigation is needed:

- ❖ Regional trials to evaluate the long-term performance of HDP/UHDP systems in different agro-climatic zones, especially in South and Central Asia.
- ❖ Cost-benefit analyses to guide farmers on profitability, investment risks, and return periods for various planting systems.
- ❖ Development and distribution of locally adapted rootstocks for disease resistance and climate resilience.
- ❖ Studies on adoption barriers and support systems (e.g., farmer training, subsidies, or cooperatives) to encourage technology uptake.
- ❖ Climate-smart orchard models that incorporate ecosystem services, carbon sequestration, and adaptive responses to extreme weather.

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