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REVIEW PAPER

A mini review of the impacts of deficit irrigation strategies for walnut (*Juglans regia* L.) production in semiarid conditions

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Abstract

The high demand for walnuts in recent years may be related to trends towards the adoption of a healthy and balanced diet. Walnut production is seeking higher yields, early entry into production and kernel quality, with technologies that combine new cultivars, mechanical harvesting, more intensive plant density, and modern irrigation systems. The walnut crop has expanded to non-traditional growing areas, some of which have semiarid climates characterized by low water availability for irrigation. This mini-review focuses on the possible effects of water deficit on plant physiology, kernel yield and quality, based on a comprehensive and comparative analysis of existing information on other dry fruit crops. Some studies estimate the maximum water demand of the walnut at about 1050–1200 mm ha^{-1} yr^{-1} with an average seasonal crop coefficient of 0.9, varying according to the phenological stage and agroclimatic characteristics Indicators of water status such as water potential, stomatal conductance, and leaf temperature are evaluated. Sustained and regulated deficit irrigation in walnuts allows a considerable reduction in vegetative growth, with little effect on production while maintaining midday stem water potential above – 0.8 MPa. There are reports of disadvantages to kernel and oil quality mediated by environmental conditions where the water deficit influence requires further study.

Introduction

Walnut tree environmental requirements

The common walnut (*Juglans regia* L.) is a species of global economic importance, cultivated for its nuts and wood. Its domestication is estimated to have started in the Euro-Asian region between the Caucasus and Northwest China (Pollegioni et al. 2017). Due to its climatic and geographic characteristics, this area would have acted as a natural refuge for this species approximately 10,000 years ago during the Last Glacial Maximum (Pollegioni et al. 2017). The introduction and expansion of this crop throughout the old world was mediated by man following the Silk Road about 5000 years ago (Vahdati 2014). The expansion and consolidation of the Persian and Roman Empires helped to incorporate the walnut as a traditional crop in Central Europe (Bernard et al. 2018). Walnuts are traditionally grown in the coastal regions of Mediterranean climates with rainfalls concentrated mainly during the winter season. In America, the introduction first took place in the sixteenth century in Chile, from where it expanded to the United States of America (USA) and Argentina (Bernard et al. 2018). During the past 15 years, walnut has been an increasing popularity due to its health benefits (Sánchez-González et al. 2017). According to FAO (FAOSTAT 2020) walnut production increased globally from 1.8 million t in 2005 to 3.3 million in 2020. Most of the increase in production is explained by increases in both new plantations (50%) and orchard productivity (30%). Currently, the world has 1.0 million ha producing ≈ 3.3 million

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t (FAOSTAT 2020). China has about 45 and 44% of the world's surface and walnut production, which ranks it as the top producer. USA is ranked second, with 15 and ≈ 12% of the world's surface and production, respectively. Iran is third, with ≈ 13 and 7% of the world's surface and production, respectively.

Crop evapotranspiration of mature walnut orchards ranges between 1050 and 1200 mm ha^{-1} yr^{-1}, so the development of economically profitable plantations in semiarid areas is only viable through irrigation. Some articles informed the walnut ETc estimated according to the water balance method (Doorenbos and Pruitt 1992; Goldhamer 1998). On the other hand, other works presented in Table 1 and Fig. 1 based the irrigation schedules according to plant-based water stress indicators, so they assume ETc equal to the total applied water to walnuts remained on the indicator's threshold. Another factor that has limited the expansion of walnuts in semiarid environments with warm winters is the chilling requirement to break bud endodormancy (Luedeling et al. 2009). However, winter cold deficiency can be mitigated through chemical management (e.g., hydrogenated cyanamide), that substitutes for dormancy and leads to more uniform bud break (Lemus 2010). Moreover, semiarid areas are characterized by high temperatures and low relative humidity during late summer and early autumn that can lead to a delay in pericarp ripening with respect to the kernel, being exposed to enzymatic and chemical oxidation (Lang et al. 2014). The difference in pericarp and kernel maturity could also be chemically managed with an ethephon application, which promotes the ripening and maturity of a variety of fruit and nut crops (Wei et al. 2020).

Walnut expansion in semiarid areas, the Argentina case

In Argentina, the walnut cultivation area is over 16,000 ha (INDEC 2020). Currently, the crop is expanding rapidly in the country's central-western region, spanning a wide latitudinal range from 25 to 40°S. It includes the provinces of Mendoza (37% of Argentina's walnut surface area), Catamarca (28%), and La Rioja (19%) (INDEC 2020). Argentina's central-western region is characterized by arid and semiarid climates with low rainfall concentrated in the summer -about 300 mm yr^{-1} (Rubí Bianchi and Cravero 2010). Irrigation water is mainly extracted from underground aquifers in Catamarca and La Rioja provinces and from both underground aquifers and rivers formed from thawing snow in the Andes Mountains in San Juan and Mendoza provinces (Searles et al. 2011). A considerable number of these orchards have been planted in the last 20 years, using high plant density (> 300 trees ha^{-1}), hedgerow formation, localized irrigation, and mechanical pruning and harvesting. Although water scarcity will be the most limiting factor for agricultural expansion in the future (Searles et al. 2011), a limited number of regulatory laws are available to ensure responsible resource deployment and prevent overexploitation of aquifers in this region. Therefore, a comprehensive review is required to improve irrigation strategy design.

The aim of this mini-review is to compile existing information on walnut crop water requirements and its response to the water deficit. Its purpose is to improve irrigation strategies to allow for maintaining both production and quality, controlling vegetative growth, and increasing water use efficiency (WUE).

Crop water needs and water status indicators

Crop water requirements are usually estimated by crop evapotranspiration (ETc); that is, the relation between reference evapotranspiration (ET0) and crop coefficient (*K*c). The crop coefficient is modified according to the crop phenological stage. It is minimum during budburst (early spring) and maximum during the fruit-filling period (late summer, Allen et al. 1998). In fruit trees, estimation of orchard water requirement should consider the fraction of ground cover, most important in young orchards or in low-density systems, where the maximum crop cover is usually lower than 50% (Table 1). Under these conditions in addition to *K*c, another coefficient denominated *K*r is applied to irrigation scheduling (Steduto et al. 2012).

Walnut *K*c values were initially estimated by Goldhamer et al. (1988) for the agroclimatic conditions of California and later adapted to other areas (Table 1). In Argentina, the *K*c estimated for California is used without considering the differences in annual ET0 and rainfall distribution (in central-western Argentina, rainfall is concentrated in the summer season as opposed to the winter season in California). The water balance method takes into account the amount of water available in the soil and the permissible level of depletion the crop can tolerate. For example, for loamy soils, a permissible soil water depletion of 50% is considered the lower threshold for achieving high yields for walnuts (Goldhamer 1998).

In Table 1, evapotranspiration of the walnut crop is compared to other nut crops. Walnut and pecan showed the highest average *K*c (0.9) over the entire growing seasons (estimated by seasonal accumulated ETc/ET0), followed by almond and pistachio (*K*c = 0.8), and hazelnut (*K*c = 0.7). Importantly, hazelnut crops grow in humid environments with lower reference evapotranspiration (average ET0 = 858 mm) than the other nut crops (ET0 greater than 1100 mm). Walnut, almond and pistachio have similar water requirements and lower than pecan. However, walnut and also hazelnut are species considered sensitive to water

Table 1 Review of published articles reporting crop water need in different nut trees and parameter used in their estimation including evapotranspiration (ET0), crop coefficients (*K*c) minimum and maximum and resulting crop evapotranspiration (ETc) for different areas

Crop	Irrigation season	ET0	ETc	*K*c			Rainfall	Age	Tree spacing	Cover crop	Area (Country, Hemisphere)	Reference
		mm season^{-1}		ini	mid	end	mm year^{-1}		(m)	(%)		
Almond	Jan–Dec	1400	851	0.40	1.10	0.40	540	4	7×6	nd	Seville (Spain, N)	García-Tejero et al. 2015
	Sep–May	1257	1450	0.93	1.10	0.55	105	11	7×5	65	Loxton (Australia, S)	Stevens et al. 2012
	Jan–Sep	1274	995	0.30	1.04	nd	548	5	6.7×4.3	55	California (USA, N)	Drechsler et al. 2022
Hazelnut	Apr–Sep	800	610	0.50	0.87	0.55	nd	9	5×6	nd	Clermont-Ferrand (France, N)	Mingeau and Rousseau 1994
	Apr–Sep	900	410	0.30	0.70	0.35	350	nd	3×7	nd	El Tarragonès (Spain, N)	Gispert et al. 2005
	Oct–Mar	875	657	0.70	0.80	nd	516	7	5×6	87	Río Claro (Chile, S)	Ortega-Farias et al. 2020
Pecan	Apr–Oct	1380	1310	0.40	1.35	0.40	300	35	9×12	70	Texas (USA, N)	Miyamoto et al. 1995
	Mar–Nov	1420	1215	0.18	1.10	0.40	234	21	9.7×9.7	67	The Mesilla Valley (USA, N)	Sammis et al. 2004
	Apr–Oct	1425	1140	0.38	1.26	0.38	nd	nd	nd	77	New Mexico (USA, N)	Samani et al. 2011
Pistachio	Feb–Oct	1453	841	0.49	0.80	0.32	139	35	10×10	nd	Urfa (Turkey, N)	Kanber et al. 1993
	Apr–Nov	1109	1036	0.07	1.19	0.35	nd	nd	5.2×5.2	60	San Joaquin, Ca (USA, N)	Goldhamer 2005
	Mar–Nov	1242	1021	0.30	1.10	0.60	300	14	5.8×5.2	60	Madera, Ca (USA, N)	Bellvert et al. 2018
Walnut	Mar–Nov	1580	1046	0.12	1.14	0.28	nd	nd	7.3×7.3	nd	San Joaquin, Ca (USA, N)	Goldhamer 1998
	Sep–Apr	1175	1050	0.35	1.14	0.35	250	nd	6×8	80	La Rioja (Argentina, S)	Morabito et al. 2006
	Mar–Nov	1192	1100	0.60	1.04	0.14	350–500	10	6.5×6.5	nd	Tehama, Ca (USA, N)	Fulton et al. 2017
	Mar–Nov	1192	1200	0.49	1.06	0.41	350–500	nd	6.6×3.3	nd	Tehama, Ca (USA, N)	Fulton et al. 2017

nd no data

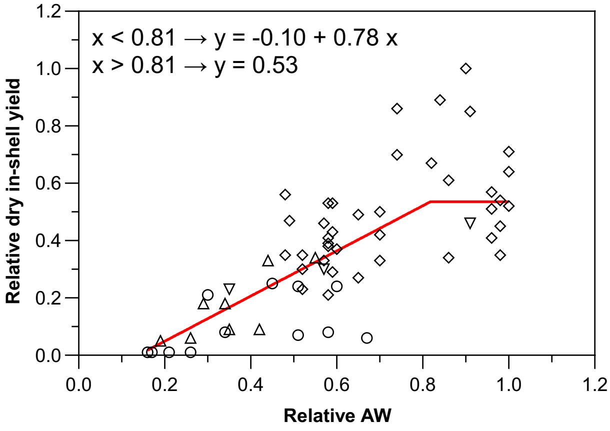

Fig. 1 Relationships between relatively dry in-shell nuts yield and relative applied water (AW) for walnuts. Data points were obtained from Goldhamer et al. (1988), Cohen et al. 1997, Ferreyra et al. 2001, Lampinen et al. 2004 and Buchner et al. 2008

stress (Liu et al. 2019; Mahmoudian et al. 2021) and the irrigation scheduling to maximum crop water demand are normally used. In contrast, almond and pistachio are considered drought-tolerant species (Pérez-López et al. 2018) and maximum production could be achieved at less than maximum water demand. Pecan can tolerate severe drought of moderate duration but a high negative impact on yield (Sparks 2005).

For irrigation management, and more particularly, when deficit irrigation strategies are used, monitoring plant water status is crucial. Water potential has been one of the most common measurements to determine plant water status (Scholander et al. 1965), expressed as leaf water potential (Ψleaf) or as stem (xylem) water potential (Ψstem) (McCutchan and Shackel 1992). In walnut trees, pre-dawn leaf potential (Ψpd) was initially used, although, the midday Ψstem is the most common indicator in use (Fulton et al. 2017). The Ψstem is determined covering a leaf with a reflective and water impermeable little bag during at least 30 min, during this time leaf transpiration stops and equilibrates with stem water potential (Fulton et al. 2001a). A midday stem water potential of less than – 0.8 MPa has been linked to yield and vegetative growth reductions throughout the walnut crop cycle (Table 2). The midday Ψstem is widely considered a reliable plant water status indicator in walnut. However, Ψstem measurements with the pressure chamber are destructive, requires a considerable labor and not suitable for automated monitoring.

Stomatal conductance (gs) is another indicator of plant water status that measures the degree of stomatal opening. Rosati et al. (2006) compared the gs of well-watered walnuts with other treatments irrigated at 50% of ETc during whole growing season. In this sense, the trees subjected to deficit irrigation showed gs in a range of 0.2–0.02 mol H_20 m^{-2} s^{-1}, while well-irrigated trees were in a range of 0.2–0.7 mol H_20 m^{-2} s^{-1}. Stomatal conductance values higher than 0.2 mol H_20 m^{-2} s^{-1} seem to be indicators of well-watered trees. These authors obtained a high degree of adjustment between gs and Ψstem ($R^2 = 0.99$), and in turn, Ψstem values were closely correlated with vapour pressure deficit (VPD; $R^2 = 0.85$). Despite the benefits that gs reference values would have for different phenological stages and their commercial use in irrigation control, no papers have been found on this subject for walnut trees.

Several studies have suggested that stomata regulate transpiration to maximize gs, while preventing critically negative xylem pressures from causing excessive xylem cavitation (Meinzer 1993; Sperry et al. 1993), which can be reverted by refilling embolized vessels. Recent studies suggest that this may occur in walnut despite the presence of moderate tension in the xylem, and water membrane channel proteins (PIP or aquaporin) are assumed to be responsible for this process (Sakr et al. 2003; Cochard et al. 2007).

Table 2 Plant water status reference based on midday Ψstem and Ψleaf for walnut irrigation scheduling. Extracted and adapted from Fulton et al. (2001a, b; 2014)

Ψstem (MPa)	Ψleaf (MPa)	Water stress level	Crop responses
0 to −0.2	0 to −0.8	–	It's not a usual in walnut
−0.2 to −0.4	−0.8 to −0.9	Low	Associated with high water availability and possible negative effects on long term tree and root health, depending on rootstock
−0.4 to −0.6	−0.9 to −1.1	Mid	Promotes the growth of the sprouts. It is ideal once the fruit size has been defined
−0.6 to −0.8	−1.1 to −1.2	Moderate	Kernel development and the following year's production are not affected. Low growth rate
−0.8 to −1.0	−1.2 to −1.4	Moderate–high	Shoot growth can be stopped. The nut size is smaller compared to well-irrigated walnuts. The following year's production can be affected
−1.0 to −1.2	−1.4 to −1.5	High	Very limited vegetative growth. Possible wilting and yellowing of leaves and pericarp. Yield and quality are reduced
−1.2 to −1.4	−1.5 to −1.7	Very high	Moderate to severe leaf fall
−1.4 to −1.8	−1.7 to −2.0	Severe stress	Total defoliation, near the death point of the trees
< −1.8	< −2.0	Plant death	Uncommon in irrigated walnuts, die before they reach this point

Thermal sensing is another promising technique used to detect plant water stress by measuring leaf temperature and a useful indicator of gs and transpiration (Jackson et al. 1981). The first determinant of leaf temperature is the air temperature, and in second place, the rate of leaf evaporation or transpiration (Jones et al. 2009). Moreover, thermal measurement is non-destructive, and can potentially be used with high temporal and spatial resolution for monitoring plant water stress at the field scale (Jones 2004). In walnuts, Dhillon et al. (2019) measured leaf and air temperature, air relative humidity, photosynthetically active radiation (PAR), and wind speed on shaded leaves in 7-year-old trees during two growing seasons to model a Crop Water Stress Index, obtaining a linear relationship with Ψstem ($R^2 = 0.67$). The authors conclude that leaf temperature could be used as an irrigation scheduling effective tool and provided daily spatial–temporal stress index values that correlated well with stem water potential measurements.

In addition, trunk diameter variations (measured by dendrometers) and sap flow show a significant correlation between measures of greater robustness such as Ψstem, gs, and soil moisture, which would allow automation of irrigation management to some extent. These techniques could be automated and the use of data logger to store growth data could minimizes labor needs (e.g., Drew and Downes 2009). In this sense, Archer et al. (2001) in walnut modelled a multiple linear regression to predict Ψstem from measurements of trunk diameter variation. They obtained a high correlation between estimated and measured values of Ψstem for both well-irrigated and drought-subjected trees ($R^2 = 0.95$). In another study, Romero et al. (2009), in Seville, Spain, reported advances with promising results in models for the management of fully automated irrigation in walnut and almond trees with measurements of sap flow, dendrometers, and soil moisture.

Irrigation strategies to increase WUE

Impact of water deficit on plant growth

In the production of fruit trees, in general, there is a marked tendency to intensify production processes associated with an increase in plant density and hedgerow formation. In walnuts, there is a clear interest in crop intensification as shown by the increase in planting density that has quadrupled in the last 50 years (from ≈75 trees ha^{-1} to > 300 trees ha^{-1}) due in part to the introduction of pressurized irrigation and mechanical harvesting (Lemus 2010). The increase in plant density has a direct impact on enhanced PAR interception, higher precocity, and production, with the added benefit of cost reduction in mechanization of pruning and harvest (Iglesias and Echeverria 2022). Goldhamer et al. (1985) compared the ETc of each plant and final yield of 4-year-old 'Chico' walnuts at high density (446 trees ha^{-1}) and low density (222 trees ha^{-1}), obtaining a reduction in ETc of 30% at high density in the months of maximum demand, while the yield in shell at high density was 2150 kg ha^{-1}, six times higher than 350 kg ha^{-1} recollected from orchard planted at low density. These results were partly explained by higher ground cover fraction for higher plant density treatment than lead to a reduction in the wetted area and the lower exposure of soil to sunlight, reducing direct water evaporation and, consequently, reducing ETc.

To achieve the advantage of high density over time, efficient control of tree structure and size is necessary to avoid excessive shading, leading to a decrease in the quantity and quality of production. In apples, pears, and more recently in almond and peach trees, the existence of dwarfing rootstocks allows efficient vegetative vigour management (Yahmed et al. 2016; Iglesias and Echeverria 2022). In other fruit trees, such as olives, where there are no rootstocks of proven vigour reduction, deficit irrigation strategies have been implemented during the shoot growth period (Trentacoste et al. 2019). In walnuts, dwarfing rootstocks have not been developed yet, and irrigation strategies focused on vigour management have been scarcely evaluated.

In walnut trees, vegetative growth is concentrated almost entirely in the period between bud break and endocarp hardening (spring), the period in which fruit number and size are defined (Charrier et al. 2011). Therefore, water deficit applied during spring seasons would lead to control of vegetative growth. However, the overlap of vegetative growth and fruit size determination is a serious limitation to the application of irrigation strategies to control vegetative growth, since it could penalize the final fruit quality. In this sense, Ramos et al. (1978) reported about the decrease in nut quality (in terms of size) when walnut trees were subjected to water deficit conditions in the early season and Fulton et al. (2001b) on the decrease in shoot growth rate in walnut trees under water deficit in late spring and early summer. The application of growth inhibitors (e.g. Paclobutrazol) has been proposed as a way to control vegetative growth, but this method has some disadvantages, such as high cost, repeated applications, and prohibition of use in many countries due to potential negative effects on crops, flora, fauna, and human health (Kishore et al. 2015). In a wide range of crops, vegetative growth is more sensitive to drought than the reproductive process (Hsiao 1973; Kozlowski and Pallardy 2002), which provides an advantage for controlling the size of plants with slight yield reduction.

Deficit irrigation strategies for vegetative growth control offer an interesting, low-cost alternative in an attempt to reduce the negative environmental impact of chemical strategies. Fulton et al. (2014) determined Ψstem values at midday ranging between – 0.6 and – 0.8 MPa to control vegetative growth (Table 2). This study also demonstrated that walnut orchards managed by mechanical lateral pruning, seasonal shoot growth were slightly responsive to water deficit. Thus, more intensive mechanical pruning could require more intensive water deficit to avoid uncontrolled excessive vigor that leads to lower bud fertility in the following seasons. Further studies are required to establish water deficit level and an associated (Ψstem) threshold for vegetative control depending on crop characteristics, and environmental conditions.

Impact of water deficit on production

WUE, defined as the ratio between the total biomass produced per tree and the amount of water used during the growing season, is difficult to estimate because root biomass determination in trees is not possible under field conditions (Howell 2001). At the production level, the final fruit yield is usually related to the amount of water applied during the growing season (Ruiz-Sánchez et al. 2010). WUE could be increased, maintaining production decreasing the amount of water applied or production reduction proportionally less than the reduction in applied water. Two irrigation strategies have been developed: Sustained Deficit Irrigation (SDI) and Regulated Deficit Irrigation (RDI). SDI consists of replenishing a lower dose of water than that estimated at maximum crop evapotranspiration throughout the season, while RDI only applies lower irrigation doses than the maximum required by the crop in a less sensitive development stage (Chalmers et al. 1981). Partial root drying (PRD) is another deficit irrigation strategy that consists of continuous or alternate irrigation of half the roots. PRD has been applied with WUE increases in apples, pears, olives, citrus, and mangos (Jovanovic and Stikic 2018). Some studies in grape and fruit crops such as orange and apple, note that there are no differences in productivity obtained under RDI and PRD (Sadras 2009; Adu et al. 2018). No reports have been found on the effects of PRD applied to walnut orchards.

Goldhamer et al. (1988) reported that restoring 33% ETc throughout the growing season for three consecutive years reduced production by 50% compared to 100% ETc irrigated control. In addition, WUE expressed in dry in-shell yield increased from 4.4 (Control) to 5.4 kg ha^{-1} mm^{-1} (33% ETc). Cohen et al. (1997) evaluated three irrigation strategies: a Control irrigated at 100% ETc, an RDI treatment with 20% ETc irrigation between June and September (northern hemisphere), and an SDI treatment irrigated at 70% ETc throughout the growing season. The two deficit treatments produced a 40% yield reduction in comparison with the Control. However, they found a significant increase in WUE dry in-shell yield from 2.4 kg ha^{-1} mm^{-1} in the Control to 5.6 kg ha^{-1} mm^{-1} in RDI and 4.7 kg ha^{-1} mm^{-1} in SDI. It is also important to note that no differences in yield were observed between RDI and SDI treatments, and that fruit quality (nut size, weight, and color) for the Control and deficit irrigation treatments was similar. WUE values comparison among studies should be with caution because unit of water considered (e.g., irrigation, or irrigation + rainfall) could differ; however, the trend of increasing the WUE under deficit irrigation seems evident.

We estimated the water productivity function of walnut from published data of dry in-shell yield and total applied water over the season (Fig. 1) and relativized each data-point according to the maximum of each variable (maximum yield = 9930 kg ha^{-1}; maximum water dose = 1350 mm ha^{-1}). The obtained function by regression ($R^2 = 0.52$) is segmentally linear. In the pre-breakpoint, the productivity increases from 0 to 0.54 (breakpoint) when the total water applied varies between 0.20 and 0.81. Water doses higher than 0.81 (post-breakpoint) do not increase productivity due to an unbalanced vegetative/reproductive growth.

Impact of water deficit on walnut quality

Although the quality of the walnut kernel is mainly defined by its color (lighter kernels are the most appreciated by the market), final size, weight, and taste also bear an influence. Ramos et al. 1978 noted that walnut trees exposed to water deficit at the early season produced smaller and lighter nuts; and if the stress occurred at the late season the kernel color was severely affected, especially in the upper canopy. The color of the kernel pellicle depends on the phenol oxidation, while the browning of other sections of the kernel is due to Maillard's reactions (Ortiz et al. 2019). This oxidation and caramelization process occurs in the late-season, the postharvest period and after nuts are shelled. It is stimulated by conditions of high temperature, luminosity, and relative humidity (Jensen et al. 2001). Additionally, a decrease in carbohydrate supply by shading and/or leaf fall can also darken the kernel integument (Fields et al. 2020). Twice applications of 3% kaolin spray in the season have been reported as a protective practice against sunburn on leaves, husk, and kernel, in environments with high temperatures and water deficit (Gharaghani et al. 2018).

Most of these adverse effects can be controlled by bringing the harvest forward once the physiological maturity of the kernel is defined. Once the harvest is over, immediate drying, cracking, and conservation of the kernel at low temperatures (below 1 °C) in an atmosphere enriched with N_2 or CO_2 is ideal to preserve aesthetic and nutritional quality of the kernel (Christopoulos and Tsantili 2011). If kernels are not kept under ideal conditions, new problems arise after non-enzymatic oxidation, such as the oxidation of unsaturated fatty acids in the oil by the action of lipase and lipoxygenase enzymes (Ortiz et al. 2019) and the increase in nut rancidity.

Perspectives on the future

Given the high-water demand for walnut trees, developing high-density crops in conjunction with deficit irrigation strategies could be an option for the crop's expansion in semiarid areas. Water deficit strategies appear to offer a way to improve both kernel and oil quality in walnuts, like what has been studied in other dry fruits, such as pistachio or almond (Carbonell-Barrachina et al. 2015; Lipan et al. 2019). The control of vegetative growth is key, but deficit irrigation strategies have been poorly evaluated for this purpose in the long-term. Therefore, it is necessary to address and explore this issue in future studies. RDI strategies can be useful when applied between sprouting and endocarp hardening to increase WUE and to reduce vegetative growth with less effect on final yield, but a possible effect on final fruit size. SDI would allow more water and control of vegetative growth, although production may decrease. Other strategies, such as PRD, have not been tested for this crop. Finally, more field experiments focusing on the definition of period, intensity, and duration of deficit irrigation and stem water potential thresholds are needed to extrapolate results to different environmental conditions and crop management strategies in walnut orchards.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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