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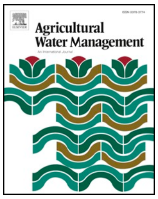

Review

Water use and irrigation management of pomegranate trees - A review

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ABSTRACT

Global warming-induced climatological changes, limited water resources and water restrictions for agriculture during drought force producers to invest in crops more suited to the potential future climate, such as drought-tolerant pomegranate trees. Skilful management of limited and poorer quality water resources is critical to optimize production and fruit quality for a total farm unit and requires appropriate knowledge regarding the crop. The review focuses on irrigation methods, water requirements of the crop, water use efficiency and productivity and water management strategies under limited water supply (irrigation and orchard management).

With regard to irrigation systems, drip irrigation appears to be favoured above the more conventional types of irrigation. Management challenges of subsurface drip irrigation systems though should be taken into account if this type of irrigation is considered. The evapotranspiration of subsurface irrigated pomegranate orchards in arid regions ranged from 53 to 953 mm for one to six-year-old trees and orchard water requirements may increase depending on the irrigation system used and whether weeds are present in the orchard. Comparison of mathematical relationships to determine crop coefficients from fractional ground cover indicated that the pomegranate cultivar ‘Wonderful’ tended to have lower crop coefficient values than grapevine, peach and other deciduous fruit at comparable canopy cover.

A comparison of advantages and disadvantages of several irrigation strategies identified potential of some to optimise farmer profitability and to comply with customer requirements. Water deficits during flowering and fruit set may increase aril red colour for some cultivars without detrimental effects on marketable yield, fruit size and chemical composition. Water deficits during ripening and sustained deficit irrigation throughout the season in some cases resulted in improved red colour of fruit peel and/or juice, but with a negative effect on fruit weight and economic income. Sustained deficit irrigation at low levels of evapotranspiration replacement is not considered a sustainable strategy for pomegranate orchards over the long term. In terms of orchard management, olive pomace mulch increased yield and decreased orchard water use. Different types of mulches can be considered to reduce soil evaporation water losses.

Variable results with different systems and different cultivars in different countries clearly indicate that results from one study cannot simply be transferred to another area where conditions and cultivar types may not be the same. This underscores the necessity of conducting research under local conditions.

1. Introduction

In South Africa, global warming-induced climatological changes are expected to impact negatively on the already limited water resources of the Western Cape (WCDOA and WCDEA and DP, 2016) and water restrictions for agriculture are already an inevitable reality during drought years. It is furthermore predicted that the western region of South Africa will have a significant reduction in streamflow, with potentially sombre implications for irrigated agriculture. Increased temperatures will result in an increased irrigation demand for deciduous fruit orchards, but the irrigation volume for the agricultural sector is unlikely to increase as the Department of Water Affairs has capped agricultural allocations at current levels. Water demand-and-supply forecasts for some water management areas indicated a severe (−20 % to −80 %) and moderate (0 % to −20 %) gap between the existing supply in 2010 and projected demand in 2030 (McKinsey & Company, 2010). Improved agricultural water use efficiency and productivity is considered a necessity to provide the water needed for the projected increased water demand by human consumption and industrial activity by 2030. Such limited water resource availability makes maximizing net income per unit water used a prerequisite for sustainable farming.

One way to cope with this situation is to invest in crops more suited to the potential future climate, such as drought-tolerant pomegranate trees (DEA, 2016; Galindo et al., 2017b). In South Africa, the

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pomegranate industry is small but growing. Production started in the early 2000’s and South Africa is presently an international role player in production and exports from the southern hemisphere to various northern hemisphere countries (Viljoen, 2019). Although pomegranate trees are considered drought-tolerant, irrigation is required during the dry summer to optimise growth, yield and fruit quality for commercial production. Skilful management of limited water resources will be a necessity if optimal production and fruit quality are to be retained for a total farm unit. For efficient in-field water management, correct irrigation system selection, design and maintenance are very important, but efficient irrigation scheduling is the key to achieving high irrigation water use efficiency.

Although there are general guidelines for the irrigation of pomegranate trees (Pomegranate Association of South Africa (POMASA, 2013), there are no local research results available to guide producers with regard to tree water use requirements or the effect of different levels of soil water depletion on pomegranate tree growth, yield and fruit quality under local conditions. A review of international pomegranate research warranted to provide guidance until local research generates guidelines for South African producers on how to achieve the best water use productivity without compromising fruit quality. This review focuses on irrigation methods, water requirements of the crop, water use efficiency and productivity and water management strategies under limited water supply (irrigation and orchard management). A separate review focuses on the effects of water deficits on tree physiology, growth, yield and fruit quality.

2. Methods of irrigation

According to Holland et al. (2009) most of the large commercial orchards in Israel, India and the United States of America use drip irrigation methods, although some producers prefer sprinklers. However, in California, USA, most pomegranate orchards are irrigated with flood or furrow, with few farmers using high-frequency surface or subsurface drip (Wang et al., 2015; Zhang et al., 2017). In India it is general practice to irrigate crops by conventional methods, i.e. flood/furrow /ring basin methods, with almost 38 % of the micro-irrigated crops in India being drip irrigated (Kumar et al., 2016; Singh and Sharma, 2013). Adoption of micro irrigation systems in the country are deterred by - amongst other factors - physical, socio-economic and institutional constraints (Kaarthikeyan and Suresh, 2019; Kumar et al., 2016). In South Africa, drip (single and double line) and microsprinkler irrigation are also practiced, whereas overhead irrigation is not recommended for pomegranates (Pomegranate Association of South Africa (POMASA, 2013; Volschenk and Mulidzi, 2019).

The benefits of drip irrigation compared to conventional irrigation in Indian pomegranate orchards included c. 42 % increased yield and c. 38 % higher net returns for farmers in the Kullu district in Himachal Pradesh (Singh and Sharma, 2013). According to Kumar et al. (2013) use of an auxiliary reservoir in combination with drip irrigation saved a substantial amount of irrigation water (c. 32 %) compared to surface methods in an arid Punjab region. The efficiency of surface irrigation methods in both of these studies was decreased by limited availability of irrigation water, and rainfall or canal operational timings, which did not necessarily match the critical development stages of crops. In comparison to surface irrigation systems drip irrigation increased pomegranate irrigation water productivity in the Punjab region by 82 % (5.32 kg m^{-3}) while net profit per mm water applied almost doubled for drip irrigation (Kumar et al., 2013). The extraordinary high irrigation water productivity for the drip irrigation system compared to the surface irrigated methods in this case may be explained by more efficiently managed crop water demand, which may have resulted in water savings, better growth and higher yield. Frequent drip irrigation furthermore limited variation in soil water availability and decreased pomegranate fruit cracking by 10–15 %, which increased marketable yield. Ghosh et al. (2013) also found that drip irrigated plants had less fruit cracking than basin irrigated plants.

Further potential advantages of drip irrigation over the conventional methods (i.e. flood, furrow, ring basin) include a saving of up to 50 % of water; lower labour costs related to weed control and application of fertilizers and pesticides, and better control over water application on sloping terrain and variable soils (Singh and Sharma, 2013). Benefits of well managed surface drip and subsurface drip irrigation systems include eliminated or reduced runoff and deep drainage, minimized surface soil and plant evaporation, reduced transpiration of drought tolerant crops and reduced fertilizer losses (Ayars et al., 1999). Subsurface compared to surface drip irrigation on a sandy loam soil in California resulted in a significant increase in yield of prime (good colour, diameter > 80 mm, minimal cracking with no open cracks) and/or subprime (suitable for juice, green, open cracked) fruit for some years (Ayars et al., 2017; Wang et al., 2015). Total yield was consistently higher in the subsurface compared to surface drip system, but due to an additional 10 % water being applied to the surface drip irrigation treatment to compensate for evaporative water loss and weed growth, not significantly different (Ayars et al., 2017). Use of subsurface drip irrigation resulted in reduced weed pressure compared to surface drip irrigation. Irrigation water productivity ranged between c. 5.15 and 5.58 kg m^{-3} for surface and between 5.97 and 6.04 kg m^{-3} for subsurface drip irrigation.

Although subsurface drip irrigation systems have advantages, there are also some disadvantages to take into account (Lamm, 2002). These include: wetting pattern issues on coarse soils; difficulties in monitoring and evaluation of system operation and application efficiency; emitter discharge rates and water redistribution disparities, restricted plant root development and its role in irrigation and fertilization and crop water stresses even when the root zone is well watered. In a study by Ayars et al. (2017), subsurface drip irrigation of pomegranate trees on a sandy loam soil required high frequency irrigation. Applying irrigation after 1 mm water use resulted in 10–12 irrigations per day during peak water use.

3. Water requirements

Information on water requirements of crops are needed to decide whether production of a certain crop is viable in a specific region. Crop water requirement is the amount of water that needs to be supplied to replace water lost through evapotranspiration. Water requirements of crops can be determined by direct measurement of the consumptive water use (energy balance and micrometeorological methods, soil water balance, lysimeters) or it can be estimated indirectly using mathematical models.

3.1. Reference evapotranspiration and crop coefficients

For purposes of irrigation scheduling, crop water requirements (ET_c) is frequently estimated according to the guidelines of FAO56 (Allen et al., 1998) using weather data based Penman-Monteith reference evapotranspiration (ET_o) and crop coefficients (K_c). To calculate ET_o the following data are needed: solar radiation, air temperature, humidity and wind speed measured at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water. The ET_o can be estimated for hourly, daily or ten-day to monthly time intervals using the appropriate calculations. Reference evapotranspiration can also be quantified using other less accurate models that require less extensive weather data sets (Meshram et al., 2011) or by monitoring Class A pan evaporation (Allen et al., 1998; Bhantana and Lazarovitch, 2010). A pan factor (K_p) is used for conversion of Class A pan evaporation to ET_o (Allen et al., 1998). Long term meteorological data have also been used to estimate ET_o for some of the pomegranate irrigation research done in India (Meshram et al., 2010a,b, 2011; Bhagat and Popale, 2016), Iran (Parvizi et al., 2014) and Egypt (Seidhom and Abd-El-Rahman, 2011).

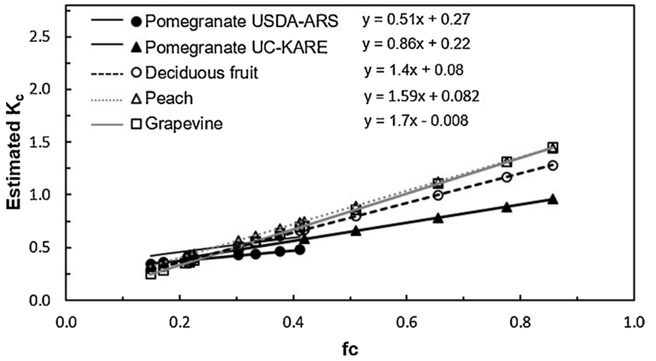

Fig. 1. Comparison between crop coefficient (K_c) estimates from fractional canopy ground cover (fc) for bearing pomegranate (USDA ARS and UC KARE research sites, Zhang et al., 2017), general deciduous fruit (Meshram et al., 2010a), peach trees (Ayars et al., 2003) and grapevine (Williams and Ayars, 2005).

Although FAO56 (Allen et al., 1998) contains K_c values for various crops, data are not listed for pomegranate trees. Crop coefficients are experimentally determined ratios of ET_c/ET_o and K_c based on Class A pan evaporation are not interchangeable with those developed using ET_o. Crop coefficients can be determined based on ET_c measured accurately using weighing or drainage lysimeters (Ayars et al., 2017; Bhantana and Lazarovitch, 2010; Zhang et al., 2017) or ET_c derived from a soil water balance (Allen et al., 1998). Alternatively, the pomegranate K_c can be estimated from site specific empirical relationships of K_c versus day of year (Ayars et al., 2017; Parvizi et al., 2014), or from fractional canopy ground cover (Meshram et al., 2010a, 2011; Zhang et al., 2017) as indicated in Fig. 1.

Zhang et al. (2017) developed different mathematical relationships between K_c and fractional canopy ground cover for bushy (UC-KARE) and vase-shaped (USDA_ARS) pomegranate (cv. Wonderful) trees in California. Comparison of these pomegranate-specific K_c estimates to those for peach (Ayars et al., 2003), grapevine (Williams and Ayars, 2005) and the general deciduous fruit equation used by Meshram et al. (2011) indicated that the pomegranate cultivar ‘Wonderful’ tended to have lower K_c values at comparable fractional ground cover (also measured as shaded area cast on the ground) than these crops (Fig. 1). The differences in slopes and intercepts of these relationships are ascribed to differences in methods used to determine ET_c and the shaded areas, and dissimilarities in cultivation practices, specifically irrigation amounts and frequencies (Williams and Ayars, 2005).

For pomegranate, from the sources used by this review, only the K_c values generated by research of Ayars et al. (2017), Bhantana and Lazarovitch (2010) and Zhang et al. (2017) are based on lysimeter measurements. Those of Bhantana and Lazarovitch (2010) were intended for use with Class A pan evaporation and are suitable for a range of irrigation water salinities between 0.8 and 8 dS m^{-1}. The Class A pan crop coefficients for non-saline conditions for one-year-old ‘Wonderful’ plants were 0.16 at bud break and 0.64 at 120 days after bud break. In California, the maximum K_c for use with Penman-Monteith derived ET_o increased for subsurface drip irrigated ‘Wonderful’ pomegranate trees from 0.85 for four-year-old trees to between 1 and 1.2 for six-year-old trees, bearing c. 33.2 and 50.4 t ha^{-1} fruit, respectively (Ayars et al., 2017). Intrigliolo et al. (2011) adapted K_c values based on those of Bhantana and Lazarovitch (2010) for Spanish research conditions (Intrigliolo et al., 2012, 2013), whereas Buesa et al. (2012) initially used the farmer irrigation schedule and experimentally developed crop coefficients, using soil water content and stem water potential measurements as calibration aid. Bugueño et al. (2016) also based their research for young pomegranate trees on a K_c value of Bhantana and Lazarovitch (2010) and recommended upward adjustment thereof since trunk growth rate was higher in the 130 % ET_c compared to the 100 % ET_c treatment. Martinez-Nicolás et al. (2019) used Bhantana and Lazarovitch (2010) as reference to obtain K_c values for seven-year-old ‘Mollar de Elche’ and ‘Wonderful’ trees. Differences in phenological development between cultivars was taken into account and the control treatment was irrigated at 115 % ET_c.

3.2. Crop evapotranspiration

From the articles sourced for this review, the only lysimeter-measured daily ET_c data for young pomegranate orchards were available from Israel (Bhantana and Lazarovitch, 2010). Daily ET_c of one-year-old *Punica granatum* L. plants during 2008 ranged from 0.23 to 5 mm d^{-1} from bud burst to peak season. The Class A pan evaporation during this period ranged between c. 3.1 and 9.2 mm d^{-1}. The young tree peak water use is about half of that measured in the Mediterranean climate of the Central Valley of California for bearing six-year-old ‘Wonderful’ pomegranate trees (10.5 mm d^{-1}) (Ayars et al., 2017). There were minor cultivar related differences in daily ET_c of the one-year-old ‘Wonderful’ and ‘SP-2’ varieties and their response to a range of irrigation water salinities between 0.8 dS m^{-1} and 8 dS m^{-1} (Bhantana and Lazarovitch, 2010). Salinity significantly reduced daily ET_c of the pomegranate plants, which should be taken into account during irrigation scheduling to prevent excessive leaching.

The seasonal ET_c (March to November) for one-year-old ‘Wonderful’ and ‘SP-2’ plants irrigated with low salinity water in Israel during 2008 was 544 mm and 557 mm, respectively, amounting to about a third of the 1521 mm cumulative Class A pan evaporation (Bhantana and Lazarovitch, 2010). Irrigation of these trees with water having salinity of 1.4, 3.3, 4.8 and 8 dS m^{-1}, reduced the seasonal ET_c relative to that of trees irrigated with 0.8 dS m^{-1} water by 15, 23, 44 and 66 %, respectively. In 2010 and 2012, yearly ET_c of one and three-year-old ‘Wonderful’ subsurface drip-irrigated plants in California was c. 4 % (c. 53 mm) and c. 35 % (483 mm) of the c. 1263 and c. 1387 mm ET_o, respectively (Ayars et al., 2017). The yearly ET_c of bearing four, five and six-year old trees were c. 683, c. 912 and c. 953 mm, respectively, which amounted to 49, 62 and 69 % of the cumulative ET_o.

Actual seasonal evapotranspiration of nine-year-old ‘Manfalouty’ pomegranate trees grown in sandy desert soils in the El-Maghara region, Egypt, was determined by measuring soil moisture content gravimetrically (Seidhom and Abd-El-Rahman, 2011). The ET_c of trees drip irrigated every second day from February to October over three years totalled c. 483 mm on average, with a maximum daily water use of 2.7 mm d^{-1} during the season. The ET_o for the 2008–2010 seasons amounted to 1334 ± 16 mm on average. Soil water balance determined seasonal evapotranspiration of six-year-old ‘Hicaznar’ pomegranate trees planted in 1.2 m deep loamy soil in Turkey ranged between 775.2 and 825.6 mm during three seasons whereas the ET_o amounted to 751.5 (± 34.4) (Dinc et al., 2018).

3.3. Irrigation water requirement

In addition to ET_c the irrigation water requirement takes effective rainfall into account and may include extra water to compensate for irrigation system efficiency and/or for leaching of salts (Allen et al., 1998). Methods for estimation of ET_c and the irrigation water requirement differed widely between countries and research studies sourced for this review due to site-specific differences in, amongst other factors, evaporative demand, orchard spacing, cultivars, tree canopy cover, soil type, wetted area and irrigation water salinity. However, the measured amounts of irrigation water applied to well-watered control treatments of drip irrigated irrigation research projects conducted in various countries in young to full bearing orchards give an indication of the variation in irrigation water requirement of pomegranate orchards (Fig. 2).

In California, on fine sandy loam, non-bearing trees of the cultivar ‘Wonderful’ received 25 and 216 mm drip irrigation, respectively, in the

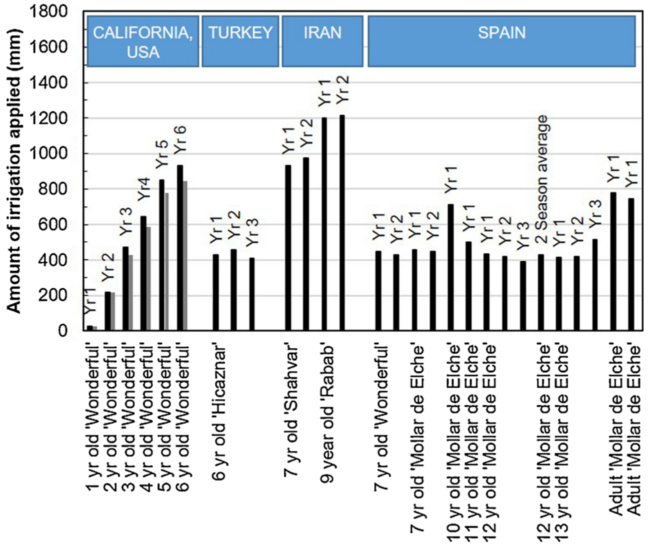

Fig. 2. Amounts of irrigation applied to well-watered control treatments of drip irrigation research projects for selected pomegranate cultivars varying in age and irrigated period in California (USA), Turkey, Iran and Spain. The grey bars indicate subsurface drip-irrigation. Data labels indicate experimental year.

first and second season (Ayars et al., 2017). The amount increased in subsequent seasons for bearing three, four, five and six-year-old subsurface drip irrigated pomegranate trees to 427, 584, 780 and 843 mm of irrigation water, and to 472, 645, 848 and 932 mm for surface drip irrigated trees of similar age. In Turkey, irrigation applied to double line drip irrigated ‘Hicaznar’ trees in loamy soil amounted to 430, 455.5 and 410 mm (Dinc et al., 2018). In Iran, the maximum amount of irrigation applied to the pomegranate cvs. ‘Shahvar’ and ‘Rabab’ on loam and fine sandy loam soils was 972 and 1214 mm, respectively (Parvizi et al., 2014; Selahvarzi et al., 2017). The amount of irrigation water applied to the cvs. ‘Mollar de Elche’ and ‘Wonderful’ in Spain on sandy loam, silt loam and sandy clay loam soils ranged between 392 mm and 776 mm (Buesa et al., 2012; Intrigliolo et al., 2011, 2012, 2013; Martínez-Nicolás et al., 2019; Mellisho et al., 2012; Mena et al., 2013; Peña-Estévez et al., 2015, 2016).

With regard to canopy cover of these orchards no information was available for the non-bearing trees in California (Ayars et al., 2017) nor for the seven-year-old ‘Mollar de Elche’ and ‘Wonderful’ trees from Spain (Martínez-Nicolás et al., 2019). However, maximum canopy ground cover for the surface drip-irrigated three, four and five-year old ‘Wonderful’ orchards was c. 20.9, 46.2 and c. 81.3 %, respectively, compared to c. 21.1, 51 and 85.7 % for the subsurface irrigated trees (Zhang et al., 2017). Canopy cover of the ‘Shavar’ cultivar in Iran is given as c. 50 %, (Selahvarzi et al., 2017), whereas the canopy diameter of ‘Rabab’ was 2 m in an orchard spaced 5m × 4m (Parvizi et al., 2014). The full canopy ground cover of most of the between 11 and 13-year-old Spanish ‘Mollar de Elche’ orchards ranged between 48 % and 56 % (Buesa et al., 2012; Intrigliolo et al., 2011, 2012, 2013).

4. Water use efficiency and water productivity

In addition to water production functions, water use efficiency and biophysical and economical water productivity indicators can assist in decision making on on-farm irrigation (Fernández et al., 2020). Definitions of the terms water use efficiency and water use productivity in the research surveyed by this review was inconsistent and the terms cannot be used interchangeably between studies (Table 1). The water use indicator terminology for this review was therefore standardised according to Fernández et al. (2020) and references therein. Crop water use efficiency is defined as the crop evapotranspiration ($m^3\ ha^{-1}$) divided by the amount of water applied by irrigation and precipitation ($m^3\ ha^{-1}$). There are several options available to calculate crop water productivity ($kg\ m^{-3}$), but for the purpose of this article it is defined as yield ($kg\ ha^{-1}$) divided by crop evapotranspiration ($m^3\ ha^{-1}$). Water productivity values calculated by using crop evapotranspiration estimated as the total of effective precipitation and irrigation as denominator is considered to be unreliable. Irrigation water productivity is defined as yield ($kg\ ha^{-1}$) divided by the total amount of water applied by irrigation ($m^3\ ha^{-1}$). Economic crop water productivity quantifies the relation between production earnings in monetary terms and water usage. Economic irrigation water productivity (currency unit per m^3) can be calculated using the gross margin (revenue accounted for variable costs), net margin (revenue accounted for variable and fixed costs) or profit (revenue accounted for variable, fixed and opportunity costs) per hectare divided by irrigation water applied ($m^3\ ha^{-1}$). Of these, the net margin or profit is considered most appropriate for decision making on profitable irrigation management of fruit tree crops (Fernández et al., 2020).

Based on general agreement, marketable yield is used as numerator to calculate irrigation water productivity (Fernández et al., 2020). However, for pomegranate orchards Dinc et al. (2018), Ghosh et al. (2013), Khattab et al. (2011), Parvizi et al. (2014) and Seidhom and Abd-El-Rahman (2011) used total yield in calculations, whereas there is not clarity whether Kumar et al. (2013) and Martínez-Nicolás et al. (2019) used total or marketable yield (refer to comments, Table 1). Ayars et al. (2017) calculated irrigation water productivity for prime fruit destined for the fresh fruit market, sub-prime fruit for juicing (included some green and open cracked fruit) and for total yield, whereas Selahvarzi et al. (2017) used marketable yield. Irrigation water productivity may be overestimated in the cases where the total yield does not represent marketable yield. Furthermore, it was not possible to accurately define the economic crop water productivity reported by Intrigliolo et al. (2013) due to lack of economic analysis information.

Higher irrigation water productivity for subsurface compared to surface drip irrigated pomegranate trees was due to higher yield and less water applied to the subsurface irrigated trees (Ayars et al., 2017). The irrigation water productivity for four, five and six-year-old trees was 6.04, 6.1 and 5.97 $kg\ m^{-3}$ for the subsurface drip and 5.15, 5.35 and 5.58 $kg\ m^{-3}$ for the surface drip irrigated trees. Deficit irrigation resulted in increasing water productivity (fruit yield divided by irrigation applied + rainfall) of ‘Mollar de Elche’ pomegranate trees (Intrigliolo et al., 2013). The average increase in water productivity over three years relative to the control (3.9 $kg\ m^{-3}$) was particularly noticeable in the sustained deficit irrigation (5.9 $kg\ m^{-3}$) treatment and where regulated deficit irrigation was applied during flowering and fruit set (4.9 $kg\ m^{-3}$). The sustained deficit irrigation and regulated deficit irrigation treatments were successful in increasing water productivity and economic irrigation water productivity, maintaining the yield value at similar levels to the control (Intrigliolo et al., 2013). However, there was a definite impact of sustained deficit irrigation on fruit size and consequently on farmer income. More recently Martinez-Nicolás et al. (2019) confirmed that withholding irrigation during flowering and fruit set for the cvs. ‘Mollar de Elche’ and ‘Wonderful’ improved irrigation water productivity by c. 14.5 % and c. 10 % on average over two seasons compared to where full irrigation was applied (irrigation water productivity 5.6 and 7.1 $kg\ m^{-3}$ for the respective cultivars). Irrigation water productivity increased due to water savings, with no significant effect of deficit irrigation on marketable yield.

Deficit irrigation applied at 75 % ET_c and 50 % ET_c increased irrigation water productivity of the cv. ‘Rabab’ by 15 % and c. 27 %, respectively, on average over two seasons compared to trees irrigated at 100 % ET_c (irrigation water productivity 4.2 $kg\ m^{-3}$) (Parvizi et al., 2014). However, partial rootzone drying strategies applied at these respective ET_c levels over the same period increased the irrigation water productivity on average by 38 % and c. 51 % compared to the fully irrigated trees (Parvizi et al., 2014). The increased irrigation water productivity of the 75 % ET_c partial rootzone drying strategy was

Table 1
Summary of water use terminology used in literature pertaining to pomegranate orchard water use and recommended standardised terms.

Author	Water use term	Definition	Units	Comment	Recommended water use indicator[a]
Ayars et al. (2017)	Water productivity (WP)	Yield divided by applied irrigation water	kg ha^{-1} mm^{-1}	For prime, subprime and total yield. Marketable yield per se not reported.	Irrigation water productivity (WP_I)
Dinc et al. (2018)	Water use efficiency	Yield divided by evapotranspiration	t ha^{-1} mm^{-1}	Total yield	Water productivity (WP_c)
	Irrigation water use efficiency	Yield divided by irrigation	t ha^{-1} mm^{-1}	Total yield	Irrigation water productivity (WP_I)
Ghosh et al. (2013)[b]	Water use efficiency	None	kg ha^{-1} cm^{-1}	Total yield WP_c based on ET_c = precipitation + irrigation	Water productivity (WP_c)
Intrigliolo et al. (2013)	Water use efficiency	Yield divided by irrigation water applied plus rainfall during the growing season	kg m^{-3}	Total yield WP_c based on ET_c = precipitation + irrigation	Water productivity (WP_c)
	Water productivity	Yield value divided by irrigation applied	Euro € m^{-3}	Marketable yield; weight and prices received by growers from cooperative	Economic Irrigation Water Productivity
Khattab et al. (2011)	Water use efficiency	Yield divided by the scheduled amount of water	kg m^{-3}	Total yield	Irrigation water productivity (WP_I)
Kumar et al. (2013)	Water productivity (WP)	Crop yield divided by irrigation water applied	kg m^{-3}	Marketable or Total yield	Irrigation water productivity (WP_I)
Martínez-Nicolás et al. (2019)[b]	Water productivity (WP)	None	kg m^{-3}	Marketable or Total yield	Irrigation water productivity (WP_I)
Parvizi et al. (2014)	Water productivity (WP)	Fruit yield divided by water used	kg m^{-3}	Total yield	Irrigation water productivity (WP_I)
Seidhom and Abd-El-Rahman (2011)	Crop water use efficiency	Crop yield divided by the amount of seasonal evapotranspiration	kg m^{-3}	Total yield	Water productivity (WP_c)
	Water economy	Crop yield divided by the amount of water added	kg m^{-3}	Total yield	Irrigation water productivity (WP_I)
Selahvarzi et al. (2017)	Water productivity	Fruit yield divided by applied irrigation	kg m^{-3}	Marketable yield	Irrigation water productivity (WP_I)

[a] According to Fernández et al. (2020).

[b] Recommended term based on research information available to calculate water productivity.

Table 2
Summary of the effect of various irrigation strategies on 'Mollar de Elche' pomegranate fruit marketability related variables and water saved relative to well-watered trees.

Author	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
Cano-Lamadrid et al. (2018)	Regulated deficit irrigation	120 % ET_c until fruit set, 60 % ET_c during fruit growth and ripening	NE Fruit size	< Yield 24 % < Juice red colour NE Sugars & organic acids NE Total phenolic compounds NE Punicalagin	39.1
Galindo et al. (2014a)	Regulated deficit irrigation	105 % ET_c until 1st half of fruit growth, 2nd half of rapid fruit growth to last harvest 33 % ET_o	> Juice red colour > TSS & MI Advanced optimal harvest time 7 – 8d	< Yield 26 %, < Fruit number & size NE Bioactive quality	68.6
Galindo et al. (2014b, 2017a)	Withhold irrigation before harvest (d)	6	NE Marketable yield & Fruit size > Bioactive compounds > Peel red colour Advanced harvest time > Fruit price	< Total phenolic compounds	14.1
		15	> Peel red colour	< Marketable yield 38 % & Fruit size < < Total phenolic compounds	32.8
		25 & 34	> Peel red colour > Juice red colour	< Marketable yield 49 & 69 % & Fruit size < < Total phenolic compounds	61.7& 100
Martínez-Nicolás et al. (2019)	Regulated deficit irrigation	Withheld irrigation during flowering and fruit set, 115 % ET_c rest of season	NE Total/marketable yield NE Fruit size/number > Aril red colour	NE Aril chemical composition	29& 19
Mellisho et al. (2012)	Grower's criteria	32 % ET_o-74 % ET_o-36 % ET_o until first half of LFG phase, second half of LFG phase and during end of fruit growth and ripening, respectively	> Peel & aril red colour	< Yield 30 %	46.3
Peña-Estévez et al. (2016)			> TSS & MI, Glucose & fructose at harvest > TSS increase after 14d storage at 5 °C > Overall sensory quality at shelf life Beneficial phenolics effect during storage > Quality & health attributes during shelf life	< Fruit size < Peel content 2nd harvest	
	Regulated deficit irrigation	32 % ET_o-NI-99 % ET_o until first half of LFG phase, second half of LFG phase and during end of fruit growth and ripening, respectively	NE Fruit moisture content	< Yield 28 % & < Fruit size (14 & 20 %) NE Peel red colour < Aril red colour, < TAC NE TSS & MI NE TEAC, sugars & organic acids	55.1
Mena et al. (2013)	Sustained deficit irrigation	43 % ET_o	NE TSS or MI	> Yellowish juice colour < Total phenolic compounds, Punicalagin < Antioxidant activity NE Total anthocyanin	42.3
	Sustained deficit irrigation	12 % ET_o	NE TSS or MI	> Yellowish juice colour, less intense red colour < Total phenolic compounds & TAC < Punicalagin & antioxidant activity	84.7

LFG - Linear fruit growth; MI - Maturity index; NE - No significant effect; NI - No irrigation; TAC - Total anthocyanin content; TEAC - Trolox equivalent antioxidant activity; TSS -Total soluble solids; WS - Water saved relative to well-watered trees.

Table 3
Summary of the effect of sustained and regulated deficit irrigation applied during different phenological phases on ‘Mollar de Elche’ pomegranate fruit marketability related variables and water saved relative to well-watered trees. Adapted from data for three seasons from Bartual et al. (2015a,b), Intrigliolo et al. (2012, 2013) and Laribi et al. (2013).

Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
Sustained deficit irrigation	50 % ET_c whole season	< Vegetative growth NE Yield > Fruit number (28 %) NE MI at harvest > TSS at harvest & 19 wks after cold storage + shelf life > Peel red colour at harvest and during storage + shelf life > > Juice anthocyanins after 19 wks storage + shelf life > > Water productivity > > Economic irrigation water productivity < Skin sinking after 19 wks storage + shelf life < Skin pitting & blemishes after 19 wks storage + shelf life < Aril browning after cold storage + shelf life < Fruit weight loss after 19 wks storage + shelf life	< Fruit size (22 %) < < Economic yield value (28 %) Sunburn Long term tree productivity NE Juice anthocyanins at harvest NE Juice anthocyanins after 8 wks storage + shelf life > Yellow peel colour after storage + shelf life NE antioxidant capacity at harvest and after 19 wks storage + shelf life	44
Regulated deficit irrigation during flowering and fruit set	25 % ET_c flowering, fruit set, early fruit growth, 100 % ET_c rest of season	> Yield > Fruit number NE TSS NE Economic yield value > Water productivity > Economic irrigation water productivity < Skin sinking after 19 wks storage + shelf life < Skin pitting & blemishes after 19 wks storage + shelf life	Slightly < Fruit size (7 %) < < MI at harvest NE Juice anthocyanins after 8wks storage + shelf life NE Antioxidant capacity at harvest and after 19 wks storage + shelf life	12
Regulated deficit irrigation during linear fruit growth	25 % ET_c linear fruit growth,100 % ET_c rest of season	NE Yield > Aril anthocyanins > TSS after 19 wks storage + shelf life NE Economic yield value > Economic irrigation water productivity > Juice anthocyanins at harvest > > Juice anthocyanins after 8 wks storage + shelf life > > > Juice anthocyanins after 19 wks storage + shelf life	Slightly < Fruit size (6 %) < MI at harvest Fruit cracking NE Water productivity NE Antioxidant capacity at harvest & after 19 wks storage + shelf life	24

(*continued on next page*)

Table 3 (*continued*)

Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
Regulated deficit irrigation during ripening	25 % ET_c last part of fruit growth and ripening, 100 % ET_c rest of season	NE Yield/Fruit number/Fruit size > TSS at harvest, after 8 & 19 wks storage > Peel red coloration > Sugar content Accelerated fruit ripening date NE Economic yield value NE Economic irrigation water productivity > Juice anthocyanins after 8 & 19 wks storage + shelf life < Skin sinking after 19 wks storage + shelf life < Fruit weight loss after 19 wks storage + shelf life	< MI at harvest NE Water productivity NE Antioxidant capacity at harvest and after 19 wks storage + shelf life	18

MI - Maturity index; NE - No significant effect; TSS - Total soluble solids; WS - Water saved relative to well-watered trees.

mainly due to increased fruit number, comparable fruit weight and 22 % less water use relative to the fully irrigated trees. For the 50 % ET_c partial rootzone drying strategy a c. 16 % yield loss and almost 45 % decrease in irrigation water use relative to the trees irrigated at 100 % ET_c resulted in the huge relative increase in irrigation water productivity. Poorer relative irrigation water productivity at the deficit irrigated trees compared to the partial root zone irrigated trees at both ET_c levels can be attributed to greater yield losses (11 % and 30 % at the 75 % ET_c and 50 % ET_c levels, respectively). Irrigating only one side of the root zone at a four-day interval throughout the season reduced fruit number and size per tree to greater extent compared to where irrigation was alternated between two sides of the root zone.

In the first and second season a regulated deficit irrigation strategy (no irrigation until end fruit set, 100 % ET_c remainder of season) applied to seven-year-old 'Shavar' pomegranate trees in Iran (Selahvarzi et al., 2017) increased irrigation water productivity relative to the control (2.15 and 2.45 kg m^{-3}) by c. 50 % and 39 %, respectively. The higher irrigation water productivity was mainly ascribed to a c. 18 % irrigation water saving as yield tended to be, but was not significantly lower relative to the control. Although the sustained deficit irrigation treatment increased irrigation water productivity in the first season by c. 59 % compared to the control, the detrimental long term effect of severe water deficits on trees reduced the irrigation water productivity of the sustained deficit irrigation strategy in the second season to levels similar to those of the control.

The irrigation water productivity of 20-year-old 'Manfalouty' pomegranate trees in Egypt was calculated as yield divided by the scheduled amount of water per treatment (Khattab et al., 2011). The treatment receiving 520 mm water per season had the highest irrigation water productivity, i.e. 3.22 and 2.91 kg m^{-3} water applied. The irrigation water productivity decreased significantly when less or more than 520 mm water was applied. The underlying reason for this trend may be water stress related yield decreases in the drier treatments, and inefficient water use in the wetter treatment. In Turkey, differences in crop water productivity of several irrigation treatments, including sustained deficit irrigation treatments, were not statistically significant (Dinc et al., 2018). During three seasons crop water productivity ranged between 2.8 and 4.6 kg m^{-3}. Irrigation water productivity ranged between 5.95 and 10.66 kg m^{-3}.

For a high value crop such as pomegranate, crop water productivity and irrigation water productivity values should be interpreted carefully as they do not reflect the effect of water use on yield and fruit quality combined, which determines farmer profit at the end of the day. For this purpose, the use of economic crop water productivity or economic irrigation water productivity is highly recommended for decision making regarding selection of suitable irrigation strategies, taking into account the specific production target (Fernández et al., 2020).

5. Water management strategies under limited water supply

Water stress can be induced deliberately in fruit trees by withholding irrigation or by applying less water than plants require for maximum evapotranspiration, a method called regulated deficit irrigation (Mitchell et al., 1984). The effect of irrigation strategies on trees may differ depending on the timing and level of the water deficit applied, the duration thereof, the climatic conditions of the area and the drought tolerance of the crop via avoidance and tolerance mechanisms. Where irrigation water is a limited or costly resource, well-managed deficit irrigation improves both water productivity and producer profitability, as compared to full irrigation (Fernández et al., 2020 and references therein). In selection of suitable irrigation strategies, the producer should focus on environmentally sustainable methods that optimise yield over the long term and on production targets (e.g. fresh fruit, juice, pharmaceuticals, cosmetics, wine) that maximise profit for a specific orchard.

Table 4

Summary of the effect of sustained and regulated deficit irrigation or partial rootzone drying on cv. ‘Wonderful’ pomegranate fruit marketability related variables and water saved relative to well-watered trees.

Country	Age	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)	Author
Greece	12	Partial root zone drying 1	After 2 months after bud break, 100 % ET_c one side of tree	NE Fruit weight < Cracking > Total soluble solids		n.a.	Noitsakis et al. (2016)
		Partial root zone drying 2	After two months after bud break, 50 % ET_c one side of tree		< Fruit weight	n.a.	
Spain	6	Regulated deficit irrigation	120 % ET_c until fruit set, 60 % ET_c during fruit growth and ripening	NE Fruit weight > Sugars	< Yield 41 % < Juice red colour NE Total phenolic compounds NE Punicalagin NE Organic acids	38.6	Cano-Lamadrid et al. (2018)
	7	Regulated deficit irrigation	Withheld irrigation during flowering and fruit set, 115 % ET_c rest of season	NE Total yield NE Marketable yield NE Fruit size/number > Aril red colour	NE Aril chemical composition	30 & 20	Martínez-Nicolás et al. (2019)
USA	5	Sustained deficit irrigation	75 % ET_c	> Yield, NE Fruit number/weight		n.a.	Zhang et al. (2017)
			50 % ET_c	NE Yield, Fruit number/ weight		n.a.	
			35 % ET_c	NE Fruit number	< Yield, Fruit weight	n.a.	

n.a. - not available; NE - No significant effect; WS - Water saved relative to well-watered trees.

Table 5
Summary of the effect of sustained and regulated deficit irrigation or partial rootzone drying on pomegranate fruit marketability related variables and water saved relative to well-watered trees in Iran.

Cultivar	Age	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)	Author
‘Rabab’	9	Sustained deficit irrigation	75 % ET$_c$	NE Juice content	< Yield, fruit number and weight	22.4	Parvizi et al. (2014, 2016), Parvizi and Sepaskhah (2015)
			One side of tree	> Irrigation water productivity	< Maturity index NE Total soluble solids, Vitamin C > Cracking		
		Partial root zone drying	75 % ET$_c$	> Yield and fruit number, NE Fruit weight > Juice content > > > Irrigation water productivity	NE Vitamin C NE Total soluble solids NE Maturity index	22.4	
		Sustained deficit irrigation	50 % ET$_c$ One side of tree	> Total soluble solids > > Irrigation water productivity	< < Yield, Fruit number and weight < Vegetative growth < Juice content, Maturity index < Vitamin C > > Cracking	44.8	
		Partial root zone drying	50 % ET$_c$	> Juice, Total soluble solids > > > > Irrigation water productivity	< Yield, fruit number and weight < Vegetative growth NE Vitamin C	44.8	
‘Shavar’	7	Regulated deficit irrigation: fruit set	No irrigation until end fruit set, 100 % ET$_c$ rest of season	< Vegetative growth	< Fruit number	18	Selahvarzi et al. (2017)
				NE Yield, > Fruit weight > Compact flowering > Fruit set > Juice content > Aril:Peel ratio; Maturity index > Irrigation water productivity 1st season, NE 2nd > Total phenolic compounds	NE Total anthocyanin content NE antioxidant activity < Hermaphrodite:male flower ratio		
		Sustained deficit irrigation	50 % ET$_c$ throughout season	> Aril:Peel ratio; Maturity index > Irrigation water productivity 1st season, NE 2nd	< Vegetative growth < Yield, fruit number and weight	50	
				> > Total phenolic compounds > Antioxidant activity	< Flowers 2nd season NE Total anthocyanin content		

NE - No significant effect; WS - Water saved relative to well-watered trees.

5.1. Irrigation management

Selected research regarding irrigation strategies for ‘Mollar de Elche’ pomegranate trees and advantages and disadvantages of the strategies are listed in Tables 2 and 3. Water savings relative to a well-watered control ranged between c. 14 % and 100 % for a range of experimental periods pertaining to the different studies. Irrigation strategies that did not affect yield negatively and maintained or improved marketability relative to well-watered trees saved between 14.1 % and 29 % irrigation water (Galindo et al., 2014b, 2017a; Intrigliolo et al., 2012, 2013; Martínez-Nicolás et al., 2019). To evaluate the suitability of a specific irrigation strategy knowledge is required regarding the effect of water deficits on crop growth during different phenological stages. Studies that focussed specifically on the effect of water deficits during linear fruit growth and/or ripening of the cultivar ‘Mollar de Elche’ include that of Cano-Lamadrid et al. (2018); Galindo et al. (2014a,b, 2017a) and Mellisho et al. (2012). However, the effect of sustained deficit irrigation (Mena et al., 2013; Intrigliolo et al., 2013) and regulated deficit irrigation at different phenological stages (Intrigliolo et al., 2013; Martínez-Nicolás et al., 2019) on the performance of the cultivar was evaluated as well.

Fruit ripening is a critical period for the cv. ‘Mollar de Elche’ as irrigation is required during most of this phenological period to achieve maximum yield (Galindo et al., 2017a). However, withholding water for six days before harvest saved 14 % water relative to well-watered trees, while it increased fruit peel colour and enhanced bioactive compound content, with no negative impact on marketable yield (37.1 t ha^{-1}) or fruit size (Table 2). Advanced harvest time may result in earlier market access and improved fruit prices. For producers interested in the processing market, red colour of juice improved, whereas fruit size at harvest decreased by c. 14 % when water was withheld for 25 and 34 days before harvest, using 62 % and 100 % less water compared to the well-watered trees. Total yield decreased by c. 8% and 23 % for these two scenarios, and marketable yield by 49 % and 69 %. According to Peña-Estévez et al. (2015), withholding water from 16 and 26 days before harvest saved c. 6% and 11 % water and increased shelf life of arils by 4 days compared to a well-watered control. Arils from deficit irrigated fruit had better visual appearance and overall quality, but had lower anthocyanin content and a slightly red-orange colour. The total soluble solids where water was withheld for 26 days was slightly higher, whereas there was no effect relative to the control where water was withheld for 16 days.

In contrast to the findings of Galindo et al. (2017a), Intrigliolo et al. (2013) found that 25 % ET$_c$ regulated deficit irrigation applied during ripening to ‘Mollar de Elche’ trees did not affect yield, fruit number, fruit weight or economic yield value, whereas the strategies saved 18 % of water and tended to have increased economic irrigation water productivity relative to the control (Table 3). Furthermore, fruit had higher levels of total soluble solids at harvest and throughout 8 and 19 weeks cold storage, enhanced red peel colour and more anthocyanins in juice after 8 and 19 weeks cold storage compared to well-watered trees. Less external physiological disorders and fruit weight loss occurred after 19 weeks storage and a seven day shelf life period. Regulated deficit irrigation applied during ripening, though, may result in increased fruit cracking in some seasons. The differences in the outcomes of this research regarding regulated deficit irrigation during ripening compared to that of Galindo et al. (2014b, 2017a) may be partially explained by differences in crop load (c. 49 % lower yield for well-watered trees), less water stress that developed and the fact that irrigation was applied six to seven times a week during summer and weekly during autumn (Intrigliolo et al., 2013).

Amongst the sustained deficit irrigation and various regulated deficit irrigation treatments the best strategy for ‘Mollar de Elche’ was 25 % ET$_c$ application only during the main flower and reproductive organs drop period, with 100 % ET$_c$ applied during the rest of the season (Intrigliolo et al., 2013). This strategy saved c. 12 % water relative to the 100 % ET$_c$ treatment, and increased yield via more fruit of slightly lower weight (Table 3). Water deficits did not affect the fruit total soluble solids. The economic yield value was not affected, but crop water productivity and economic irrigation water productivity increased relative to the control. External physiological disorders after cold storage was less compared to the control. Disadvantages of this strategy are that it decreased the maturity index at harvest and had no positive effect on the juice anthocyanins or antioxidant capacity. For the cvs. ‘Mollar de Elche’ and ‘Wonderful’ the flowering and fruit set phenological phase can be considered non-critical because sensitivity to water stress during this period was low (Martinez-Nicolás et al., 2019). Under the conditions of the study withholding irrigation during flowering and fruit set saved between 19 % and 30 % irrigation water with no detrimental effect on marketable yield, fruit size or chemical composition (Tables 2 and 4).

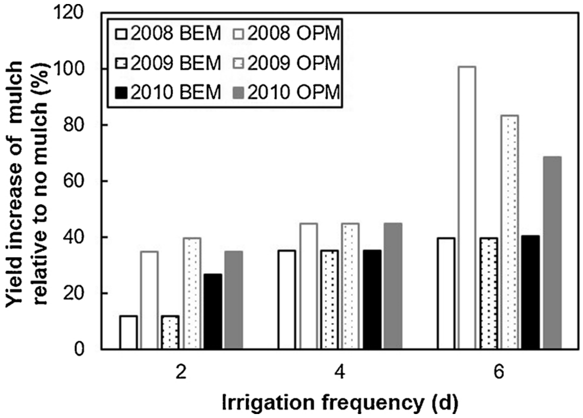

Fig. 3. The yield increase of ‘Manfalouty’ pomegranate trees mulched with bitumen emulsion (BEM) and olive pomace (OPM) relative to where no mulch was applied, drip irrigated at different irrigation frequencies during three subsequent seasons. Adapted from Seidhom and Abd-El-Rahman (2011).

A regulated deficit irrigation strategy applying 25 % ET$_c$ during the linear fruit growth period reduced fruit weight by only c. 6% and saved 24 % of water relative to the control (Intrigliolo et al., 2013; Table 3). This strategy had no effect on the economic yield value, but increased economic irrigation water productivity. Juice total soluble solids, compared to the control, increased after 19 weeks storage and seven days shelf life, although the maturity index was lower at harvest. Juice anthocyanins at harvest and notably after 8 and 19 weeks of storage and shelf life period increased relative to the control. Fruit irrigated

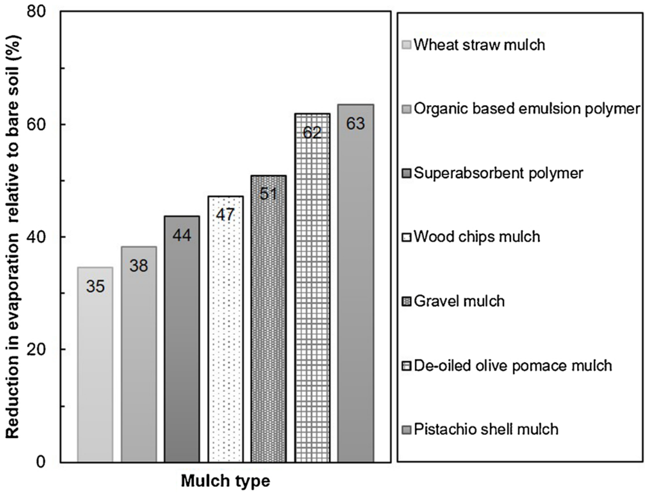

Fig. 4. Effect of mulch type on evaporation relative to bare soil. Adapted from Farzi et al. (2017).

according to this strategy may in some seasons be susceptible to cracking.

Although 50 % ET_c applied for three years during the entire growing season (sustained deficit irrigation) saved 44 % water relative to the 100 % ET_c treatment, it had no negative impact on yield in the Mediterranean area of southeastern Spain (Table 3). Over three years, trees were on average bearing c. 28 % more fruit of c. 22 % lower weight, which decreased the economic yield value relative to the control by 28 % (Table 3, Intrigliolo et al., 2013). Red fruit peel colour was enhanced at harvest and throughout cold storage and shelf life, but turned yellowish at the end of storage and shelf life. Despite the latter, fruit were still more red than those of the other irrigation treatments (Laribi et al., 2013). Juice anthocyanins increased notably relative to the control after 19 weeks of storage and the following shelf life period. Taking the smaller fruit size and marketability thereof into account, the sustained deficit irrigation strategy may be more suitable for producers targeting the juice industry (Intrigliolo et al., 2013).

Fruit had less external physiological disorders and aril browning, and less fruit weight loss after cold storage and shelf life compared to a well-watered control. Furthermore, the sustained deficit irrigation reduced vegetative growth markedly, which may affect tree productivity in the long term - especially if trees are still young (Intrigliolo et al., 2013) when the strategy is imposed. Fruit of trees subjected to the sustained deficit irrigation strategy may in some seasons also be prone to increased sunburn compared to well-watered trees. Of all the irrigation strategies evaluated in this research, sustained deficit irrigation increased water productivity and economic irrigation water productivity the most relative to the control. According to Bartual et al. (2015a), sustained deficit irrigation and to a lesser extent, 25 % ET_c regulated deficit irrigation during ripening could be used as tools to accelerate the fruit ripening date of ‘Mollar de Elche’ fruit due to faster sugar accumulation. This has important implications for marketing pomegranate fruit. The red coloration and higher sugar content may advance harvest time if the cultivar is picked according to external coloration with the prospect to fetch better prices if you can get in the market earlier (Laribi et al., 2013).

With regard to the cultivar ‘Wonderful’, 75 % ET_c sustained deficit irrigation increased yield relative to trees irrigated at 100 % ET_c in the third year that deficit irrigation was applied (Zhang et al., 2017). However, there is a paucity of data regarding quality of the fruit and the exact amount of water applied (Table 4). Indications during the second year of deficit irrigation were that sustained deficit irrigation at 35 % ET_c may have a detrimental effect on fruit colour (Centofanti et al., 2017). Irrigation at 60 % ET_c during fruit growth and ripening also had a detrimental effect on fruit juice colour and reduced yield by 41 % (Cano-Lamadrid et al., 2018), whereas applying 100 % ET_c to only one side instead of to the full root zone may reduce incidence of cracking (Noitsakis et al., 2016).

Research from Iran for the cv. ‘Rabab’ indicated positive effects of 75 % ET_c partial rootzone drying on yield and juice content, with c. 22 % water saved relative to a well-watered control (Parvizi et al., 2014, 2016). This irrigation strategy increased irrigation water productivity significantly compared to a well-irrigated control and trees deficit irrigated at 75 % and 50 % ET_c on one side of the root zone only (Table 5). One has to keep in mind, though, that the partial rootzone drying strategy can increase labour or irrigation system costs. In contrast to the findings of Noitsakis et al. (2016) regarding cracking for the cv. ‘Wonderful’, fruit cracking increased for ‘Rabab’ relative to a well-watered control where irrigation was applied at 75 % or 50 % ET_c to one side of the root zone. Also in Iran, for the cultivar ‘Shavar’ no irrigation applied from the beginning of the season until fruit set, followed by irrigation at 100 % ET_c during the remainder of the season resulted in reduced vegetative growth with a compact flowering period, improved fruit set and weight, with no effect on yield and increased total phenolic compounds compared to the control (Table 5, Selahvarzi et al., 2017). On the contrary, sustained deficit irrigation applied at 50 % ET_c decreased yield and had negative carry-over effects on vegetative growth and flowering in the second season, although fruit juice had higher total phenolic compounds and antioxidant activity compared to the control. The regulated deficit irrigation strategy applied c. 18 % less water compared to the control, and the sustained deficit irrigation strategy 50 % less. Both strategies had higher irrigation water productivity compared to the control treatment in the first season, but were comparable to well-watered trees in the second.

Based on the currently sourced research (Tables 2–5) sustained deficit irrigation may supply a market for smaller pomegranates with increased red peel and/or juice. However, a sustained deficit irrigation strategy applying 50 % ET_c or less in dry and arid regions may in most cases not be sustainable and cannot be recommended over the long term for profitable pomegranate production. In this regard more research addressing the carry-over effects of water deficits on vegetative growth and reproductive bud development between seasons is needed.

5.2. Orchard management

In Egypt, ET_c decreased and yield progressively increased as the drip irrigation interval for ‘Manfalouty’ trees in fine sandy soils increased from 2 to 4 to 6 days (Seidhom and Abd-El-Rahman, 2011). According to Seidhom and Abd-El-Rahman (2011) and references therein the highest pomegranate yield is obtained when the soil reaches 60 % or 40 % of field capacity between irrigations. Young ‘Ganesh’ trees achieved maximum yield where 40 % of evaporated water was replaced, while application of more water promoted competition between vegetative and fruit growth, which decreased yield (Afria et al., 1998). Application of olive pomace mulch decreased ET_c compared to no mulch (+ weeds), or petroleum applied as bitumen emulsion mulch (Seidhom and Abd-El-Rahman, 2011). Olive pomace mulched trees had the highest yield, followed by the bitumen emulsion mulched trees, with the lowest yield in trees with no mulch. Irrespective of mulching treatment, yield increased as irrigation interval increased (Fig. 3). Yield increases relative to the crop without mulch ranged between 12 and 40 % for the bitumen emulsion mulch, and between 35 and 101 % for the olive pomace mulch. The positive effect of the olive pomace mulch may be associated with pronounced increases in soil temperature which may increase both water and nutrient consumption by tree roots, which in turn affect the crop yield. The highest crop water productivity was obtained for a combination of a 6-day irrigation interval and olive pomace mulch. The crop water productivity increased as trees aged and it amounted to 5.55, 5.59 and 5.65 $kg\ m^{-3}$ for three respective seasons. Similarly, the irrigation water productivity equalled 4.14, 4.31 and 4.49 $kg\ m^{-3}$ during the three seasons. The positive effect of mulches on pomegranate fruit yield have been reported previously, whereas mulching also reduced fruit cracking (Seidhom and Abd-El-Rahman and references therein, 2011).

However, straw mulching in drip irrigated pomegranates did not improve crop water productivity, but ineffectiveness of mulch treatments was attributed to water infiltration problems, especially during dry months (Ghosh et al., 2013). Use of new mulches for soil water conservation in arid regions has been introduced as an alternative to conventional (plastic) mulches (Farzi et al., 2017). Different mulch materials differed in soil water conservation efficiency and reduced evaporation relative to bare soil by between 35 % and 63 %. De-oiled olive pomace mulch and pistachio shell mulch – as new mulch materials – seems more favourable for conserving soil water compared to the other materials (Fig. 4).

Makus et al. (2014) found in-row durable white plastic to be beneficial to retain soil water, reduce chemical weed control required, increase total fruit yield (by c. 20 %) and improve juice colour. White plastic improved midday orchard floor reflectance, reduced surface temperatures and decreased variability in soil temperatures at several depths up to 300 mm deep. White plastic had no significant effect on fruit peel colour. Trees grown under white plastic mulch had more basal sucker production at the end of the season, whereas irrigation rate also increased sucker frequency and size.

6. Conclusions

To be able to farm water efficient, profitable and sustainable currently remains a challenge for pomegranate producers. Although biophysical and economic water productivity indicators may be useful in on-farm irrigation decision making, reliable crop evapotranspiration information for the calculation of these indicators is not readily available to farmers. To determine orchard crop evapotranspiration accurately is complex and expensive. For the moment the use of irrigation water productivity and economic irrigation water productivity that takes into account the costs involved in perennial fruit crop production and the specific markets targeted appears to be a more viable approach.

Further research is required to provide the necessary information to improve irrigation management and as such support sustainable farming amidst climate change (i.e. higher temperatures; changing rainfall patterns) and increasingly limited water resources. With regard to irrigation scheduling, crop coefficients developed for different irrigation systems and different cultivars in different countries cannot necessarily be applied directly elsewhere. It will be very useful if the water use (transpiration and evapotranspiration) of a range of young to full bearing pomegranate orchards is quantified accurately with the purpose of developing a model for practical estimation of crop coefficients under local conditions. Such a model - covering a range of fractional light interception regimes - could enable extrapolation of the study findings to other orchards in other production areas. Splitting the orchard crop coefficient into a separate transpiration and soil evaporation coefficient may enable a more accurate estimate of orchard water use. Such a model will aid producers to schedule irrigation according to tree water requirements and prevent over- or under-irrigation which impacts the environment (leaching of fertilizers and water losses) and fruit tree performance (yield and quality).

With regard to irrigation strategies, variable results with different systems and different cultivars in different countries clearly indicate that results from one study cannot simply be transferred to another area where conditions and cultivar types may not be the same. This underscores the necessity of conducting research under local conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106375.

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