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REVIEW ARTICLE

Walnut Farming Systems: Review

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K E Y W O R D S

Mechanization;
Orchard systems;
Technological advancement;
Tree density;
Varieties

A B S T R A C T

Walnut is a major temperate tree crop that has experienced significant technological advancements in its cultivation. This study provides a comprehensive review of walnut farming systems worldwide, highlighting technological applications and innovations that enhance efficiency in modern agricultural practices. Although intercropping seasonal crops in young walnut orchards remains common, there has been a marked shift from traditional low-density agroforestry and natural forest-based farming toward high-density planting systems in contemporary walnut cultivation. Various planting designs—including hedge row, square, diamond, and hexagonal patterns—have increased orchard tree densities to over 500 trees per hectare. Intensive, high-density planting systems have demonstrated superior productivity compared to conventional farming methods. Mechanization of key operations such as harvesting, along with the adoption of precision agricultural techniques supported by digital devices and software, play a crucial role in improving resource use efficiency, production, and soil and crop management. The integration of digital tools in soil and crop management optimizes water usage and mitigates moisture stress. Intensive and super-intensive walnut farms demand superior varieties characterized by dwarfism, early maturation, lateral bearing, early rooting, and enhanced resistance to biotic and abiotic stresses. Advances in breeding technologies—including genome sequencing, haploid production, transcriptomics and genetic engineering—have accelerated the development of cultivars exhibiting these desirable traits. Furthermore, propagation techniques such as budding, grafting, and micropropagation have significantly improved the quality of planting materials. In summary, the walnut farming industry has increasingly embraced technological innovation to improve productivity, sustainability, and profitability within this agricultural sector.

Introduction

English walnut (*Juglans regia* L.) is one of the most economically and nutritionally significant tree crops in the Juglandaceae family (Akca and Sahin, 2022). It is primarily cultivated in temperate and Mediterranean regions. Walnuts have long been valued not only as a nutrient-dense food source but also as a symbol of prosperity, often exchanged as gifts during festivals and rituals particularly in ancient societies (Thapa *et al*., 2021; Vahdati, 2014). Walnut trees produce high-grade timber for the wood industry and a source of biomass for the environment. Walnut is a source of nutritious kernels rich in energy,

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carbohydrates, sugars, starch and other products with dermatocosmetic and phytotherapeutic properties (Sarikhani *et al*., 2021; Popa *et al*., 2023; Wu *et al*., 2020). Consumption of walnut kernels contributes to better cardiovascular health, brain function, and overall wellness (Jahanban-Esfahlan *et al*., 2019). These health benefits have propelled global demand for walnuts in recent decades;100g of walnuts contain about 70.8g of oil, 20.0g of protein, and 6.9g of carbohydrates (Sarikhani *et al*., 2021; Jan *et al*., 2024; Jahanban-Esfahlan *et al.,* 2019 Doldur, 2017). In addition, they contain numerous vitamins and minerals mainly A, B, C, and E, and minerals such as Calcium, Potassium, Iron, Phosphorus, Sodium, Selenium, Zinc, Manganese, and Magnesium (Fatima *et al*., 2018; Leahu *et al.*, 2016; Sen *et al*., 2015; Ozcan, 2009).

Globally, walnut production has witnessed remarkable growth, doubling over the last three decades, with in-shell walnut production reaching 2.8 million metric tons in 2021, a significant increase from previous years (Popa *et al*. 2023). This rise in production is largely driven by China's dominance in the sector, which accounted for approximately half of the global output, producing 1.4 million metric tons in 2022, followed by the United States at 0.68 million metric tons (FAO, 2024).

Regionally, walnuts have deep historical roots, with origins tracing back to the eastern Balkans, the Himalayas, and Southwest China (Popa *et al*., 2023). They spread across continents due to their adaptability and value, and today, walnuts are cultivated in over 50 countries, including those in the Americas (Mexico, the USA, Chile), Europe (France, Italy, Greece, Ukraine), Asia (China, India, Turkey), and parts of Africa (Morocco, South Africa) (Marrano and Neale, 2019; Pradhan, 2014; McGranahan *et al*., 2009). Central Asia, particularly Kyrgyzstan and Afghanistan, is home to extensive natural walnut forests, which are still an important part of local agricultural systems. These regions have cultivated walnuts for centuries, incorporating the trees into their traditional farming systems and using them as a source of both food and valuable wood (Vahdati, 2014).

Historically, walnuts were considered a luxury item, reserved for royalty in ancient civilizations and used as offerings in various cultural rituals. The Roman Empire, for instance, introduced walnuts to Europe, while the Silk Road facilitated the spread of walnuts across Central Asia to the Mediterranean and beyond. In regions like the Caucasus and parts of Eastern Europe, wild walnut trees are still found growing naturally, underscoring the tree's long-standing agricultural and cultural significance.

Today, the walnut industry continues to thrive, incorporating modern agricultural practices to increase efficiency and sustainability. Innovations in precision agriculture, breeding technologies, and farm mechanization have transformed walnut farming into a high-yield, high-efficiency enterprise, meeting the growing global demand for both walnuts and walnut-based products. This review documents the various walnut farming systems, with an emphasis on the technological advancements and management strategies that have improved productivity and sustainability in modern walnut orchards.

Farming systems

Crop farming systems may be defined based on the choice of crop, acreage, management practices, inputs and output including technological advancement applied from crop production to post-harvest handling. Dixon *et al*., (2001) identified several farming systems based on the available natural resource and main farm activities and livelihood. The farming systems are as shown in Fig. 1.

The world's cropland is dominated by rainfed farming systems accounting for over 80% of the total area with crops relying heavily on rain for water (Bhattacharya, 2019; He *et al*., 2013). Despite their vulnerability to climate variability and extreme climate events, rainfed systems produce the largest share of food (Reddy *et al*., 2015; Fekete, 2013). Both seasonal and perennial crops can be cultivated under rainfed farming systems (Molden *et al.,* 2011). Rainfed farming systems are either crop-specific or mixed crop and livestock. On the other hand, irrigated farming systems are where water is artificially applied to soil through various systems like tubes, pumps and sprays among others.

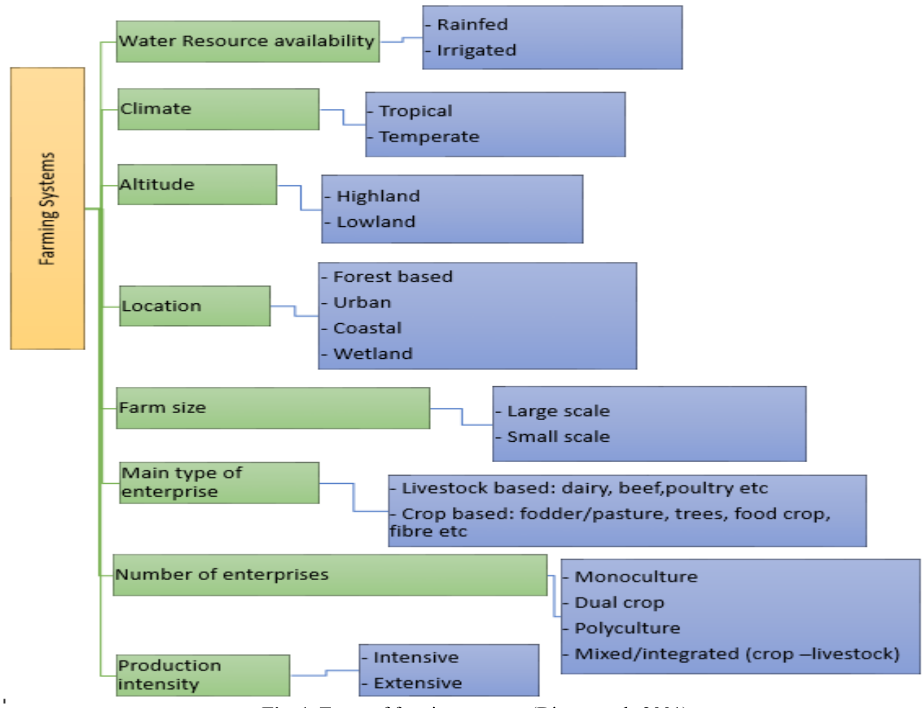

Fig. 1. Types of farming systems (Dixon *et al.,* 2001)

On the other hand, tropical farming systems are characterized by two distinct seasons, the wet and dry seasons with mean monthly temperatures above 18°C (Dondeyne *et al.*, 2023; Spaargaren *et al*., 2005). The weather is predominantly hot throughout the year. Most tropical farming systems have diverse crops, small in size, and are less productive compared to temperate systems (Chang, 1977). Temperate farms experience four seasons, summer, autumn, winter, and spring with average temperatures between -3°C and 18°C in the coldest month and average temperature above 10°C in the warmest month. They are geographically located in mid-latitudes and higher elevations of lower latitudes (Aslamarz *et al.*, 2010; Kingston *et al.,* 2024).

The forest-based farming system also called referred to as agroforestry is the oldest farming method informally practiced globally since the ancient days. It is the combination of woody perennials with either crops or animals (Rehnus *et al*., 2013). The indigenous communities in North America planted mulberries and maples in forests for syrups, wine, and culinary products. White mulberries from the forests were used to make bread flour in Afghanistan, whereas feedstock and staple human food were obtained from *Pithecellobium* trees in the forest in Southeast Asia and the Pacific Islands (Chamberlain *et al*., 2009). It is important to note that to date, this farming system still exists. Vast natural walnut forests are found in the mountainous areas of Central Asia, South and East Asia, Middle East including the Caucasus region (Shigaeva *et al*., 2020; Hardy *et al.*, 2018). In the hilly areas of Banat and Oltenia region of Romania where weather conditions are favorable with Mediterranean influence, walnuts grow spontaneously occurring as solitary or mixed with other trees (Popa *et al*., 2023). The Fergana and Chatkal ranges in southern Kyrgyzstan are habitat to expansive natural walnut forests where farmers practice mixed farming (Azarov *et al.,* 2022). Traditional forest-based walnut systems are largely characterized by low or no input usage, often dominated by old mature trees with low yields (Hassan *et al*., 2019; Rehnus *et al*., 2013).

In agroforestry systems, walnut trees for timber are grown as mixed forest trees in natural stands or man-made plantations growing as tall straight trees with branchless stems and small canopy bearing very few nuts (Webber *et al.*, 2022). The trees are closely spaced at about 3 to 3.6 meters square with a population of 450 to 312 trees per acre respectively (Burde 1988). Due to the compactness of the tree stands, very limited light penetrates below the canopy. On the contrary, walnuts grown for nut production in agroforestry systems have wider spacing shorter stems, and wider canopies allowing sunlight to reach below the tree canopy. It is important to note that walnuts have played a critical role in combating soil erosion and a protective shield against wind (Popa *et al*., 2023). Young walnut orchards were intercropped with seasonal food crops whereas, in older orchards, silvopasture is commonly practiced (Anonymous, 2024). In some countries like Kyrgyzstan, walnut farming is practiced alongside other crops such as plums, apples, pistachio, pear, and hawthorn as well as animals like cattle, sheep, and horses for meat and milk (Azarov *et al*., 2022).

Large-scale farming also called corporation or industrial farming has played a critical role in food production. It is commonly practiced on large tracts of land targeting a specific niche such as fruits, wheat, corn, and livestock among others, characterized by extensive mechanization (Black, 1931). On the other hand, small scale is practiced on small parcels of land mostly by individual farmers of families characterized by diverse crops with very limited or no mechanization.

Monocultures entail growing a single crop which can be annual crop such as corn, wheat, barley or perennial field and tree crops. In the field at a time while polyculture focus on diverse crops (Salaheen *et al*., 2019). On the other hand, dualistic farming systems have two distinct enterprises, the commercial and subsistent production sectors running parallel (Preez, 1975) with diverse production techniques.

Most traditional extensive walnut farming systems face serious challenges of pests and diseases hence poor-quality nuts. However, the increased labour gap in the agricultural sector, growing increased demand of nuts coupled with climate change that pauses a threat to crop production in various countries has necessitated adoption of modern farming systems to increase and sustain crop production including fruits and nut (Vaishnavi *et al*., 2022).

Extensive farming is characterized by the cultivation of large tracts of land with low inputs such as shifting cultivation. However, intensive farming entails the use of small land areas with high levels of input to produce very high output. Intensive farming systems such as greenhouse farming, hydroponics, and aeroponics are characterized by high output within smaller spaces of production.

Although they present a limited part of the global walnut production area, niche-based farming systems have also been adopted in walnut growing targeting unique market needs such as the gourmet market.

Modern/ intensive walnut farming systems

Increasing demand for walnuts, coupled with technological advancements and the challenges posed by climate change has spurred interest and adoption of modern, intensive walnut farming systems. These aim to maximize productivity and resource efficiency through high-density planting, mechanization, and precision agriculture (Popa *et al*., 2023; Lowenberg-DeBoer, 2022). Some intensive systems have also integrated organic farming practices. Major walnut-producing countries like Chile, California, Argentina, South Africa, France, Romania, and other European countries have adopted modern walnut farming systems. In other countries like Hungary, intensive walnut orchards with at least 200 grafted trees per hectare receive state's support.

High density planting

High-density planting and structured canopies are core features of intensive walnut farming systems (McNeil, 2019; Javaid *et al*., 2017). The tree density can range from 69 trees per hectare (in low-density systems) to over 500 trees per hectare in high-density designs. The choice of planting design, spacing, and canopy depends on the target primary product that is whether nuts or timber, agroecological conditions, and planned management practices (Javaid *et al*., 2017). Common planting designs include square, diamond, hedgerow, offset square, and hexagonal design Spacing may vary from 12 by 12 meters to 6 by 6 meters as shown in Table 1.

Table 1. Plant population per Hectare using the Square and Diamond planting design.

Row and inter-row spacing (Feet)	Plant population per hectare	
	Square	Diamond/Quincunx Square
6	277	536
7.5	177	332
9	128	237
10.5	90	177
12	69	133

Intensive systems could have population densities of up to 536 trees per hectare relative to conventional farms with 100-120 trees per hectare (McNeil, 2019). For example, in Romania, intensive plantations use a spacing of 8 by 6 meters, while super-intensive systems have a narrower spacing of 7 by 5 meters (Popa *et al*., 2023). The presence of dwarf rootstock has promoted the adoption of high-density planting with precocious varieties giving early returns on investment relative to low-density systems (Devin and Bujdoso, 2022; Lemus, 2001; Barritt, 2000). For example, 417 trees/ha of Wen 185 variety yield 240 kg in year 2 in Xinjiang, China (Duan *et al.,* 2017). However, a wider spacing of 12 by 18 meters has also been used in agroforestry systems to allow for intercropping with other crops like barley, wheat, and peanuts (Webber *et al.*, 2022, Žalac *et al.,* 2022, Yun *et al., 2012*).

Plant spacing in black walnut plantations for timber can range from 3 to 3.5 square meters, providing a population of 1,077 or 746 trees per hectare respectively. This spacing is sufficient for mechanized weed control and enables trees to reach the 5-inch average diameter at breast height without thinning (Burde, 1988).

Tree training and Pruning

Tree training and pruning play an essential role in optimizing light interception, air circulation, and overall orchard management (McNeil, 2019). Training entails fastening, bending, or twisting the tree using supports to acquire the desired shape. Pruning entails the removal of selected plant parts after planting using heading back and thinning cuts (Britannica, 2018; Bruce *et al*., 2015). Pruning is mainly done in early spring; 3-4 inches of all terminal growths are clipped off. It promotes bud break, the formation of a dense canopy, and a strong trunk (Webber *et al*., 2022). In training, sapling branches below 1.5 - 1.8 meters from the ground are removed, heading the leader and desirable scaffold limbs, less desirable branches are left for early nut production. Low scaffold training is an alternative method that maintains the leader and selects low scaffold branches above 0.9 meters to enhance trunk size and early nut production. Studies show that low scaffold training in Chandler walnut orchards has significantly larger trunks, larger leaf areas, greater production, and 50% less pruning costs in mature trees (Webber *et al*., 2022; Olson *et al*., 2005). Common walnut training systems are central leader and open-center systems. In high-density orchards, the central leader system may require modifications to adapt to closer tree spacing and facilitate mechanical harvesting. The open-center method allows for better light distribution and air circulation within the canopy, which is particularly important in high-density plantings. Walnut trees trained in a central leader system in high-density orchards have been shown to produce earlier and higher yields (Lemus, 2001)

Fertilizer application

Walnuts require macronutrients (Nitrogen, Potassium, Phosphorus, Magnesium, Sulfur, and Calcium) and micronutrients (Boron, Iron, Manganese, Nickel, Molybdenum, Copper, Zinc, and Chlorine) including soil organic matter for proper growth (Bryson *et al*., 2014).

Soil and plant analysis including regular observations of saplings and mature trees in walnut orchards are important considerations to establish the levels of essential elements (Inglese *et al*., 201; Bryson *et al*., 2014; Olsen, 2006). Other important soil diagnostics are electrical conductivity, and cation exchange capacity including soil structure and texture (Inglese *et al*., 2019; Olsen, 2006). Besides soil examination, leave sampling and analysis of are used to evaluate the level of essential elements. Samples are randomly obtained from the current year's leaves from shoots of average vigor. Studies show that the required concentration levels should be as indicated in Table 2 (Adem, 2009).

Table 2. Concentration levels of selected essential elements in walnut leaves.

Element	Normal concentration
Nitrogen	2.2-3.2%
Phosphorus	0.1-0.3%
Potassium	>1.2%
Calcium	>1.0%
Magnesium	>0.3%
Boron	>36-200ppm
Manganese	>20ppm
Copper	>4.0%

Source: Adem (2009)

In walnut-producing regions like California, nitrogen is the only critical nutrient required during fertilization because most soils have adequate phosphorus and potassium for young walnut orchards in the first five to six years (Anonymous, 2015). The application rate almost doubles in the first three years. The N application rate is estimated as illustrated in Table 3 in a density of 160 trees per hectare using a drip or micro-sprinkler irrigation system (Anderson, 2006).

Table 3. Nitrogen application rates in the soil.

Age of tree in Years	Nitrogen (N)	
	Kg/hectare	g/tree
1	11 - 22	90-130
2	22 - 56	180-360
3	56 - 110	360-680
4	70 - 140	450-860
5	84 - 168	540-1000

Although the fertilizer application rates vary depending on the geographic location of the orchard and crop performance, studies indicate that the start of the rapid growth phase of shoots and roots in late winter and early spring is the best time to apply fertilizer. Fertigation where fertilizer solution is delivered through drippers and microjets in the irrigation water is an efficient fertilizer application technology. However, proper management is important to prevent acidification. Foliar applications using sprayers and drone technology in walnut orchards provide a quick corrective measure to nutrient deficiencies. However, the technologies have short-lived responses, are expensive and policy regulations on drone use particularly in agriculture are still being developed in some countries (Adem, 2009).

Irrigation

Walnut orchards require a lot of water; a mature walnut tree could require up to 431 gallons of water per day in summer (Jerszurki *et al*., 2017; Hendrickson *et al*., 1949). Inadequate water in the orchard can adversely reduce nuts size, cause sunburn, and increase susceptibility to pest and disease infestations like mites and deep bark canker (Jerszurki *et al*., 2017; Goldhamer, 1998). Similarly, over irrigation particularly in young trees can cause *Phytophthora* root rot and dieback (Jerszurki *et al*., 2017). Water stress affects the leaf's water potential and depresses root activities, impairing the absorption of essential elements from the soil, leading to poor crop performance (Chen *et al*., 2022; Musacchi *et al*., 2021). Thus, irrigation is needed to maintain adequate water supply. Modern farming systems utilize advanced soil moisture monitoring techniques to establish water supply and storage, available water content, allowable depletion rates, and evaporation demands among others. This information is used to design precise irrigation schedules based on the crop's coefficient (Imark, 2008; Goldhamer, 1998). Surface irrigation systems such as furrows, border check irrigation systems, and flooding are used in conventional orchards. However, worldwide increase in demand for water coupled with irregular precipitation attributed to climate change, the "*one drop for more trees*" approach is gaining popularity in the quest for better yields and quality as well as reduced cost. Use of permanent set and mobile sprinklers including low-volume irrigation systems like drip and micro-sprinkler irrigation systems are used to control water application rate in walnut orchards (Prichard, 1997).

Improved cultivars

The use of carefully selected varieties is an important consideration to ensure a mix of compatible trees with different flowering and fruiting times for optimal pollination (Hassankhah *et al.*, 2020). Studies show that dwarf rootstocks and genetically certified grafted seedlings are preferred because they not only produce earlier but are also efficient to spray, convenient to harvest, and give higher yields and quality fruits than trees grown from seeds (Popa *et al*., 2023; Devin and Bujdoso, 2022). In addition, late-leafing cultivars with high lateral bud fruitfulness, high chilling requirement, drought tolerance, and resistance to diseases like walnut blight and anthracnose are also preferred in modern walnut orchards (Aslamarz *et al.*, 2009; Lotfi *et al.*, 2010; Popa *et al* 2023; Hassani *et al*., 2020; Ertürk and Akça, 2014). Lateral varieties have relatively higher yields ranging from 1.7 – 4.1 tons per hectare (t/ha) than terminal-bearing trees with 1.5 – 2.6 t/ha dried nuts (Botu *et al*., 2010). However, selected terminal and intermediate fruiting varieties with superior qualities like resistance to low winter temperatures and quality nuts are also used. Breeding programs in producing countries use carefully selected native and domesticated foreign cultivars to establish and release new cultivars that address country-specific production needs. Table 4 below highlights walnut varieties grown in various producing countries.

Table 4. Varieties in major walnut producing countries.

Country	Native/local variety	Domesticated variety	Reference
China	Baofeng, Baokexiang, Zha343, Luguang, Xiangling, Hanfeng, Wen185, Jinboxiang, Zhongling, Jinlong, Luguo, Yangza, Jinxiang, Zanmei, Zhenzhuxiang, Luwen, Jin RS, Daixiang, Daihui, Liaoning	Hartley, Franquette, Chandler, Chico, Amigo, Qingxiang	Devin *et al*., 2022; Zhao *et al*., 2020; Benard *et al*., 2018, Chen *et al*., 2014
United States	Payne, Hartley, Waterloo, Adams, Ashley, Idaho, Carmello, Serr, Vina, Amigo, Tehama, Pedro, Gustine, Durham, Pioneer, Midland, Chico, Lompoc, Chandler, Howard, Sunland, Tulare, Cisco, Sexton, Forde, Gillet, Ivanhoe, Solano, Durham, Leto	Franquette, Lara	Manthos *et al*., 2021; Benard *et al*., 2018
Romania	Germisara, Jupânesti, Redval, Sibisel 44, Timval, Unival, Valcor, Valcris, Valrex, Valmit, Verisval, Velnita, , Verisval	Hartley, Lara, Franquette, Ferjean, Fernor, Franquette, Vina, Payne, Pedro, Tehama, Serr	Popa *et al.,* 2023; Botu *et al.,* 2021; Botu *et al.,* 2010
Chile	None	Serr, Chandler, Howard, Franquette, Vina, Tulare, Cisco	González *et al*., 2021; Lemus, 2010; Theo, 2023
Hungary	Alsószentivani 117, Alsószentiváni kései, Bonifác, Eszterházi kései, Érdió 1, Milotai 10, Milotai botermo Milotai intenzív, Milotai kései, Tiszacsécsi 83, BD6, Eszterházi 2	Chandler, Pedro, Franquette	Bujdosó *et al*., 2022, 2021, 2020
India	Gobind, Roopa, Pratap, Sholding, Hamdan, Sulaiman, CITH-Walnut 1,2,3,4,5,6,7,10, Chakrata 2,4,6,13,14, Placentia, Wilson, Opex Caulchry	Lake English, Colby Blackmore, Turtle 16, Turtle 31, Nielson, Orth, Serr, Natra, Attiro, Hartley, Payne, Ashley, Chico, Eureka, Franquette	Sharma *et al*., 2014; Sofi *et al.,* 2010
Bulgaria	Dryanovski, Izvor 10, Perushtinski, Sheynovo, Silistrenski, Kuklenski, Slivenski	Chandler, Fernor, Lara, Alsószentivani 117, Milotai 10, Tulare, Franquette, Fernette, Red Livemore, Tiszacsecsi 83, Serr, Hartley, Adams, Tehama	Gandev, 2019; Gandev, 2017; Gandev *et al*., 2015 Gandev *et al*., 2013
Ukraine	Bukovynszky 1, Grozynetsky, Klishkivsky, Tsernivetsky 1	None	Andrienko *et al*., 1990
Turkey	Ahir Nut, Bilecik, Kaman 1, Kurtulus 100, Maras 18, Sebin, Sutyemez 1, Yalova 1, Yalova 3 Maras 12, Sen1, Sen 2, Akça1	Chandler, Fernette, Fernor, Howard, Pedro, Serr, Franquette and Hartley	Ahi *et al*., 2023; Benard *et al*., 2018
Moldova	Kishinevsky, Korzheutsky, Kazacu, Kogalniceanu, Kostiujenskii, Kalarasskii, Schinosskii, Pescianski, Koijeuti	Chandler, Lara, Fernor, Franquette	Pintea *et al.,* 2022; Tsurkan, 1988
France	Feradam, Ferbel, Ferjean, Fernette, Fernor, Ferouette, Fertignac, Franquette, Lara, Grandjean, Mayette, Parisienne, Corne, Marbot	Pedro, Chandler	Devin *et al*., 2022; Benard *et al*., 2018
Iran	Damavand, Persia, Jamal, Alvand, Chaldoran Caspian	Chandler, Pedro, Hartley, Lara, Serr, Vina, Franquette, Ronde de Montignac	Devin *et al*., 2022; Fallah *et al*., 2022; Hassani *et al*., 2020; Benard *et al*., 2018

Advancements in walnut farming operations

Modern walnut farming has undergone significant technological transformations, resulting in increased efficiency, sustainability, and productivity. These advancements are particularly critical in meeting the growing global demand for walnuts, driven by their diverse uses and health benefits. Historically rooted in traditional agroforestry systems, walnut cultivation has evolved into a high-tech industry incorporating cutting-edge tools and practices to optimize both production and environmental stewardship. Technology has been applied in operations such as the selection and breeding of cultivars, seedling propagation, irrigation, fertilizer application, weed management, pest and disease management, harvesting, and post-harvest handling including marketing.

Selection and breeding of cultivars

Conventional walnut breeding programs, which historically involved long time, space, and inputs for the selection of desired traits such as adaptability to abiotic stress, nut quality of nut, resistance to biotic stress, rootstock-scion compatibility, vigor, precocity and phenology, suckering, and rooting ability among others (Samantara *et al.,* 2022; Sütyemez *et al.,* 2022; Vahdati *et al.,* 2021; McGranahan *et al.,* 2009). Genome sequencing, genetic engineering, haploid production, transcriptomics and molecular markers like SSRs and SNPs have reduced the walnut breeding cycle and genetic improvement through gene selection and transfer to improve target traits such as early maturity, disease resistance, drought tolerance, and increased lateral bearing (Leslie *et al.,* 1997; Grouh *et al.*, 2011; Bernard *et al.,* 2018; Vahdati *et al.,* 2019; Sadat-Hosseini *et al.*, 2020).

Regions with well-established walnut production, such as the United States, China, and parts of Europe (e.g., France, and Romania), have invested heavily in breeding programs that aim to develop region-specific cultivars. For example, in China, extensive research has led to the development of new varieties like 'Luguang' and 'Wen185' that are well-suited to the country's diverse agroecological zones (Devin *et al*., 2022). Similarly, in California, cultivars such as 'Chandler' have been bred for high yields and quality, contributing to the state's dominance in global walnut exports.

Seedling propagation

The propagation of walnut trees has also seen significant advancements. Traditional methods such as budding and scion grafting remain prevalent (Gandev, 2015; Lopez, 2004). However, micropropagation techniques have also gained prominence in walnut nurseries, producing high-quality disease-free planting materials (Ahloowalia, 2003; Leslie *et al.,* 1992). Seedlings are developed from small plant parts like calluses, single cells, shoot tips, root tips, stems, and embryos in aseptic *in vitro* cultures (Read *et al*., 2014; Vahdati *et al.,* 2006 and 2009). It allows for the production of large numbers of uniform, healthy seedlings in controlled environments, accelerating the establishment of orchards. This technique is particularly important in regions like Hungary and France, where the demand for grafted, precocious varieties has increased due to government-supported initiatives encouraging high-density walnut plantations (Bujdosó *et al*. 2022).

Precision agriculture and orchard management

Frequent occurrences of adverse weather conditions and rising crop production costs including increasing demand for food have necessitated the adoption of precision agriculture technologies in modern farming systems for increased production and profitability (Huang *et al.,* 2023). Global navigation satellite systems (GNSS), geographic information systems (GIS), automated tractors, sensors, drones, and software are integral to orchard management. They are used to collect, process, and analyze data providing real-time monitoring of soil conditions, water requirements, and pest pressures, facilitating data-driven decisions that optimize resource use and reduce environmental impact (Shaheb *et al.,* 2022; Dhillon *et al.,* 2014). For example, in the arid regions of California and Xinjiang, China, precision irrigation systems utilizing soil moisture sensors and crop evapotranspiration data have improved water efficiency while ensuring optimal tree growth and nut development (Jerszurki *et al*., 2017).

Mechanization of harvesting and postharvest handling

Walnut harvesting, which has traditionally been a labor-intensive process, has seen significant improvements through mechanization. Modern walnut orchards, particularly in large-scale operations in the U.S. and Chile, use mechanical shakers, sweepers robotic harvesters equipped with cameras, sensors, and/or air-blasts. The equipment shakes and dislodges walnuts, which are then collected using sweepers or vacuum systems (Kootstra *et al.,* 2021; Anonymous, 2019). In regions with small-scale farming, like parts of Romania and Turkey, mechanization is gradually being adopted as a means to improve efficiency and meet growing demand.

Hot air drying has widely been used to reduce the moisture content of freshly harvested nuts. However, the rising cost of energy has driven the development of more efficient technologies to optimize the hot air-drying process (Chen *et al.,* 2022). In some advanced processing plants, energy for hot-air drying is now generated from pruned wood collected during the dormant season, significantly lowering production costs and improving sustainability. Computers-based systems are also being used to grade dried nuts and kernels enhancing precision and marketability.

Irrigation technologies

Given that walnut trees are water-intensive, efficient irrigation is a critical factor in modern walnut farming. The shift from traditional surface irrigation methods, such as furrow and flood irrigation, to low-volume systems like drip and micro-sprinklers has revolutionized water management in walnut orchards. In regions like California, where water scarcity is a major concern, precision irrigation systems help conserve water while maintaining high yields. These systems are designed based on real-time soil moisture data and crop coefficients, ensuring that water is applied only when and where it is needed, thereby reducing waste and improving tree health (Goldhamer, 1998; Jerszurki *et al*., 2017).

Sustainable and organic farming practices

Consumer demand for organically grown nuts has surged, particularly in Europe and the United States leading to growing interest in sustainable organic walnut farming (Jensen *et al* 2011). The current global organic food market is estimated at USD 228.35 billion and a projection of USD 658.38 billion in 2034 (Precedence Research, 2024). Many modern walnut orchards incorporate organic farming principles, such as the use of natural fertilizers and integrated pest management (IPM), to cater to the growing organic market niche that demands high-quality, chemical-free nuts with premium returns (Popa *et al*. 2023).

Gaps/Challenges in walnut farming

Despite significant technological advancements and the growing global demand for walnuts, the industry faces a labyrinth of challenges impacting both traditional and modern farming systems at different degrees (Anonymous, 2023; Simon, 2007).

Adverse climatic and environmental conditions

Climate change is perhaps the most pressing issue affecting walnut farming worldwide. Unpredictable weather patterns, including the occurrence of heat waves, extreme frost, hailstorms, and insufficient winter chills cause irregular leafing and flowering leading to poor nut quality and low yields (Gauther *et al.,* 2011; Hassankhah *et al.*, 2018). Insufficient chilling hours in regions with mild winters can delay or disrupt flowering, leading to poor fruit sets and reduced yields, an issue increasingly observed in the Mediterranean basin and parts of Central Asia. Hot air in spring can affect pollen receptivity because it decreases the pollen germination leading to poor nut set. Hot and dry summers affect kernel development, decreasing the kernel rate. Extreme dry conditions at nut maturity in late August or early September delay the opening of green husks and harvesting. This leads to the darkening of kernels, decreasing their quality (Hardy *et al.,* 2018).

Natural walnut-fruit forests have declined in the last 50 years. In Central Asia, these forests have been reduced to only 5-10% due to deforestation and land degradation, making it difficult to sustain long-term production. In response, walnut farmers in these regions are exploring climate-resilient cultivars and irrigation systems, although resource constraints often limit the widespread adoption of these innovations. (Shigaeva & Darr 2020, Wilson *et al* 2019).

Pests and diseases

Pest and disease management continues to be a significant challenge for walnut farmers across the globe. Walnut husk flies, codling moths and aphids can cause extensive damage to walnut orchards if not controlled. On the other hand, walnut blight, anthracnose, leaf blotch, crown gall, blackline disease, stem canker, and armillaria root rot are some of the most devastating diseases in walnut production (Bracalini *et al.,* 2023; Khan *et al.,* 2015; Garcin *et al.,* 2001). Pest infestations and disease outbreaks pose a serious threat to the industry because they not only increase production costs but also cause economic losses if not managed on time. Other documented challenges include limited access to appropriate planting/seed material (standard rootstocks and scion cultivars), suitability of pollinizers, and long juvenile periods of trees and harvesting (Sharma and Kumar, 2001).

High production costs and labor shortages

Modern walnut farming, particularly in intensive and super-intensive systems, requires significant inputs, including water, fertilizers, labor, and energy. Rising costs for these inputs, particularly energy, and labor, have become a growing concern in many walnut-producing countries. For example, in California, one of the largest walnut-producing regions globally, the high costs of water for irrigation and the increasing scarcity of labor have prompted farmers to invest in mechanized solutions such as automated harvesters and irrigation systems. However, these technologies are expensive, and small-scale farmers in regions like Central Asia, India, and Eastern Europe often struggle to afford such investments, further widening the productivity gap between large-scale industrial farms and traditional, smallholder operations (Vaishnavi *et al*., 2022).

Labor shortages, particularly during peak harvest times, are also a major challenge. In regions like Italy, France, and California, the agricultural labor force has declined, due to urban migration, stringent immigration policies, and negative public perception of the sector with respect to wages and career prospects, limiting the availability of workers. This labor gap has been partially addressed by mechanization, but the initial investment and maintenance costs remain prohibitive for many smaller farms (Ryan, 2023).

Limited valorization of by-products

Walnut trees produce various valuable by-products beyond the kernels, including husks, shells, and wood which are underutilized. Some walnut-producing countries like the United States and France, have made progress in utilizing walnut shells in bioenergy production or as a raw material in industries such as cosmetics and food additives, there remains significant untapped potential in developing countries. However, most traditional farming systems burn or discard the by-products during processing posing a threat to the environment (Liu *et al.,* 2021). Investing in technologies to process these by-products into value-added products could offer additional revenue streams for walnut farmers. However, the lack of infrastructure and knowledge on how to capitalize on these by-products continues to pose a challenge, especially in regions where farmers are already constrained by limited financial and technical resources.

Geopolitical instability and market fluctuations

Geopolitical instability in key walnut-producing regions, such as Ukraine and parts of the Middle East, has had a negative impact on both local production and global supply chains. Ongoing conflicts in these areas disrupt farming operations, export routes, and access to markets. For example, the war in Ukraine, a significant walnut producer in Europe, has led to a sharp decline in production, affecting both local farmers and the global walnut trade.

Additionally, fluctuations in market prices, driven by changing consumer demand, tariffs, and global trade policies, create uncertainty for walnut farmers. In countries like Turkey and Chile, which rely heavily on walnut exports, farmers are often vulnerable to price swings that can erode profit margins, particularly if they do not have access to well-organized cooperatives or government support mechanisms.

Opportunities

The walnut industry presents enormous growth opportunities due to increased nutritional health awareness leading to expanded global market demand. It also presents a source of cheap raw material for key cosmetic and therapeutic industries and the trees play an important role in environmental protection (Lui *et al*., 2021). Despite the existing challenges, technological advancement presents a myriad of turnaround opportunities. Locally adapted applications of digital automation solutions can ease the burden of labor gaps, as well as increase efficiency and productivity. Technology improves environmental sustainability while building resilience to climate change impacts (FAO 2022 a; FAO 2022 b; Lowenberg-DeBoer, 2022).

Conclusions

Walnut is an ancient temperate tree crop. As farming systems of other crops evolved, so did the case of walnuts. The once very passive traditional walnut farming systems have changed necessitated by various factors like increasing demand, technological advancement, and climate change among others. There is a tremendous shift from conventional low-input rainfed forest-based walnut farms due to the need to sustain high production of quality nuts to meet market demands. Technological advancements like speed breeding have revolutionized the development of superior cultivars that are not only suited for local agroecological conditions but also allow for the establishment of high-density orchards in modern walnut farming systems. Unlike traditional farms, modern walnut farms are also predominantly high input use including labor, fertilizer, and pesticides. Modern walnut farms in producing countries use superior cultivars that are efficient and suited for local agroecological conditions. In addition, there is the adoption of mechanization and digital automation of farm operations like harvesting, irrigation, and spraying including collection and processing data for informed decision-making.

Despite the increasing growth with respect to yield and hectarage, the primary products in most farming systems today the kernels and wood. Walnut trees including by-products like green husks are endowed with bioactive phytochemical compounds. However, many walnut farming systems have not fully exploited the pharmacotherapeutic potential of the crop. Product valorization opportunities still exist that can enhance sub-sector returns.

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Conflicts of interests

The authors have declared no conflict of interest in this article.

Author contributions

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All data was collected from the published research papers.

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