

# A Review on Advances in High-Density Planting Systems for Fruit Crops

## Abstract

High-density planting (HDP) and super-high-density (SHD) systems have changed modern fruit production. They boost early yields, improve land use, allow mechanization, and enhance orchard and vineyard economics. Recent developments include selecting rootstocks and scions (dwarfing and semi-dwarfing rootstocks), creating new training and canopy designs (hedgerows, vertical canopies, trellis and V-systems), delivering water and nutrients precisely (drip irrigation and fertigation), using mechanized operations (pruning and harvest platforms), and integrating sensors and decision support. This review summarizes recent literature from 2020 to 2025. It highlights major technological and agricultural advancements, discusses benefits and challenges (like pest and disease dynamics, nutrient and water management, and establishment costs), and identifies research gaps and future directions for scaling HDP in temperate and subtropical fruit systems.

## Keywords

high-density planting (HDP), super-high-density (SHD), dwarfing rootstocks, canopy training, mechanization, fruit crops

## 1. Introduction

High-density planting (HDP) is a paradigm change in fruit production, focusing on more efficient land use, increased early yields, and more efficient orchard management (Ahmad, 2001). Differing from traditional orchards, where wider tree and canopy spacing lead to delayed fruiting and poor light use efficiency, HDP minimizes spacing and regulates tree or vine vigor using rootstock, canopy training, and input control (Yadav, 2020). This enables increasing numbers of plants to be housed per unit area, resulting in earlier maturation and greater cumulative yields over the productive life of the orchard.

**Table-1: Genetically Dwarf Scion Varieties of Fruit Crops (Saroj & Singh, 2018)**

<b>Fruit Crop</b>	<b>Dwarf/Compact Varieties</b>	<b>Key Characteristics</b>
Apple	Red Chief, Oregon Spur, Red Spur, Stark Spur Gold, Well Spur, Starkrimson Delicious	Bear more spurs, dwarf stature, high yield
Cherry	Lambert, Meteor, North Star	High yielding, self-fruitful, dwarf
Guava	Pant Prabhat	Less spreading, high yielder
Mango	Amrapali	Precocious, regular bearer
Litchi	Calcutta, China	Upright growth habit
Papaya	Pusa Nanha, Pusa Dwarf, Red Lady	Dwarf, tend to bear at lower height

Peach	Red Heaven, Candor	Dwarfing, high yielding
Sapota	PKM-1, PKM-3	Columnar shape, dwarf stature

HDP has evolved most significantly in apple, citrus, grapes, guava, mango, stone fruits, and nut crops like almond, where traditional systems cannot cope with the economic and labor demands of contemporary agriculture (Kumar, et al., 20021). In such crops, conventional open-vase or typical bush orchards are increasingly being replaced by hedgerow, vertical axis, spindle, and trellised systems that optimize canopy efficiency and fruit quality (Mitra, et al., 2017). Not only are these methods more efficient at intercepting light, but the cost and drudgery of cultural operations are lowered, allowing mechanization of pruning, spraying, and harvesting.

### High Plant Density and Planting System

Plant density exerts a significant influence on tree size, yield, and light interception the latter being the single most important determinant of orchard productivity. Tree density is largely governed by factors such as the vigor of the scion and rootstock combination, along with soil fertility status. The concept of optimum density refers to the planting arrangement that ensures maximum light distribution and interception within the canopy, thereby enhancing photosynthetic efficiency and yield potential. For instance, the combination of dwarfing rootstocks with spur-type varieties produces considerably smaller trees compared to the same rootstock paired with non-spur types (Robinson, 2014). In high-density apple orchards, a spacing of 1 m × 3 m between trees and rows is generally recommended to maintain canopy balance and productivity.

Beyond simple spacing adjustments, manipulation of planting systems also plays a critical role in optimizing orchard performance. Common arrangements include single hedgerow, double hedgerow, paired planting, and cluster planting. In pineapple, the cultivars ‘Kew’ and ‘Queen’ have shown remarkable suitability for high-density planting under the double-row system, where suckers or slips are planted at 25–30 cm within rows, 45–60 cm between rows, and 90–105 cm between beds. This system accommodates up to 63,000 plants per hectare, substantially increasing yield potential.

Similarly, in guava, superior fruit quality can be achieved from varieties such as ‘Allahabad Safeda,’ ‘Lalit,’ and ‘Sardar (L-49)’ through the integration of judicious canopy management and well-designed tree training systems (Singh, 2008). Under meadow orcharding, trees planted at a spacing of 2.0 m × 1.0 m can accommodate up to 5,000 plants per hectare. Regular topping and hedging during the initial growth stages assist in controlling tree size while extending the period of fruit availability (Goswami et al., 2014).

Together, these examples highlight how high-density orchard systems, when coupled with suitable training, canopy management, and crop-specific adaptations, can significantly enhance fruit yield and quality on a sustainable basis.

### Table-2: High Plant Density and Planting Systems in Different Fruit Crops

Crop	Variety/Scion Type	Spacing & Planting System	Plant Density (plants/ha)	Special Management/Remarks
Apple	Spur-type on dwarfing rootstocks	1 m × 3 m (row × tree) spacing	~3,333	Ensures optimum light interception; canopy balance critical (Robinson, 2014).
Pineapple	'Kew', 'Queen'	Double-row method: 25–30 cm (within row), 45–60 cm (between rows), 90–105 cm (between beds)	~63,000	Highly suitable for HDP; uses slips/suckers; improves yield and quality.
Guava	Allahabad Safeda, Lalit, Sardar (L-49)	2.0 m × 1.0 m under meadow orcharding	~5,000	Regular topping and hedging; judicious canopy management; improves fruit quality (Singh, 2008).
General	Spur vs. Non-spur types	Depends on scion × rootstock vigor	Varies	Spur types on dwarf rootstocks yield smaller trees; better suited for HDP.

**Table-3: Types of High-Density Planting (HDP) Systems**

(Radha & Mathew, 2007)

Type of HDP	Plant Density (plants/ha)
Low High-Density Planting	70–250
Moderate High-Density Planting	250–500
High High-Density Planting	500–1250
Ultra High-Density Planting	>1250
Super High-Density Planting	20,000

During the last two decades, key technological developments have facilitated widespread adoption of HDP and super-high-density (SHD) systems (Joshi, et al., 2020). Dwarfing and semi-dwarfing rootstocks now play a pivotal role in vigor management, while advancements in canopy training (e.g., slender spindle, Tatura trellis, V-shaped and Y-shaped systems) have maximized light interception and promoted mechanization (Anthony, 2017). Integration of micro-irrigation, fertigation, growth regulators, and precision orchard management tools has also enhanced system sustainability.

**Table-4: Categories of High-Density Orchard Planting Systems**

Category	Plant Density (plants/ha)	Rootstock Type	Management Practices	Time to Potential Production	Orchard Life/Notes
Low Density Planting	70–250	Seedling / Vigorous	Minimal training & pruning; low inputs; non-intensive	15–20 years	Long orchard life (~40 years); traditional & popular among growers
Medium Density Planting	250–500	Semi-dwarf	Proper training & pruning; higher labor & management needed	9–15 years	Higher yield & quality fruits; long productive life
High Density Planting	500–2000	Dwarfing rootstocks	Rigorous training & pruning; chemical use; technical backup needed	6–9 years	Higher yield but higher expenses; requires skilled management
Ultra High Density Planting	2000–5000	Dwarfing rootstocks	Severe pruning & canopy management; chemical & nutrient support	4–7 years	Requires technical backup & precision management
Super High Density Planting	5000–10000	Dwarfing rootstocks	Severe top pruning (grassland mowing type); heavy use of PGRs	1–2 years	Very high yield potential; early returns; intensive care required
Meadow Orchard	10000–100000	Dwarfing rootstocks	Severe top pruning (grassland mowing type); canopy & nutrient management;	1–2 years	Extremely intensive; ultra-modern system with very high input requirement

			heavy PGR use	
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**Table-5: High-Density Planting in Guava (Singh, 2008)**

Planting Option	Row-to-Row Distance (m)	Plant-to-Plant Distance (m)	Plant Density (trees/ha)	Remarks
A	3.0	1.5	2222	Very high density for early and quality production
B	3.0	3.0	1111	High density for improved yield and management
C	6.0	3.0	555	Moderate density, traditional spacing with pruning

Yet, challenges exist. High cost of establishment, increased susceptibility to biotic and abiotic stresses, intensive management requirement, and long-term sustainability issues (soil health, pest population dynamics, replant problems) restrict extensive application, especially in smallholder-dominated parts of Asia and Africa (Choudhary, et al., 2020). Research is therefore ongoing to find cost-effective rootstocks, inexpensive training systems, integrated pest management practices, and digital solutions to precision decision-making.

This review integrates recent developments in high-density and super-high-density fruit production systems (2020–2025). It identifies major technological interventions, records benefits and limitations, and pinpoints areas of research gaps that require filling to enable broader scaling of such systems in various temperate, subtropical, and tropical environments.

**Table 6: Comparison between Traditional Planting System and High-Density Planting (HDP) System for Fruit Crops**

Attributes	Traditional Planting System	HDP / Meadow Orchard System
<b>Plant Density</b>	Few large trees (70–250 trees/ha)	Many small trees (250–100,000 trees/ha)
<b>Precocity</b>	Very late (after 3 years)	Very early (from 1st year)
<b>Productivity</b>	Low yield	Very high yield
<b>Management</b>	Difficult due to large tree size	Easy due to small tree size
<b>Labor Requirement</b>	More	Less
<b>Production Cost</b>	Higher	Lower
<b>Harvesting</b>	Difficult	Easy

<b>Quality</b>	Large canopy, poor air & sunlight penetration, poor fruit quality	Small canopy, better air & light penetration, minimum disease incidence, high-quality fruits with good color
<b>Establishment Cost</b>	Less	Very high
<b>Machinery Use</b>	Difficult to use	Required for reducing cost

## 2. Scope and Search Approach

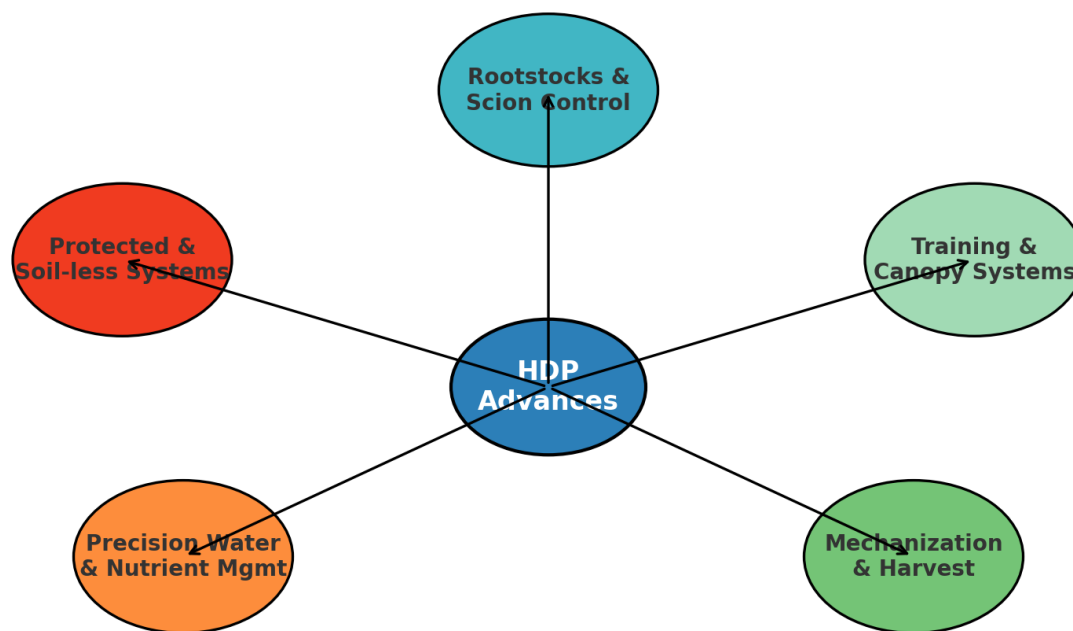
The current review integrates recent developments in high-density and super-high-density fruit crop planting systems. Literature between 2018 and 2025 was reviewed, with preference to peer-reviewed journal articles, extension bulletins, technical reports, and new review articles (Costa, et al., 1996). The search focused on crops where HDP had gained meaningful adoption or experimental advancements, such as apple, grape, citrus, mango, guava, stone fruits, plum, almond, and protected/soil-less table grape systems.

Costa, G., Beltrame, E., Zerbini, P., & Pianezzola, A. (1996, July). High density planted apple orchards: Effects on yield, performance and fruit quality. In VI International Symposium on Integrated Canopy, Rootstock, Environmental Physiology in Orchard Systems 451 (pp. 505-512).

Representative, impactful papers were chosen to demonstrate both the technological and agronomic/economic aspects of HDP systems, with emphasis on research that combines mechanization, precision input management, and long-term orchard sustainability.

Fig .1 Major Technical Advances in High-Density Planting(HDP) Systems

## Major Technical Advances in High-Density Planting (HDP) Systems



**Table 7: List of different dwarf rootstock and varieties of various fruit crops (Saroj & Singh, 2018; Goswami et al., 2014)**

Fruit Crop	Dwarfing Rootstocks
Apple	M27, M9T337, M26, Bud9, P22, Ottawa3, MM111, MM1006
Ber	<i>Zizyphus rotundifolia</i> , <i>Z. nummularia</i>
Citrus	Trifoliolate orange ( <i>Poncirus trifoliolate</i> var. Flying Dragon), Troyer Citrange, Citrangequat, Feronia, <i>Severinia buxifolia</i> , Karna Khatta, Sour Orange
Guava	<i>Psidium friedrichsthalianum</i> , <i>P. pumilum</i> , <i>P. chinensis</i> , Pusa Srijan, Aneuploid-82
Mango	Vellaikolumban (Alphonso), Olour (Himsagar, Langra)
Pear	Quince C
Peach	Siberian C, St. Julien X, <i>Prunus besseyi</i> , Rubira
Plum	Pixy
Cherry	Colt, Charger

(Source, Subedi et al., 2020)

### Principles of High-Density Orchard

Improved early yield coupled with better fruit quality is obtained through the use of more nursery trees per unit area. This raises the total productivity of the orchard in the early years, enabling farmers to repay establishment costs quicker and realize steady income (Shukla, et al., 2021).

Optimal use of natural resources maximizes returns per unit input through effective use of vertical and horizontal space, both temporally and spatially. In the high-density orchard, sunlight

interception is maximized, root-zone use is optimized, and water and nutrients are more uniformly distributed. This results in increased photosynthetic efficiency, improved soil and moisture conservation, and sustainable consumption of inputs like fertilizers, irrigation, and labor (Halder, 2022).

Balanced development between vegetative and reproductive stages is one of the fundamental principles, which stresses "producing fruits, not trees." Vegetative growth is checked by limiting it through the utilization of dwarfing rootstocks, selective pruning, and controlled nutrition, thus funneling more of the assimilates towards fruit production and quality enhancement (Mishra, and Goswami, 2016).

Maximizing branches that produce fruit and minimizing structural branches results in more productivity per unit of canopy volume. By promoting more fruiting wood and restraining unnecessary vegetative structure, more efficient yield results without plant harm.

Scientific training and pruning techniques are followed so that every branch gets sufficient sunlight and air movement, minimizing mutual shading and enhancing fruit color, size, and general quality. Canopy architecture also makes mechanization easier, harvesting easier, and improves pest and disease control (Ahmed, and Kaur, 2022).

### **Elements of High-Density Orchard**

The success of high-density orchard to a great extent relies on having the correct balance of tree vigor and fruiting. When tree vigor is weak, the trees will set too much fruit, which in most cases translates to small-sized fruits, poor quality, and increased tendencies towards biennial bearing. Additionally, weak trees cannot occupy their assigned canopy space rapidly, which gives way to inefficient orchards and lower profit (Shukla, et al., 2021). On the other hand, when there is too much tree vigor, more energy is channeled towards vegetative growth than reproductive growth, which translates to lower flowering and fruiting. In this instance, canopy management, optimal light penetration, and intended planting geometry become significant issues (Yadav et al., 2023).

In order for the tree canopy to receive even light distribution and for there to be a harmonious balance between vegetative and reproductive development, optimum orchard performance is necessary. Such a balance yields tranquil and orderly trees that are able to fruit predictably and consistently each year (Robinson et al., 2014).

Tree vigor and size can be controlled by various complementary methods. The adoption of genetically dwarf or compact scion cultivars is among the best means of limiting tree growth naturally while guaranteeing more efficient fruiting. Dwarfing and semi-dwarfing rootstocks, together with the adoption of inter-stocks, also restrict tree height and canopy spread, thus permitting closer plant spacing and easier handling. Training and pruning systems are also an important contribution, as they are specifically aimed at creating an open, well-lit canopy that allows for enhanced light interception, enhanced air flow, and lesser mutual shading between branches (Reddy, et al., 2014).

Besides genetic and structural controls, physiological strategies are also used. Growth retardants are commonly employed to control excessive vegetative vigor, whereas in some specific cases, the

application of incompatible rootstocks or the stimulation of light viral infections can be used to restrain overgrowth. Water and nutrient management also play a role in vigor control; for example, controlled irrigation in combination with balanced fertilization, especially the judicious use of nitrogen at moderate levels, prevents undue vegetative flushes while promoting gradual fruit development.

Last but not least, implementing proper crop management strategies specific to orchard conditions guarantees that all these measures function in unison. In combination, these measures allow growers to keep trees within prudent size parameters, provide effective use of the orchard space, and realize repeatedly better yields of better-quality fruits sustainably (Subedi et al., 2019).

### **Genetic Methods**

It is possible to control tree vigor by using genetically dwarf or compact scion varieties that inhibit growth automatically without losing fruiting efficiency. Dwarfing and semi-dwarfing rootstocks and inter-stocks are also extensively used to regulate tree height and canopy spread for closer planting and management simplification (Sansavini, S., Musacchi, 2000).

### **Canopy Structure and Training Systems**

Effective training and pruning systems are necessary to form the tree canopy in a way that maximizes light interception and air movement. Properly designed canopy structures prevent branches from overshadowing each other, which enhances fruit color, size, and quality. In addition, proper training enables mechanization, management of pests and diseases, and ease of picking in high-density orchards (Poni, et al., 1996).

### **Physiological and Growth Regulation**

In addition to genetic controls, tree size and vigor are also controlled through physiological processes. Growth retardants are utilized to inhibit unnecessary vegetative growth. In specific specialized contexts, incompatible rootstock utilization or induction of light viral infections has been employed to restrict tree vigor. These procedures add another dimension of control to achieve equilibrium between vegetative and reproductive stages.

### **Water and Nutrient Management**

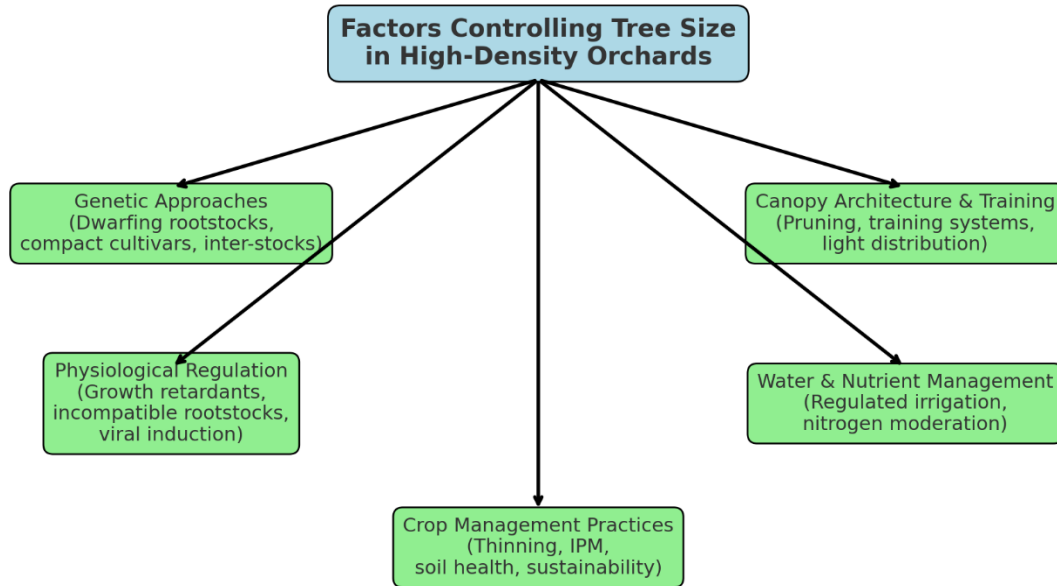
Controlled irrigation and even nutrient application are key to keeping orchard balance intact. Either excess irrigation or nitrogen fertilization tends to induce undesired vegetative flushes, resulting in the decrease of fruiting efficiency. In contrast, water and fertilizer applications in moderate quantities at the right time produce steady development, regular flowering, and superior-quality fruit.

### **Crop Management Practices**

The use of proper crop management practices consistent with local orchard conditions is essential for sustainability over the long term. Measures like selective thinning, integrated pest management, and maintenance of soil health go in tandem with genetic, physiological, and architectural methods. These in combination ensure the trees are kept within limits of manageable size, make

optimal utilization of space, and yield fruits of superior quality on a sustainable basis (Subedi et al., 2019).

Fig. 2 **Tree Size in High-Density Orchards: Controlling Key Factors**



## Key Technological Breakthroughs

### Rootstock and Scion Combinations

Dwarfing and semi-dwarfing rootstocks are still the foundation for high-density planting systems. They limit how much plants grow, promote early fruiting, and allow for close planting without losing canopy structure (Hung, et al., 2010). This is especially important for crops like apple, citrus, and almond, where size control affects orchard design and machinery use. Recent experiments across multiple locations show that the choice of rootstock and planting density strongly impacts total yield, fruit size, and tree lifespan. For example, M.9 and M.26 in apples or Carrizo citrange in citrus help achieve balanced canopy growth in hedgerow and spindle systems. Current research focuses on the interactions between density and rootstock to improve early profits, long-term stability, and reduce financial risks for growers.

### Training Architectures and Canopy Systems

Training and canopy management systems have improved a lot in HDP. Vertical spindle, slender spindle, bi-axis, and refined hedgerow designs are now commonly used (Iglesias, et al., 2023). Trellis-supported systems allow for very high planting densities, with 1,000 to 4,000 trees per hectare in apples and 5,000 to 6,000 vines per hectare in grapes. For subtropical crops like mango, citrus, and guava, hedgerow and meadow orchard systems are being improved for better compatibility with pruning, mechanization, and early returns (Reddy, 2024). Research now focuses

more on light distribution metrics, such as photosynthetically active radiation capture, row orientation, and pruning intensity as key factors affecting canopy efficiency and fruit quality in dense systems.

**Table 8: Optimum Plant Spacing for Spur Types and Standard Color Mutants of Apple in Himachal Pradesh, India (Awasthi et al., 1997)**

Variety Type	Rootstock	Crop Geometry (m)	Plant Density (trees/ha)
Standard Type	Crab Apple Seedling	7.0 × 7.0	204
Spur Type	Crab Apple Seedling	5.0 × 5.0	400
Standard Type	MM106, MM109	5.0 × 5.0	400
Spur Type	MM111, MM109	4.0 × 4.0	625
Spur Type	MM106, M7	3.0 × 3.0	1111
Standard Type	M9	3.0 × 1.0	3333
Spur Type	M9	3.0 × 0.75	4444

(Source, Subedi et al., 2020)

**Table 9: Optimum Plant Spacing, Density, Yield, and Yield Increment of Various Fruit Crops in Himachal Pradesh, India (Awasthi et al., 1997)**

Crop	Crop Geometry	Plant Density (trees/ha)	Yield (mt/ha)	Yield Increment (%)
Apple	3.0 × 1.0 m	3333	25	260
Banana	1.4 × 1.4 m	4444	145	250
Guava	1.0 × 2.0 m	5000	50	250
Kinnow	6.0 × 3.0 m	555	177	200
Mango	2.5 × 2.5 m	1600	19	250
Pineapple	25 × 35 × 90 cm	64,000	90	200

(Source, Subedi et al., 2020)

### Mechanization and Harvest Systems

Mechanization is a major factor driving the adoption of super-high-density (SHD) farming. Narrow hedgerow orchards make it possible to use platform-based harvesters, mechanical pruning machines, and integrated sprayer systems, which significantly lower labor needs and operational costs per unit. Engineering improvements are matching tree design with machine design, allowing for mechanized pruning, spraying, and harvesting without hurting fruit quality. For crops like grapes, almonds, and citrus, mechanized harvesting is becoming more practical, making SHD an appealing choice for commercial growers in areas with limited labor (Falcone, et al., 2022).

**Table 10. Effect of planting density/spacing on growth, yield and quality of fruit crops**

Name	Planting Spacing/Density	Key Findings	Reference

Dragon fruit	1815 plants ha <sup>-1</sup> 1556 plants ha <sup>-1</sup> 1361 plants ha <sup>-1</sup>	Highest density at <b>1815 plants ha<sup>-1</sup></b> produced highest yield 48.7 t ha <sup>-1</sup>	Then, 2017
Banana	1.75 × 1.75 m	<b>1.25 × 1.25 m:</b> Highest TSS (23.05%), TSS/acidity ratio (101.90), reducing sugar (14.71%) and total sugars (16.67%)	Mahmoud, 2013
	1.50 × 1.50 m		
	1.25 × 1.25 m		
Mango	5.00 × 5.00 m	<b>10.00 × 10.00 m:</b> Highest number of fruits tree <sup>-1</sup> (347), fruit weight (271.10 g) and the highest TSS (19.62)	Gaikwad et al., 2017
	5.00 × 1 0.00 m		
	10.00 × 10.00 m		
		<b>5.00 × 5.00 m:</b> Yield ha <sup>-1</sup> (21.6 t)	
Papaya	2.00 × 1.50 m	<b>2.00 × 1.50 m:</b> Tallest (2.12 m) plant and highest number (117,217) of fruits ha <sup>-1</sup> <b>2.50 × 2.00 m:</b> Highest number (72.33 fruits plant <sup>-1</sup> ) with the longest (10.93 cm) and widest (8.80 cm) fruit	Valleser, 2016
	2.00 × 2.00 m		
	2.50 × 2.00 m		
Sweet orange, mandarin	3.30 × 6.60 m	<b>3.30 × 3.30 m:</b> Highest plant height and lowest yield (2.11 kg plant <sup>-1</sup> ) <b>3.30 × 6.60 m:</b> Maximum fruit yield plant <sup>-1</sup>	Dogar et al., 2017; Nawaz et al., 2017
	3.30 × 3.30 m		
	6.60 × 6.60 m		
Pineapple	45,000plants ha <sup>-1</sup>	<b>45,000plants ha<sup>-1</sup>:</b> Heavier fruit mass	Valleser, 2018
	55,000plants ha <sup>-1</sup>		
	65,000plants ha <sup>-1</sup>		
	75,000plants ha <sup>-1</sup>		

(Source, Krishma et al., 2025)

**Table-11: High density planting of banana**

Sl no.	Planting method	Spacing (m)	No. of plants per ha
a	HIGH DENSITY PLANTING	1.2 × 1.2 x 2.0	5200
	Paired row planting system		3850
b	Dwarf varieties Grand Naine, Poovan, Rasthali, Ney Poovan	1.5 × 1.5 x 2.0	
	3 suckers/hill (45 cm apart in the pit) Grand Naine, Nendran, Rasthali	1.8 × 3.6 1.8 × 3.0	4600 5550
c	Two plants per hill (Ney Poovan, Poovan, Rasthali, Nendran,	2.1 × 2.4 2.1 × 2.7	3525 3960

	Monthan)		
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(Source, Krishma et al., 2025)

**Table-12: High density planting of papaya**

Crop	Variety	Spacing	Plant population	Reference
Papaya	Pusa Nanha	1.2 × 1.2 m	6,400 plants/ha	NHB, 2025
	Coorg honey dew	1.2 × 1.8 m	4629 plants/ha	IIHR, 2025

(Source, Krishma et al., 2025)

**Table 13: High density planting of Vazhakulam pineapple (Joy, 2010)**

Plant population/ha	Spacing (cm)		
	Plant to plant within a row	Row to row	Between paired rows
43,500	30	60	90
53,300	25	60	90
63,000	22.5	60	75
63,758	22.5	45	90

(Source, Krishma et al., 2025)

### Precision Water and Nutrient Management

In HDP systems, high plant populations increase competition for water and nutrients in the root zone. Precision drip irrigation and fertigation, supported by sensors like soil moisture probes, sap flow meters, and canopy reflectance indices, are being used more frequently to align supply with crop demand. This not only makes better use of inputs but also maintains fruit yield and quality during high-stress conditions. Research on SHD plum and grape systems has shown that regulated deficit irrigation (RDI) can save water while keeping yield and fruit quality at acceptable levels. New decision-support tools now combine sensor data with crop growth models to improve fertigation scheduling (Kuldeep, et al., 2024).

**Table-14: Spacing of Various Fruit Crops under Different Planting Systems (Saroj & Singh, 2018)**

Crop	Traditional System (m)	High Density System (m)	Meadow System (m)
Apple	10.0 × 10.0	3.0 × 0.75	3.0 × 0.37–0.60
Aonla, Sapota	10.0 × 10.0	5.0 × 5.0	–
Banana	2.0 × 2.0 – 2.0 × 3.0	1.5 × 1.5 – 1.8 × 1.8	1.2 × 1.2 – 3.0 × 0.5
Citrus	6.0 × 6.0 – 8.0 × 8.0	3.0–6.0 × 3.0–4.5	–
Guava	6.0 × 6.0 – 8.0 × 8.0	3.0 × 3.0 – 3.0 × 1.5	2.0 × 2.0 – 2.0 × 1.0
Mango	7.5 × 7.5 – 12.5 × 12.5	3.0 × 2.5 – 5.0 × 5.0	2.5 × 2.5 – 3.0 × 1.0
Papaya	2.0 × 2.0 – 3.0 × 3.0	1.8 × 1.8	1.2 × 1.2 – 1.0 × 1.0

(Source, Subedi et al., 2020)

### Protected Cultivation and Soil-less Systems

Protected and soil-less fruit production represents the cutting edge of HDP intensification. For crops like table grapes, strawberries, and certain high-value tropical fruits, hydroponic and container-based systems in controlled environments allow for planting densities of 10,000 to 20,000 plants per hectare or more. These systems enable vertical stacking, year-round production, and precise control of the root zone, allowing growers to target premium markets with a consistent supply and quality. While the startup costs are high, these methods provide very high productivity per unit area and create opportunities for climate-resilient fruit production in non-traditional regions. Current research focuses on optimizing substrates, automated fertigation, and regulating microclimates to enhance cost-effectiveness and sustainability ( Reddy, 2024).

**Table-15: Density of Mango Plants under Different Planting Systems (IIHR, Bangalore, India, Singh et al., 2017)**

Planting System	Crop Geometry (m)	Plant Density (trees/ha)
Low Density	12.0 × 12.0	70
Medium Density	7.0 × 7.0	204
High Density	5.0 × 5.0	400
Ultra High Density	5.0 × 2.5 / 2.5 × 2.5	800 / 1600

(Source, Subedi et al., 2020)

**Table-16: Density of Guava Plants under Various Planting Systems (CISH, Lucknow, India, Singh, 2008)**

Planting System	Crop Geometry (m)	Plant Density (trees/ha)
Low Density	8.0 × 8.0	156
Medium Density	6.0 × 6.0	278
High Density	6.0 × 3.0	555
Ultra High Density	3.0 × 1.5	2222
Meadow Orchard	2.0 × 1.0	5000

(Source, Subedi et al., 2020)

### Crop-Specific Highlights & Case Studies

#### Apple

The widespread use of slender spindle and vertical systems with dwarfing rootstocks has made it possible to plant several thousand trees per hectare in commercial orchards, especially where trellis infrastructure and mechanized operations are practical (Kafle, et al., 2021). Multi-year economic studies show earlier returns on investment, better profitability in the first few years, and improved orchard uniformity. However, success depends on careful pruning and training practices (Mushtaq et al., 2023).

## Grapes

High-density (HD) and super high-density (SHD) vineyard systems are becoming popular for influencing berry size, canopy microclimate, and mechanization efficiency (Feng, & Huang, 2025). Canopy management practices like leaf removal and cluster exposure are key for improving fruit quality. Soil-less high-density table grape systems have also shown the possibility of achieving very high plant populations per hectare by using precise fertigation and training method (Chiaki, et al., 2019).

**Table 17: Density of Kinnow Mandarin Plants under Various Planting Systems (Haryana Agricultural University, Hisar, India, Dalal et al., 2013)**

Planting System	Crop Geometry (m)	Plant Density (trees/ha)	Fruit Yield (mt/ha)
Conventional	6 × 6	277	106
Medium Density	6 × 5	333	120
High Density	6 × 3	555	177

(Source, Subedi et al., 2020)

## Citrus

Super high-density citrus hedgerows are gaining attention for their early yield benefits and suitability for mechanical harvesting (Dogar, et al., 2017). Practical adoption has been seen in Spain, with experimental systems being tried in other citrus-growing areas. Planting densities can range from 200 to 900 trees per acre, depending on the system design (de Carvalho et al., 2018). Successful results rely heavily on choosing the right varieties and using semi-dwarfing rootstocks to balance vigor control with fruit size (Nawaz, et al., 2007).

**Table 18: Density of Acid Lime Plants under Various Planting Systems (CCRI, Nagpur, Maharashtra, India, Ladaniya et al., 2020)**

Planting System	Crop Geometry (m)	Plant Density (trees/ha)	Yield (mt/ha)
Low Density	5.0 × 5.0	400	7.4
High Density	5.0 × 2.5	800	25.1
Ultra High Density	2.5 × 2.5	1600	35.4

(Source, Subedi et al., 2020)

**Table 19: Density of Banana Varieties under Different Planting Systems (NRCB, Tiruchirapalli, Tamil Nadu, India, Kumar et al., 2019)**

Varieties	Planting System	Crop Geometry (m)	Plant Density (trees/ha)
Gandhi Selection	Paired row	1.2 × 1.5 × 2.4	2808
Grand Naine, Basrai	Paired row	1.0 × 1.2 × 2.0	6250
Malbhog, Dwarf Cavendish, Rasthali, Palayankodan, Robusta, Jahaji	Paired row	1.2 × 1.2 × 2.0	5208

Rajpuri, Grand Naine, Jahaji, Nendran, Robusta, Alpan, Kothia	3 suckers/hill (45 cm apart)	2.0 × 3.0	5001
Robusta, Grand Naine, Alpan, Kathia	3 suckers/hill	1.8 × 3.6	4629
Ney Poovan, Poovan, Rasthali, Nendran, Monthan	2 suckers/hill	2.1 × 2.4 / 2.1 × 2.7	3525 / 3960

(Source, Subedi et al., 2020)

### Stone Fruits & Plums

In plums and other stone fruits, SHD orchard systems have been combined with deficit irrigation strategies to save water while maintaining yield and fruit quality (Bhat et al., 2021). European case studies show that careful management of irrigation and canopy structure can make SHD systems practical in regions with limited water.

**Table-20: Different fruit crops varieties and planting distance**

Crop	Spacing & System	Plant Density (plants/ha)	Yield Impact
<b>Mango (Amrapali)</b>	2.5 × 2.5 m (Triangular)	1600	Yield per hectare <b>2.5× higher</b> than low-density orchards of vigorous cultivars
<b>Mango (Dashehari)</b>	3.0 × 2.5 m (Square)	1333	<b>9.6 t/ha</b> under HDP vs <b>0.2 t/ha</b> in low density
<b>Citrus (Kinnow on Troyer Citrange &amp; Karnakhatta)</b>	1.8 × 1.8 m	3000	Increased plant population supports higher yield
	3.0 × 3.0 m	1088	Suitable density for sustainable production
<b>Pineapple</b>	63,758 plants/ha (with improved agro-techniques)	63,758	Yield increased from <b>15–20 t/ha</b> to <b>70–80 t/ha</b>

(Source, Subedi et al., 2020)

### Benefits

High-density (HD) and super high-density (SHD) orchard plantation systems in fruit crops have a number of agronomic, economic, and management benefits that are responsible for their fast acceptance in different fruit-production regions (Senthilnathan, 2023).

#### Earlier bearing and faster cash flow

With the use of dwarfing and semi-dwarfing rootstocks in combination with optimized training systems, HDP orchards come into bearing much earlier than the traditional ones. The savings in the juvenile phase result in growers being able to harvest marketable fruit within 2–3 years in apples and grapes, as opposed to 5–7 years in conventional orchards. Increased productivity with a quicker harvest translates to earlier revenue streams, hence enhanced return on investment (ROI) as well as lessened payback period for establishment costs.

### **Increased cumulative yield and land-use efficiency**

The most reliable benefit of HDP is the tremendous boost in yield of fruit per hectare. By allowing many thousand trees or vines per unit of land, productivity of the land increases exponentially, which is particularly important in areas with land fragmentation and increased land prices. It is also evidenced that cumulative yields over the life cycle of an orchard are significantly higher, rendering HDP systems more sustainable for commercial fruit businesses.

### **Mechanization compatibility and lower labor costs**

Labor shortfalls and high labor costs are significant hindrances in fruit production. HD and SHD systems are mechanization-compatible, with mechanical pruners, hedgers, and harvest platforms. Canopies that are narrow and uniform enable easier movement of machinery and minimize dependency on intensive labor. This reduces per-unit production costs directly and anchors profitability even in environments with labor shortages.

### **Enhanced fruit quality and uniformity**

Canopy management research points out that dense orchards, when properly designed, maximize the distribution of photosynthetically active radiation (PAR) within the tree row. This maximizes photosynthesis efficiency, facilitates better color development, and leads to more uniform fruit size and ripening. Uniformity of fruit quality means higher pack-out percentages and enhanced market acceptance, especially in export-oriented markets.

### **Improved resource-use efficiency**

High-density systems are often controlled under drip fertigation and precision irrigation regimes. This enables greater water, fertilizer, and other input use efficiency with less wastage and reduced environmental effects. Effective root-to-shoot balance also contributes to sustainability by reducing the carbon and water footprints per unit of fruit output.

### **Environmental and sustainability benefits**

By maximizing yield per unit area, HDP systems reduce pressure to expand cultivation into ecologically sensitive or marginal lands. Adoption of precision technologies in such orchards contributes to reduced pesticide drift, improved soil health, and alignment with climate-smart agricultural strategies.

### **Constraints and Challenges**

Even with the various agronomic and economic advantages, the use of high-density and super high-density planting systems is not without challenges. Some of the major constraints are:

**Capital intensity and establishment cost:** Initial outlays on trellising, specially planted material (dwarfing/semi-dwarfing rootstocks), irrigation system, and mechanization platform are significantly greater than for a conventional orchard. Such expenses can act as a barrier to entry for medium and small growers, and recoupment rests on careful orchard management and market conditions.

**Pest and disease pressure:** Heavy canopies produce humid microclimates conducive to the development of fungal and bacterial diseases if not ventilated. Restricted air circulation also hinders pesticide coverage, necessitating precision sprayers or machine application. Strategic canopy management (summer pruning, hedging, row orientation) is thus critical.

**Soil water and nutrient depletion:** Higher plant population increases intra-row competition for water and nutrients. In the absence of sophisticated fertigation and irrigation management plans, variable growth and localized stress can be induced, impacting yield as well as fruit quality. Contemporary experiments focus on bringing together soil moisture sensors, plant monitoring instruments, and regulated deficit irrigation to ensure uniformity.

**Long-term sustainability issues:** Although the early yields are desirable, long-term observations of root competition, cycles of renovation of orchards, and soil health effects in highly dense systems are still few. Ongoing observations of soil organic matter, root growth, and economic life of orchards need to be made to guarantee sustainability over production cycles.

### **Knowledge Gaps and Research Needs**

While remarkable progress has been achieved in high-density (HDP) and super-high-density (SHD) planting, there are still a number of research gaps that need to be filled to ensure long-term viability, sustainability, and greater uptake across varying fruit systems:

#### **Long-term comparative economics and environmental footprint**

Whereas the majority of HDP research emphasizes initial productivity returns and profitability in the first few years, longitudinal datasets (>10–15 years) for comparing HDP and traditional orchards are lacking. Issues relating to orchard longevity, renovation cycle, total input costs, and environmental effects (soil erosion, carbon footprint, loss of biodiversity) remain unclear. Interregional and intercrop comparative life cycle assessments (LCA) are urgently required to determine the absolute sustainability of HDP.

#### **Integrated pest–disease and canopy microclimate models**

Thicker canopies significantly modify humidity, temperature, and penetration of light, which cascade to influence pest–pathogen dynamics. Not many predictive models explicitly incorporate these microclimate changes. There is a need for research to establish dynamic, HDP-tailored pest and disease forecast tools that integrate canopy geometry, weather patterns, and precision spraying. Adaptive canopy management practices like summer hedging, shoot thinning, and row-orientation research must be integrated with these models in order to implement effective integrated pest management (IPM).

#### **Rootstock × scion × density optimization across agroecologies**

Current HDP knowledge is biased towards temperate apples and, to a lesser extent, grapes. There is limited information on tropical and subtropical fruit like mango, guava, banana, papaya, and citrus. Research must critically test genotype × environment × management (G × E × M) interactions to find stable combinations of rootstocks, scions, and densities that optimize precocity,

fruit size, and long-term orchard health. Region-specific recommendations are urgently necessary for new adopters in Asia, Africa, and Latin America.

### **Water-saving and climate-resilient irrigation practices**

Wide plant density promotes evapotranspiration requirements and heightens water competition. While regulated deficit irrigation (RDI), partial root-zone drying (PRD), and subsurface drip systems have been promising in apples, plums, and grapes, their use in SHD citrus, mango, and nut crops is largely untapped. As climate variability is heightened, research must concentrate on developing adaptive irrigation schedules that sustain productivity at enhanced water-use efficiency.

### **Soil health, carbon dynamics, and root competition**

The long-term effects of very dense orchards on soil organic matter, microbial ecology in the root zone, and nutrient cycling are still unclear. Root competition in a continuous state can result in soil depletion, nutrient disequilibrium, and increased replanting pressure. Research integrating soil carbon sequestration, rhizosphere biology, and rejuvenation strategies of orchards is essential to maintain ecological sustainability.

### **Socio-economic and adoption barriers**

Whereas large-scale commercial plantations can absorb the capital requirement of HDP, smallholders might not have access to high-quality planting material, credit, and technical information. There is a need to investigate scalable HDP models that are appropriate for resource-constrained farmers, extension tools, participatory trials, and policy support mechanisms that close the adoption gap.

### **Future Directions**

The future of high-density (HDP) and super-high-density (SHD) systems will increasingly be determined by the intersection of technological innovations, advances in breeding, and sustainable management practices. A number of emerging areas deserve consideration:

#### **Decision-support system integration**

Digital agriculture innovations will transform the management of orchards. Combining satellite and UAV-mounted multispectral/hyperspectral imaging, proximal sensing (LiDAR, canopy sensors, soil probes), and AI-driven analytics will provide real-time canopy vigor, soil moisture, and nutrient dynamics monitoring. Such decision-support systems have the potential to enable site-specific irrigation, fertigation, pruning, and crop protection management, enhancing both resource-use efficiency and profitability.

#### **Breeding and selection for SHD ideotypes**

HDP/SHD success relies heavily on plant architecture. Compact growth habit, spur-type bearing, self-thinning, increased photosynthetic efficiency, and biotic/abiotic stress resistance will be the focus of future breeding activities. New technologies like marker-assisted selection, genomic

selection, and gene editing may speed up the formulation of rootstock–scion combinations tailored for varying density regimes and agroecological zones.

### **Mechanization and automation for subtropics**

Although mechanization is already in progress in temperate orchards, subtropical and tropical fruit industries (e.g., citrus, mango, guava) are more constrained by canopy architecture and irregular bearing patterns. The future development of mechanical harvesters, hedging machinery, and multi-functional sprayers specifically designed for narrow hedgerows and varied orchard topography will be critical to wide-scale adoption. Robotics and autonomous platforms also hold potential solutions for labor shortages and increasing costs of production.

### **Climate resilience and resource efficiency**

The new generation of HDP systems should be climate-smart horticulture-oriented. Deficit irrigation techniques, solar/renewable energy-based irrigation, biodegradable mulches, microclimate management (shade nets, reflective films), and low-carbon input systems will reduce the environmental impact of intensive planting.

### **Value chain integration**

Adoption of HDP will be stepped up only if integrated with post-harvest management, cold-chain logistics, and market access. New models can be designed to integrate production with value addition (minimum processing, packaging, storage technologies) so that farmers have economic viability at all scales.

### **Conclusion**

High-density and super-high-density planting (HDP/SHD) systems are a paradigm shift in fruit production, converting orchards into more productive, efficient, and economically sound units. The last two decades have seen tremendous progress in canopy management, precision irrigation, fertigation, and orchard floor management leading to earlier yields, homogenous fruit quality, and greater profitability relative to conventional systems. The complementarity of dwarfing rootstocks, optimal pruning and training, and mechanization has further increased the scalability of such systems, especially in apple, citrus, and grape cultivation.

The adoption of HDP and SHD at the wider scale continues to be limited by knowledge gaps on long-term sustainability, rootstock–scion–density interactions, and pest–disease processes under changed microclimates. Likewise, mechanization technology for subtropical crops, water-use efficiency practices, and climate variability resilience still need focused research.

In the future, HDP/SHD systems will be driven by digital agriculture, advanced breeding, and climate-smart practices. Remote sensing integration, AI-driven decision support, and automation will improve real-time management, while new ideotypes designed for compact growth and stress tolerance will increase the scope of intensive systems for deployment in diverse agroecologies. Further, grounding these production systems in sustainable value chains and low-carbon models of production will be critical to guarantee farmer profitability as well as environmental sustainability.

## COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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