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Response of pomegranate trees (*Punica granatum* L., cv. Mollar de Elche) to deficit irrigation at different phenological stages

By

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B	Boron	**m^3**	Cubic metre
BA	Benzyl Adenine	**ME**	Mollar de Elche
BCE	Before Common Era	**mg**	milligram
CE	Common Era	**microS/cm**	microSiemens per centimetre
cm	Centimeter	**ml**	milliliter
cv.	Cultivar	**mm**	millimeter
$dS\ m^{-1}$	deciSiemens per meter	**mM/L**	milliMolar per Liter
EC	Electrical Conductivity	**Mn**	Manganese
etc.	et cetera	**MPa**	Megapascal
ETo	Reference evapotranspiration	**m/s**	Meter per Second
ETc	Estimated crop evapotranspiration	**N**	Nitrogen
FC	Field Capacity	**OM**	Organic material
Fe	Iron	**ppm**	Parts per million
g	Gram	**RDI**	Regulated Deficit Irrigation
GA_3	Gibberellic acid	**RH**	Relative Humidity
H	Hermaphrodite	**SDI**	Sustained Deficit Irrigation
h	Hour	**t**	Ton
ha	Hectar	**TA**	Titratable acidity
HIV	Human Immunodeficiency Virus	**TSS**	Total Soluble Solids
IVIA	Instituto Valenciano de Investigaciones Agrarias	**USDA**	United States Department of Agriculture
K	Potassium	**WP**	Wilting Point
Kc	Crop coefficient	**WUE**	Water use efficiency
Kg	Kilogram	**Zn**	Zinc
L	Liter	**ºC**	Degree centigrade
L/h	Liter per hour	**€**	Euro
m	Metre	**Ψ_{stem}**	Stem water potential

With the global water scarcity problem, the amount of water used by agriculture sector must be decreased without affecting crop performance. Under this context it is necessary to have adequate knowledge about water requirement, irrigation schedule and the degree of plant drought resistance. Little information is available about the influence of sustained and regulated deficit irrigation (SDI and RDI) on pomegranate trees due to lack of investigations on this crop. This experiment was carried out in 2012 for studying the effects of SDI and RDI on 12 years-old pomegranate trees (cv. Mollar de Elche) performance in a commercial orchard in Elche, Alicante, Spain (Latitude 38º 13' 53, 98" N, Longitude 0º 39' 20, 00" W and elevation 97 m). Irrigation treatments consisted of a control irrigated at 100% of the estimated crop evapotranspiration (ETc), SDI where trees were irrigated at 50% of the ETc during the entire season and three RDI treatments. In the RDI regimes, water stress (50% ETc) was applied during one of three phases: flowering and fruit set (RDI_1), fruit growth (RDI_2) and fruit ripening (RDI_3). Results indicated that pomegranate trees under different deficit irrigation treatments could maintain yield level with better fruit quality and enhancing water use efficiency and water productivity compared to the control trees. The SDI trees maintained during the season the lowest midday stem water potential (Ψ_{stem}) values, reaching a minimum value of -1.94 MPa. RDI trees had lower plant water status than the control; the differences being more clear in the middle of the deficit irrigation cycle. In the RDI trees when water returned to full usage, trees recovered quickly their optimum water status. SDI was the only treatment that had negative effects on vegetative growth with a decrease of 23% in canopy volume with respect to control trees. The effect of deficit irrigation on flowering was clear in the SDI treatment as it decreased hermaphrodite flowers drop (19% less than control trees). However, because in the SDI trees there was a high fruit set (13% more than control trees) there was an increase in the number of fruit collected per tree (18% more than control trees). Despite the high crop load, SDI trees recorded lower yield weight (about 15% less than control trees) due to a lower fruit weight (30% less than control trees). The reduction in yield of SDI and RDI_1 trees resulted in decreasing yield value compared to control trees by 21% and 11%, respectively. SDI was the only treatment that increased significantly the number of cracked and sun-burned fruits resulted in decreasing of the percentage of commercial fruit and the yield value. Deficit irrigation enhanced some fruit quality attributes such as juice %, TSS and fruit skin and juice colouration.

Water stress during fruit growth (RDI_2) and fruit ripening (RDI_3) had a clear effect on juice content as juice % was significantly increased by 16% and 25%, respectively with respect to control trees. Higher TSS and more reddish skin colouration were observed in pomegranates from SDI and RDI_3, while better juice colour was obtained in the RDI_2 fruits. Despite the high water saving by SDI (44%), it was at the expense of fruit weight, yield, commercial fruits percentage and the yield value. On the other hand, RDI_2 led to 25% water saving without affecting the yield and fruit weight. All deficit irrigation treatments increased water use efficiency and water productivity except RDI_1. It is concluded that RDI can be used according to the desired goals (control harvest precocity (fruit ripening) and improve pomegranate fruit quality) and water availability (as a method to handle with water scarcity and high water prices) depending on the phenological stage when water stress is applied.

Keywords: Pomegranate - Deficit irrigation - Water status - Vegetative growth - Flower drop - Yield - Fruit quality - Water saving - Water use efficiency.

Introduction

1. The Pomegranate

The origin of pomegranate (*Punica granatum* L.) is widely considered to Iran and its surrounding areas, including some parts of the Mediterranean area (Mars, 2000), other theories referred its origin in the region from Iran to northern India (wild plants appeared in many forests of these areas). The pomegranate had been cultivated in Mediterranean region since ancient times (Morton 1987; Stover and Mercure 2007).

The pomegranate tree is highly adaptive to a wide range of climates and soil conditions, so it is grown in many different geographical regions (Holland *et al*, 2009). Edible pomegranates were cultivated in Persia (Iran) by 3000_{BCE} (Anarinco, 2006). By 2000_{BCE}, Phoenicians had brought pomegranates to Tunisia and Egypt through Mediterranean Sea colonies in North Africa. Around the same time, pomegranate was cultivated in Turkey and Greece. The pomegranate continued to be dispersed around the world, reaching China by 100_{BCE} (Anarinco, 2006). By 800_{CE}, the fruit was spread throughout the Roman Empire, including Spain.

The Spanish introduced pomegranate to Central America, Mexico and South America in the 1500s and 1600s (LaRue, 1980). Pomegranate was growing in California by 1770 (Seelig, 1970; Morton, 1987).

Pomegranate is widely grown in many countries where it is well adapted. Commercial orchards are now grown in many regions, especially in the Mediterranean Basin, where high fruits quality are obtained (Stover and Mercure, 2007; Holland *et al*., 2009). In tropical and subtropical areas, pomegranate is considered one of the most important fruits because of low maintenance cost, good yields and ability to grow under adverse conditions (Indian Council of Agricultural Research, 2005).

The main regions of pomegranate production are Iran, Afghanistan, India, Mediterranean countries (Morocco, Spain, Turkey, Tunisia and Egypt) and Middle Eastern countries (Jbir *et al*., 2008 and Melgarejo *et al*., 2009). India is the top pomegranate producer in the world with approximately 50% of the world’s production, an area of 112,000 ha is cultivated with a production of 772400 tons and an average yield of 7 t / ha (NHB, 2012). The cultivated area in Iran is 65,000 ha of pomegranate produces 600,000 tons/year with about 30% of yield exported (Mehrnews, 2006). Pomegranate production in Turkey was 56,000 tons/year in 1997 (Gozlekci and Kaynak, 2000a). Spain, with ~3000 ha, is the largest western European producer of pomegranate and the world's main exporter of pomegranate (more than 55% of the world's pomegranate trade), production has been increasing as a result of high market prices (Costa and Melgarejo, 2000; Hernández *et al*., 2012). In the USA, there are 5600 ha of pomegranate, the dominant cultivar is Wonderful, but there is interest in earlier and later cultivars to extend the market season (Kotkin, 2006).

Recently, pomegranates consumption has changed from fresh fruit to be in great demand by the processing industry to obtain different products as juice, jam etc. (Fig.1). Recently, many studies have confirmed the health benefits associated with pomegranates. Pomegranate juice and products are referred to show efficacy and prevention effect against a wide range of cases, including cancer, coronary heart disease, atherosclerosis, hypercholesterolemia, hyperlipidemia, hypertension, diabetes, HIV, infectious diseases, aging, and brain disorders (Langley, 2000; Michel *et al*., 2005; Seeram *et al*., 2006; Katz *et al*., 2007; Lansky and Newman, 2007; Tzulker *et al*., 2007; Andreu Sevilla *et al*., 2008; Basu and Penugonda, 2008; Holland *et al*., 2009; Tehranifar *et al*., 2010; Legua *et al*., 2012). This has led to a higher awareness of the public to the benefits of pomegranate and a prominent increase in the consumption of the fruit and juice (Holland *et al*., 2009).

Figure1. Pomegranate products (Juice – Jam).

2. Taxonomy and Botanical Classification (USDA-NRCS)

Kingdom	**Plantae – Plants**
Subkingdom	**Tracheobionta – Vascular plants**
Superdivision	**Spermatophyta – Seed plants**
Division	**Magnoliophyta – Flowering plants**
Class	**Magnoliopsida – Dicotyledons**
Subclass	**Rosidae**
Order	**Myrtales**
Family	**Punicaceae – Pomegranate family**
Genus	**Punica L. – pomegranate**
Species	***Punica granatum*** L. **– pomegranate**

3. Plant Morphology and description

3.1. Vegetative growth. The pomegranate plant is a shrub develops multiple trunks naturally and has bushy appearance (Fig. 2A). In orchards, plants are normally trained to a single trunk, forming a small tree that grow up to 5 m at maturity, also there are some dwarf cultivars that do not exceed 1.5 m. (Levin 1985, 2006b; Liu 2003). Under cultivation, it is maintained as a low headed bush of 2 to 4 m. Trees may be trained to multiple trunks in colder areas, to reduce risk of total tree loss. Most of the pomegranate varieties are deciduous trees. However, there are several genotypes behaved as evergreen in India (Singh *et al*, 2006a), also Sharma and Dhillon (2002) evaluated 30 evergreen cultivars in India. Plants aggressively sucker from the crown area and the roots. The young branches are thin and polygonal with bark color differ from light green to pink-purple (Fig.2C) depend on varieties and mature branches become round (Holland *et al*, 2009). The tree is more or less spiny with small, narrow, oblong leaves with short stems (Morton, 1987). Young Leaves color is reddish and turns to green in adult leaves (Fig.2B) which are entire, smooth and hairless with short petioles (Holland *et al*, 2009). The leaves are opposite or in whorls of 5 or 6, entire, oblong-lanceolate and dark green (Özgüven *et al*, 2012; Moreno, 2005).

Figure 2. Pomegranate vegetative growth A) Pomegranate tree, B) Adult leaf and c) young shoots.

3.2. The flowers. The pomegranate flowers are most commonly red to red–orange and are funnel shaped. Pomegranate can be self-pollinated or cross-pollinated by insects (Morton, 1987). Flowers are primarily borne sub-terminally, primarily on short lateral branches older than 1 year (El- Kassas *et al*., 1998), although in some varieties flowers are on spurs (Fig.3). Flowering percentage on old wood is around 70% of total flowering in all cultivars, the other 30% of flowering on current growth (Reddy, 2002). Flowers can appear solitary, pairs or in clusters of up to five, most of the solitary flowers appear on spurs along the branches while the clusters are terminal (Reddy, 2002; Holland *et al*, 2009).

Figure 3. Different positions of pomegranate flowers.

Flower initiation in pomegranate does not occur during the previous season, but on new growth with numerous flowers induced in terminal and lateral buds (Wetzstein and Ravid. 2008). Pomegranate blooms about one month after bud break with most flowering from mid-May to early June (about 1 month) with three waves of flowering (Ben-Arie *et al*. 1984; Shulman *et al*. 1984; El Sese 1988; Assaf *et al*. 1991; Hussein *et al*. 1994; Mars 2000). Also may be continued until end of summer, especially in young trees. Stigma receptivity lasts 2 to 3 days and declines quickly in unpollinated flowers (Melgarejo *et al*., 2000a).

Flowering in pomegranate is characterized as having both hermaphrodite flowers (fertile or vase-shaped) and functionally male flowers (infertile or bell-shaped) on the same plant (andromonoecy). The hermaphrodite flowers (Fig. 4) are bisexual, have well-formed female (stigma, style, ovary) and male (filaments and anthers) parts, they are the type that set fruit. The male flowers produce well-developed male parts, but on closer examination of the pistil contain reduced female parts, described as functionally male flowers because they have degenerated female parts. Fruits develop only from bisexual flowers (Fig.5) and male flowers fail to set fruit and typically drop (Shulman *et al*., 1984; Holland *et al*., 2009; Wetzstein *et al*., 2011). Other classification by Chaudhari and Desai (1993) showed pomegranate flowers into three types: male, hermaphrodite, and intermediate.

Figure 4. Difference between hermaphrodite (left) and male (right) flowers in shape and size.

The stigma position in the hermaphrodite flowers is at the anthers height or emerging above them, so self-pollination is dominated beside pollination by insects. The proportion of these two flower types differs among varieties and season (Martinez *et al*., 2000); male flowers percentage may reach to more than 60% to 70% (Chaudhari and Desai, 1993; Mars, 2000; Holland *et al*, 2009; Wetzstein *et al*., 2011). Sex ratio in pomegranate can impact fruit set capacity, crop productivity and yield. The percentage of bisexual flowers has a positive effect on bearing capacity (El Sese, 1988; Chaudhari and Desai, 1993; Holland *et al*, 2009). Hermaphrodite flowers have 6% to 20% of pollen may be infertile; in male flowers, 14% to 28% are infertile. The size and fertility of the pollen vary with the cultivar and season (Morton 1987).

Figure 5. Hermaphrodite c flowers development from Balloon stage to fruit set.

3.3. The fruit. The pomegranate fruit is nearly round and crowned at the base by the prominent calyx which is maintained to maturity and is a distinctive feature of the pomegranate fruit (Fig.6). A leathery rind (or husk) enclosing many seeds surrounded by the juicy arils, which comprise the edible portion of the fruit (Watson and Dallwitz, 1992). The tough leathery skin is typically yellow overlaid with light or deep pink or rich red. The husk is comprised of two parts: the pericarp, which provides a cuticle layer and fibrous mat; and the mesocarp (known also as the albedo), which is the white spongy tissue and inner fruit wall where the arils attach. The multi ovule chambers (locules) are separated by membranous walls (septum) and fleshy mesocarp (Fig.7). Usually the lower part of the fruit contains 2 to 3 chambers while its upper part has 6 to 9 chambers. The chambers are filled with many seeds or arils (Holland *et al*, 2009).

Figure 6. Pomegranate fruits, in fruit growth stage (left) and fruit ripening stage (right).

Fruits ripen about 6 to 7 months after flowering (Morton, 1987) and are harvested when qualities reach to the expected market need; the external skin color does not refer to ripening degree because it can reach its final color long before the arils are fully ripened. The fruit is mainly used for dessert purpose, also for processing highly demanded products like juice, syrups, jams and jelly. The arils are the edible parts (Fig.7) of the fruit and contain a large amount of sap which is usually red, contain considerable amount of proteins, carbohydrates, minerals, sugars, vitamins, polysaccharides and polyphenols (Mir *et al*, 2012).

Figure 7. Longitudinal sector of pomegranate fruit showing chambers and arils (edible part).

The size and weight of the fruit increased up-to 150 days after anthesis to maturity. The initial elongated oval shape turned to round at harvest maturity. Texture of the fruit remained smooth during the period of growth (Dhillon & Kumar, 2004a). There is a big difference among pomegranate cultivars for fruit weight, fruit volume, seeds number, fruit colour and general appearance (Mir *et al*, 2010 a-b).

According to cultivar, arils range from deep red to virtually colorless, whereas the enclosed seed varies in content of sclerenchyma tissue, which affects seed softness. The number of locules and arils (and enclosed seeds) varies, but may be as high as 1300 per fruit (Levin, 2006a). The edible parts of pomegranate fruit represented 52% of the total weight, comprising 78% juice and 22% seeds (El-Nemr *et al*, 1990).

The growth curve of fruits showed a single sigmoid curve from fruit set to maturity (Ben-Arie *et al*., 1984, Gozlekçi and Kaynak, 2000b and Varasteh *et al*., 2008). Juice, TSS and anthocyanin content increased continuously during maturation while acidity decreased (Shulman *et al*, 1984). Soluble solids of the cultivars examined increased approaching ripening, the predominant sugars were fructose, particularly glucose, sucrose and maltose contents were almost negligible and the principal acids were malic and citric, pH stabilized during early fruit development (Legua *et al*., 2000). Fruit volume, aril weight, juice percentage and organoleptic rating increased during fruit growth, while rind weight decreased with advancement of maturity, also TSS and vitamin C content increased up to 150 days of anthesis but acidity decreased during fruit development. (Dhillon and Kumar, 2004b).

Fresh juice contained 85.4% moisture, 10.67% total sugars, 1.4% pectin and every 100 ml contained: 0.1 g total acidity (as citric acid), 0.7 mg ascorbic acid, 19.6 mg free amino-nitrogen and 0.05 g ash. The seeds were rich in total lipids, proteins, crude fibre and ash, representing 27.2, 13.2, 35.3 and 2.0%, respectively and also contained 6.0% pectin and 4.7% total sugars. The juice minerals content (Fe, Cu, Na, Mg and Zn) was lower than that of seeds, except potassium which was 49.2 mg/L in the juice (El-Nemr *et al*, 1990). The red color of the peel and juice is due to the presence of anthocyanins, six anthocyanin pigments were found to be responsible for the red colour of pomegranate juice in different cultivars (Melgarejo *et al*, 2000b). The fruit skin was quite rich in tannins ranging from 47 to 68% in different cultivars (Malhotra *et al*., 1983).

Fruit bagging using colored polyethylene bags affect some of fruit characteristics, the highest average fruit weight was recorded with green bags (338.8 g) and fruit diameter with red bags (8.31 cm). Bagging did not influence fruit physical and chemical parameters, pink fruit colour was obtained with transparent bags and with no bagging (exposed fruits). However, fruits under colored bags were light green in colour (Padmavathamma & Hulamani, 1996). Fruit yield in terms of number and weight was highest when 4 stems were left, also gave the greatest canopy spread, largest fruits and highest juice and TSS content (Balasubramanyan *et al*, 1997).

4. Mollar de Elche Cultivar (pomegranate studied cultivar)

A number of characteristics vary between pomegranate genotypes and are keys to identification, consumer preference, preferred use, and potentially niche marketing. The most important traits are fruit size, husk color (ranging from yellow to purple, with pink and red most common), aril color (ranging from white to red), hardness of the seed, maturity, juice content, acidity, sweetness, and astringency.

'Mollar de Elche' and 'Valenciana', in Spain, are among the most widely grown and marketed pomegranate cultivars in Western Europe (Costa and Melgarejo, 2000). The 'Mollar' cultivar is harvested much later (end of September until mid-November) and displays more sun and split damage, but has higher yield, excellent internal fruit quality (sweet fruit with soft seeds), larger size, longer harvest period, and greater consumer acceptance (Costa and Melgarejo, 2000). The outside color is pink-red and the arils are red.

The different phenological stages of 'Mollar de Elche' cultivar between winter dormancy and leaf fall were defined by Melgarejo *et al*. (1997) using BBCH General Scale (Table 1) and described (Fig.8-9).

Table 1. Growth stages, phenological code, duration and heat units (Melgarejo *et al*, 1997).

Growth stage	BBCH code	Duration days	Duration ºC days
Bud in winter dormancy	00	61	-
Bud swelling	01	11	12
Red tip	09	6	25
Sprouting of first leaves	10	6	21
Leaf separation	10	4	20
Leaf growth	11	12	44
Lengthening of internodes	31	119	1228
Appearance of the flower buds	51	3	21
Swollen calyx	55	11	88
Opening of calyx	59	3	24
Open flower	61	6	59
Petals fall	67	2	27
Fruit setting	69	10	129
Young fruit	71	17	182
Fruit growth	73	90	1323
Second bud sprouting	39	45	700
Fruit ripening	81, 85	35	366
Leaf fall	93	57	-

* The duration of each phenological stage was measured in days and heat units starting at the beginning of bud development. The heat units were measured as the sum of the differences between mean daily temperatures and a base temperature of 10°C which corresponds to the temperature at which bud development is activated (Baldini, 1992). The use of heat units allows comparisons to be made across different years and geographical areas.

00: Bud in winter dormancy
The bud is greyish brown and completely closed, deeply linked to the twig and sharply pointed at its tip.
01: Bud swelling: The bud swells and becomes paler and rounder in shape.
09: Red tip: The bud opens to show the new shoot, which is spear shaped and has a red tip.

10: Sprouting of the first leaves
The first leaves appear; they are furled and are bright red with a pale midrib green and the rest of the leaf is bright red.
10: Leaf separation: The new leaves separate.
11: Leaf growth: Leaves grow in length and width, and change colour from bright red to light green.

31: Lengthening of internodes
Internodes lengthen and shoot growth is rapid.

51: Appearance of the flower buds
Flower buds appear among the leaves on shoots, being greenish at first, but becoming red after a few days. The sepals are visible and close together.
55: Swollen calyx
The buds increase in size, and become pear-shaped; the differences between male and hermaphrodite flowers become apparent in the shape and the colour of the calyx: the terminal branches bud together with several flowers, usually abscise.
59: Opening of the calyx
The sepals open, to show the folded red petals inside. Toward the end of this stage, petals unfold and the pistil anthers become visible.

61: Open flower
The calyx opens totally and the protruding petals, which are folded and purple, unfold over the sepals. The petals seem to be inserted between every two sepals, on their inner side, giving the impression of alternating petals and sepals. The anthers of the stamen change to deep yellow when the pollen is ripe and capable of fertilizing. It is during this stage that pollination takes place.
67: Petal fall
Petals wither and fall; the calyx turns colour from red to orange-red; stamens bend toward the longitudinal axis of the flower and the anthers become greyish-yellow. The terminal part of the style withers.
69: Fruit setting
The fertilized ovary grows in size and the base of the calyx swells; the stamens wither and the fruit slam changes from orange-red to greenish brown.

71: Young fruit
The fruit increases in size rapidly and the colour turns from greenish brown to green.
73: Fruit growth
The fruit enlarges almost to its final size through cell enlargement; the sepals form a crown, the dry stamen being inside.

39: Second bud sprouting: Resumption of shoot growth on the tree.

81, 85: Fruit ripening
The fleshy seeds change from white *to* pinkish-red or red; the skin of the fruit changes from green to greenish yellow, and finally to brownish-yellow with reddish patches.

93: Leaf fall: The leaves turn yellowish, and fall; and when complete, winter dormancy starts.

Figure 8. Description of phenological stages of pomegranate - Mollar de Elche variety (Melgarejo *et al*, 1997)

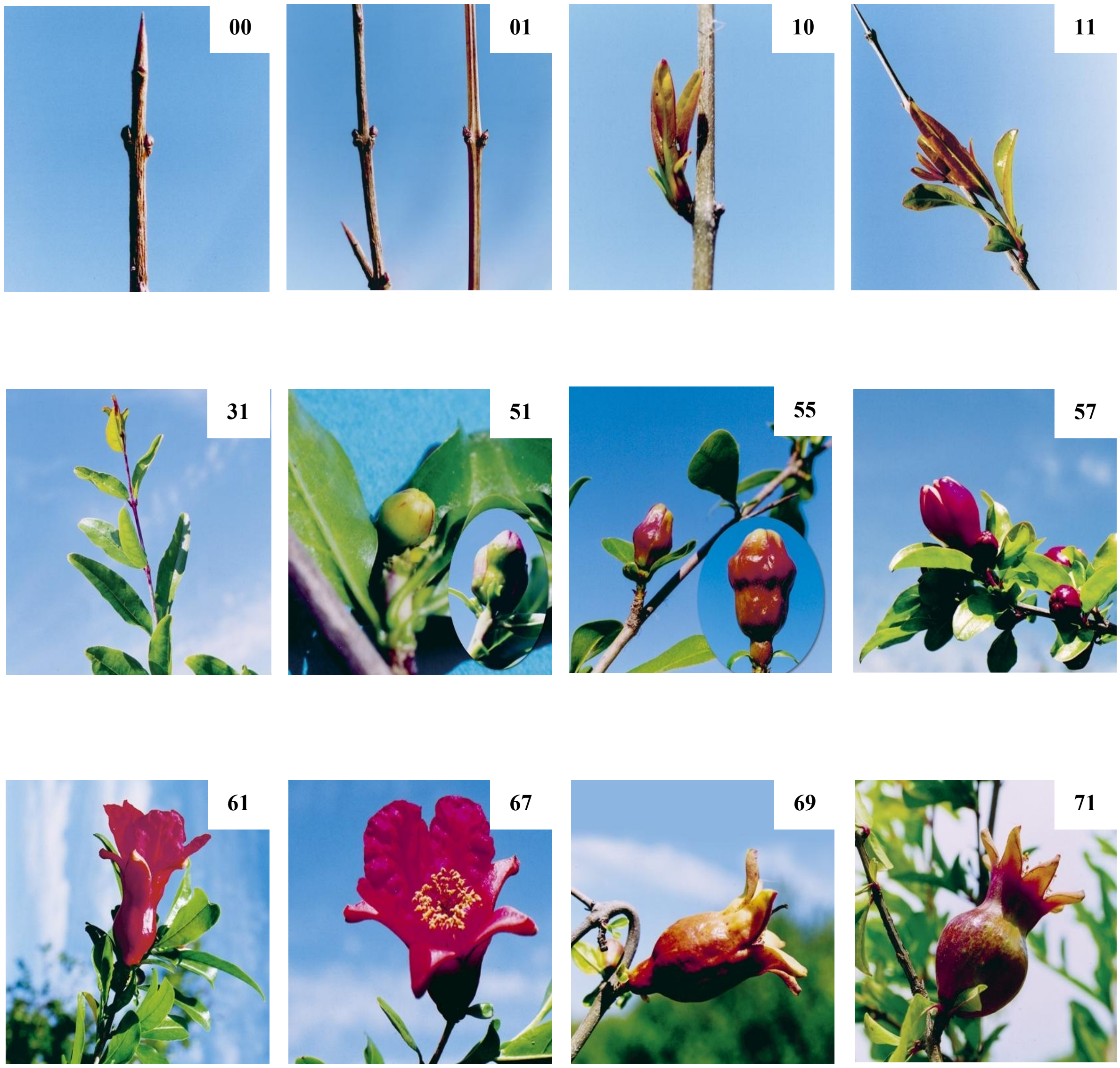

Figure 9. Phenological stages of pomegranate: *Punica granatum* (I. López, D.M. Salazar, Dpto. Producción Vegetal, U.P.V., http://www.afrasa.es/utilidades/estados-fenologicos/id_10/estados-fenolgicos-del-granado).

Because of differences in quality and productivity observed in commercial plantings, Spanish researchers have selected distinct clones of their most important cultivars. Selections were made in 1986, in the provinces of Alicante and Murcia. Numbered clones were propagated and are undergoing replicated trials to identify the best materials (Amoros et al., 2000). There are many selections of 'Mollar de Elche' variety (ME1, ME5, ME6, ME14, ME15, ME16 and ME17), ME14 and ME15 have the highest yield (Martinez *et al*, 2000).

5. Horticultural management

5.1. Climate. Pomegranate is especially well adapted to Mediterranean environments with cool winters and hot summers to ripen properly so commercial production is limited to coastal areas or those with mild summers (Melgarejo & Martinez, 1989), but can be grown in the humid tropics or subtropics and has the ability to resist frosty conditions, but injured by temperatures less than -11ºC (Morton, 1987). It is evergreen in the tropics and deciduous in the subtropics. A temperature of 38°C and dry climate during fruit development produce best quality fruits. Areas with high relative humidity or rain are totally unsuitable for its cultivation as fruits produced under such conditions tend to taste less sweet (Kumar, 1990). Commercial production is concentrated in dry summer climates, and pomegranate is extremely drought tolerant once established, but crops much better with more generous moisture.

5.2. Soil. Pomegranate cultivated in a wide range of soils with drought hardiness and has a high tolerance to salinity (Melgarejo, 2003), the pomegranate grow best in well-drained soil, and can grow on calcareous or acidic loam as well as in rock strewn gravels (Özgüven *et al*, 2012).

5.3. Propagation. Pomegranate cuttings root so easily that sometimes placed directly into the orchard (Blumenfeld *et al*., 2000). Pomegranate is easily propagated by hardwood cuttings so it is not necessary to use rooting hormones (Özgüven and Ak, 1993) and plants grow to a marketable size in a year and first fruit production after about 3 years. Cuttings should be taken in winter from mature, one-year-old wood and inserted about two-thirds their length into the soil.

5.4. Planting distance. To provide optimal light for fruit development, pomegranate trees are planted with wide spacing (typically 6 x 4 m) despite relatively small tree size. Some growers plant denser orchards (6 x 2 m) to obtain higher yields in early years with removal of alternate trees in later years.

5.5. Pruning and Training. Plants are trained to 1:5 trunks, the branches are trained to grow as an open vase (Blumenfeld *et al*. 2000) and the tree height is typically kept below 4 m. Trees should receive light annual pruning to maintain the production of short spurs, which bear most fruit, and such pruning also reduces the potential for wind scarring on long whippy shoots. The problems of multiple trunks system are that it difficult to do many cultivation practices (pruning, spraying, and fruit harvesting), after the improvement of effective pesticides against stem borers, it is possible to use the single stem system. Topping after 2-3 years from planting reduces fruit production. Light affect bearing capacity and fruit quality, so pruning is done by thinning out the unwanted branches and shoots and also by cutting water sprouts and suckers (strong tendency for producing suckers). Severe pruning of the plant crown can be done for renewing plants (Özgüven *et al*, 2012). Pawar *et al*. (1994) found that shoot length and leaves number per shoot increased with pruning intensity but delayed the bud sprouting, flower appearance and harvesting. The highest yield was obtained from control trees (without pruning), although the fruit quality increased with the severity of pruning.

5.6. Fertilization. Although pomegranate grows well in low fertility soils, production can be increased by application of manures and fertilizers. Nutritional needs of the plant vary according to the given ecological conditions. The optimum amounts for N is 200 kg/ha and for K is 300 kg K_2O /ha (Kosto *et al*. 2007), with P of 60 kg P_2O_5 /ha. N is applied with the beginning of growth through the entire irrigation period up until two weeks before harvest, K is applied throughout the irrigation season and P is applied as phosphoric acid or in complete fertilizer mixtures. Excessive applications of nitrogen increase vegetative growth and reduce fruit production, also may delay fruit maturity and color. Pomegranate trees respond well to organic fertilization (Özgüven *et al*, 2012). Microelements, such as Zn, Fe, and Mn, applied as foliar application increasing yield and juice content (Balakrishnan *et al*. 1996). Bambal *et al*. (1991) studied the effect of foliar application of some micronutrients such as Fe, B, Mn and Zn. The Mn and Zn increased yield of the plant and B reduced cracked fruits percentage. The micronutrients when sprayed in combinations were found promising and the highest number of fruits was obtained in Fe + Zn combination (Table 2).

Table 2. Chemical characteristics of pomegranate fruits as influenced by various foliar micro-nutrients sprays (Bambal *et al*, 1991).

Treatment	Average fruit weight (g)	Average volume of fruit (ml)	Percentage of grain	Percentage of peel	No. of grains in 100 g	Percentage of juice	TSS (°Brix)	Acidity (%)	Color of fruit	Aril color
Control	313.89	296.22	58.36	41.64	318.89	69.33	13.44	0.34	Yellowish green	Light pink
Fe	328.33	322.44	62.82	35.85	310.57	72.77	14.73	0.32	Greenish yellow	Light pink
B	381.11	365.55	63.12	36.88	316.56	71.72	13.63	0.31	Red	Dark pink
Fe+B	368.88	359.77	64.18	35.80	309.78	72.33	14.61	0.32	Reddish yellow	Dark pink
Mn	400.77	376.88	64.54	35.46	321.11	78.00	13.85	0.34	Greenish yellow	Light pink
Fe+Mn	315.53	311.11	66.17	33.83	350.11	73.22	14.39	0.34	Greenish yellow	Light pink
B+Mn	325.00	317.22	66.71	33.89	309.57	76.89	14.82	0.34	Reddish yellow	Dark pink
Fe+B+Mn	361.11	344.00	67.40	32.60	312.57	77.78	14.12	0.34	Reddish yellow	Pink
Zn	338.33	325.00	66.85	33.15	341.44	76.78	14.02	0.32	Greenish yellow	Pink
Fe+Zn	344.55	333.33	68.31	31.69	314.78	70.56	14.41	0.33	Greenish yellow	Pink
B+Zn	367.77	355.00	64.21	35.79	317.56	72.77	14.12	0.34	Red	Dark pink
Fe+B+Zn	350.52	329.66	68.26	31.74	320.00	72.73	14.06	0.33	Red	Dark pink
Mn+Zn	368.55	352.78	67.32	32.68	309.78	73.00	13.94	0.36	Greenish yellow	Pink
Fe+Mn+Zn	333.00	306.22	67.83	32.16	318.67	76.89	14.02	0.34	Greenish yellow	Pink
B+Mn+Zn	333.33	328.33	67.36	32.64	312.56	73.33	13.87	0.34	Reddish yellow	Pink
Fe+B+Mn+Zn	379.44	362.33	63.73	36.27	312.00	79.67	13.73	0.34	yellow	
S.E.	12.52	10.63	1.29	1.28	8.22	2.64	0.28	0.01		
CD at 5%	36.16	30.70	3.75	3.72	N.S	N.S	N.S	N.S		

Iron as $FeSO_4$ at 0.4%; Boron as Boric acid 0.2%; Manganese as $MnSO_4$ at 0.3%; Zinc as $ZnSO_4$ at 0.3%

5.7. Irrigation. Fruit culture in arid and semiarid areas must be directed towards the use of less water-demanding and more stress-resistant plant materials which, together with deficit irrigation, will allow significant water savings and the profitable production of high quality fruits (Rodríguez *et al*, 2012).

Pomegranate is considered to be a drought-resistant crop because it supports heat and can thrives well in arid and semiarid areas, even under desert conditions (Aseri *et al*., 2008). However, in arid and semiarid conditions, to reach optimal growth, yield and fruit quality for commercial production the crop requires regular irrigation throughout the dry season (Prasad *et al*., 2003; Shaliendra and Narendra, 2005; Sulochanamma *et al*., 2005; Levin, 2006b; Holland *et al*., 2009).

Irrigating of pomegranate trees is very important. To establish new plants, they should be watered every 2 to 4 weeks during the dry season. The pomegranate can withstand long periods of drought. Most orchards are irrigated under furrow system, but sprinkler and drip irrigation systems are used in some orchards. Fruit splitting and cracking are commonly seen unless the plants are regularly irrigated (Özgüven *et al*, 2012). Irrigation management like drip irrigation system has a positive effects on vegetative growth (tree height, stem diameter, and plant spread), yield and fruit weight (Prasad *et al*., 2003; Shaliendra and Narendra, 2005; Sulochanamma *et al*., 2005). Most of commercial orchards in different areas utilize drip irrigation methods which saved up to 66% of water compared to surface irrigation (Behnia 1999; Chopade *et al*. 2001). Irrigation water requirements for pomegranate trees for the entire season are around 5,000 to 6,000 m^3/ha related to soil type and the climate conditions with expected yields of 25 to 45 t/ha as reported in some commercial areas for pomegranate production (Holland *et al*., 2009).

Applying different irrigation regimes make it possible to control the desired time of fruit yield in pomegranates (Sonawane and Desai, 1989). Quality of available irrigation water is important and affects plant growth and fruit production, pomegranate trees are tolerate to irrigation water salinity with range between 1600- 2500 ppm (Maas, 1990). Excess watering or excessive rain during the maturation period may cause fruit splitting and cracking (Onur, 1988). When possible, providing adequate moisture is recommended throughout the growing season (with soil moistures similar to those used in citrus production), which contributes to growth, production, and a reduction in splitting (LaRue, 1980). It is especially important to avoid drought stress during initial fruit set (Still, 2006).

Soil and tree water status is very important for the quality and quantity of pomegranate fruits; they must be measured to apply better irrigation intervals and optimum water amount (useful source of information for irrigation management). Irrigation scheduling is also very important to optimize the use of water resources. Water deficit has been shown to influence various physiological and biochemical processes in plants (Hepaksoy *et al*, 2009). In general terms, plant water status can be estimated from visual symptoms or measured quantitatively in terms of water content or free energy status, the water potential (Kramer, 1988). The pressure chamber has been widely used in the measurement of total water potential and pressure-volume relations of leaves, twigs and, to a lesser extent, roots (Turner, 1988).

5.8. Harvest and Yield. Pomegranate fruit is non-climacteric, should be picked when fully ripe. Harvesting of immature or overripe fruits reduces the quality. The fruits are ready for harvest in 5 to 6 months after the appearance of blossom. The fruits are harvested when the skin turns slightly yellow and fruit gives a metallic sound when tapped or pressed (Mir *et al*, 2012). Harvesting time of pomegranate varies from August to November depending on regions and cultivars. Harvesting should be done very carefully to prevent bruising and wounding. Pomegranates will set a few fruit in the second or third year after propagation, but generally reach good commercial production at 5 to 6 years. Mature yields of 33 t / ha are expected in California commercial orchards (Karp, 2006).

5.9. Postharvest and Marketing. Storage life of the pomegranate is quite long and equals the apple, and the fruits ship very well (Morton, 1987), although bruising can be an issue. The pomegranate fruit is non-climacteric (Kader *et al*., 1984) and it means that the fruit keeps low rate of respiration when it harvested which is decreased with time after the harvest, also low amount of ethylene is produced, indicated that the pomegranate fruit will not ripe postharvest and should be harvested at full maturity stage. Harvest and storage factors affecting postharvest quality of pomegranate have been summarized in a recent review (Kader, 2006). Numerous techniques are being explored to enhance postharvest life and quality of fresh pomegranate (Artés and Tomás-Barberán, 2000). The fruit will keep many weeks at room temperature and longer in cold storage; pomegranate fruits can be stored for four months under optimum conditions (Özgüven *et al*., 1997). The rind shrinks and becomes thinner and tougher in storage, improving the eating quality (Özgüven *et al*, 2012). During fruit maturity on the tree, there are some changes like reduction in the titratable acidity with parallel increase in TSS, pH, and color intensity (Kader, 2006). The main problems in storage of pomegranate fruits are loss of fruit weight, fruit size reduction, skin damages such as husk scald or browning fruit rot and postharvest decay by *Botrytis cinerea* which is the primary limiting factor for long-term storage (Or-Mizrahi and Ben-Arie 1984; Ben-Arie and Or 1986; Adaskaveg and Forster 2003; Tedford *et al*. 2005; Defilippi *et al*. 2006). Waxing combined with antifungal treatments is used to extend the shelf life and improve fruit quality under cold storage and ambient conditions (Serakale *et al*. 2003; Ghatge *et al*., 2005). Utilizing a new technology (modified atmosphere packaging) that involves the usage of special bags with small pores for long storage period with reducing weight loss, scald and crown decay when fruits were stored at 6ºC for 4 months with keeping commercial quality. (Porat *et al*. 2006; Sachs *et al*., 2006). For consumer satisfaction and producer profitability require two important characteristics in pomegranate fruits: health-related quality (antioxidative capacity) and fruit attractiveness (colour and the taste of the arils and their juice) (Borochov-Neori *et al*, 2009). Premium prices for fresh fruit are obtained only for large blemish-free pomegranates. Grading, packing and transportation are important process for marketing fruits. The fact that obtaining high quality and marketable fruits every year depends on the knowledge about all the morphological and physiological events from flower bud formation to fruit maturation (Gozlekci and Kaynak, 2000b).

Production problems. The principal problems for pomegranate cultivation are lack of cultivated area due to various pests and diseases, blackening of arils, flowering induction, high fruit quality for export, cracking, etc.

6. Pomegranate fruit cracking phenomenon

Fruit cracking may affect yield and sometimes cause significant commercial damage. Cracking is occurred in many pomegranate cultivars because of fruit overripe, for other cultivars in earlier stages of fruit development (Fig.10), but also there are some cultivars are resistant to cracking which suggest that aspects of fruit cracking in pomegranate are genetically with effects of environmental conditions (Trapaidze and Abuladze, 1998; Hepaksoy *et al*., 2000; Tabatabaei and Sarkhosh, 2006; Holland *et al*., 2009). It is mainly correlated with soil moisture alteration, day and night temperatures, relative humidity and of rind pliability. Mature fruits crack due to moisture imbalances, as they are very sensitive to variation in soil moisture and relative humidity. Drought for long period causes hardening of the peel, followed by irrigation or rains, the pulp grows and ultimately the peel cracks (Cracking is a problem in regions where the fruit ripening stage overlaps with rainy period in autumn). Boron and calcium deficiency may be led to fruit cracking. Shading may induce cracking by alteration of water balance due to lower radiation (Yazici and Kaynak, 2006). There is a secondary damage by attack of insects or fungal on the cracked fruits, so fruits become unfit for marketing (Mir *et al*, 2012). Selection of proper planting material, controlled and systematic irrigation (regular irrigation, particularly by drip irrigation) to keep soil moisture in balance, flowering regulation, spraying of boron and GA_3 and control of mites at accurate stage can decrease cracked fruits percentage in pomegranate (Prasad *et al*. 2003; Singh *et al*. 2003; Sheikh and Rao 2006; Singh *et al*., 2006b). Spraying GA_3 (150 ppm) with BA (40 ppm) could significantly reduce fruit cracking (Sepahi 1986; Mohamed 2004; Yilmaz and Özgüven 2006).

Other important fruit physiological disorder is sunburn which combined action of high solar radiation, low humidity, and high temperatures as fruit surface temperatures more than 41ºC (Yazici and Kaynak, 2006). Late cultivars that ripen in autumn are much more susceptible to sunburn by exposed to strong solar radiation and high temperatures during the summer (Fig.11). Application of Kaoline and 35% shading are effective to reduce sunburn on pomegranate fruit (Melgarejo *et al*. 2004; Yazici and Kaynak 2006).

Figure 10. Pomegranate fruit cracking phenomenon during fruit growth and ripening.

Figure 11. Sunburn of pomegranate fruits.

With the Global water scarcity problem, the amount of water used by agriculture sector must be decreased without affecting the production. This policy can be achieved through different strategies like modernization of irrigation system to reduce water loss and increase the cultivated area with low water demand crops as pomegranate. So, it is necessary to have adequate knowledge about water requirement, irrigation schedule and degree of drought resistance. For these reasons, the objectives of the present study were to:

1. Develop an irrigation scheduling for pomegranate trees.
2. Investigate the effect of water stress applied in certain phenological stages on the performance of pomegranate tree (vegetative growth, flowering, fruiting and yield).
3. Study the changes in fruit quality attributes as one of water stress effects.
4. Evaluate water use efficiency and productivity as evidence of pomegranate trees performance under deficit irrigation regimes.
5. Provide the knowledge about the degree of pomegranate trees tolerance to water stress.

Materials and Methods

1. Experimental plot

This study was carried out in 2012 at a commercial pomegranate orchard in Elche, Alicante, Spain (Latitude 38º 13' 53, 98" N, Longitude 0º 39' 20, 00" W and elevation 97 m). The entire orchard was of about 15 ha, and the experiment was performed in a 0.8 ha block (Fig.12).

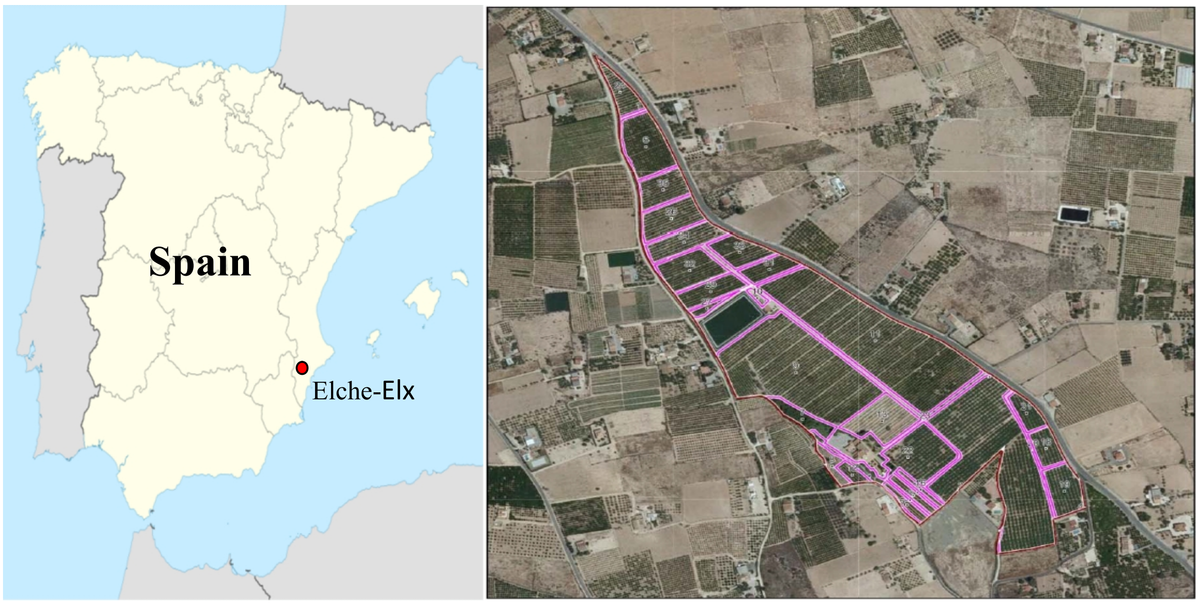

Figure 12. Location of pomegranate orchard in Elche, Spain.

2. Plant material

12 years-old pomegranate trees (*Punica granatum* L., cv. Mollar de Elche) with spacing of 5 x 4 m. At the beginning of the experiment, the average tree shaded area was 56% of the soil allotted per tree. The selected trees were uniform in size and shape with trunk diameter of 60 cm in average. Trees received 100 kg/ha of N, 40 kg/ha of P_2O_5, and 80 kg/ha of K_2 during season through drip irrigation system. Agricultural practices followed were those common for the area, including a very light hand thinning generally performed in early August in order to remove fruit that were clustered in some fruiting shoots.

3. Soil samples analysis

The soil samples were collected from different points of the plot by auger riverside type at different depths. Samples were sent to soil laboratory at Centro para el Desarrollo de la Agricultura Sostenible in IVIA (at Moncada, Valencia, Spain) for analysis of some physical and chemical characteristics.

The soil was a typical calcaric fluvisol sandy-loam with an effective depth over 120 cm. It is highly calcareous and low fertility as described in (Table 3).

Table 3. Analysis of soil samples.

A. Physical characteristics						
Soil profile	**Sand %**	**Silt %**	**Clay %**	**Coarse %**	**FC (cm^3/ cm^3)**	**WP (cm^3/ cm^3)**
0 -10 cm	32.17	34.05	33.79	1.28	0.32	0.18
10 – 30 cm	33.22	31.68	35.11	4.70	0.38	0.27
30 - 60 cm	44.96	22.52	32.52	5.08	0.33	0.23
30 – 90 cm	45.14	21.97	32.89	8.47	0.36	0.24
90 – 120 cm	45.31	28.76	25.93	8.47	0.30	0.21
120 -150 cm	22.46	42.25	35.30	8.47	0.42	0.29
B. Chemical characteristics						
Soil profile	**pH**	**OM (%)**	**$CaCO_3^-$ (%)**	**EC (microS/cm)**		
0 -10 cm	8.40	2.2	64.4	198		
10 – 30 cm	8.42	1.1	71.7	461		
30 - 60 cm	8.62	0.8	61.8	308		
30 – 90 cm	8.93	0.1	68.2	273		
90 – 120 cm	9.05	0.1	73.8	318		
120 -150 cm	8.70	0.1	67.7	583		

4. Water samples analysis

The source of irrigation water is Tajo-Segura transfer. Water samples were collected from water resource and sent to soil laboratory at Centro para el Desarrollo de la Agricultura Sostenible in IVIA (at Moncada, Valencia, Spain) for analysis.

The irrigation water had no risk of salinization with an average electrical conductivity (EC) at 25ºC of 1.23 dS m^{-1} (Table 4).

Table 4. Analysis of water samples.

EC (dS m^{-1})		1.23	
pH		8.18	
Cation (mM/L)		**Anion (mM/L)**	
Ca^{2+}	3.15	SO_4^{2-}	3.47
Mg^{2+}	2.41	NO_3^-	0.03
Na^+	3.20	$CaCO_3^-$	3.41
K^+	0.1	Cl^-	2.88

5. Climate data

Climate data were recorded at an automated weather station equipped with: a datalogger CR1000 (Campbell Scientific, Logan, UT, USA), an air humidity and temperature sensor 1.1005.54 (Thies clima, Göttingen, Germany), a wind speed sensors 4.3519.00 (Thies clima), a solar pyranometer CMP· (Kipp & Zonen Delft, The Netherlands) and a rain gauge ARG 100 (Campbell Scientific). The weather station was located at 5 km distance from the orchard. Meteorological variables measured included air temperature, air relative humidity, wind speed, solar radiation and precipitation (Table 5 – Fig.13). This weather station belongs to the Spanish national weather station net for irrigation recommendations.

Table 5. Climate data of 2012 from Elche (Elx) weather station.

Month	Average temp. (ºC)	Max Temp. (ºC)	Min Temp. (ºC)	Average RH (%)	Max RH (%)	Min RH (%)	Total precipitation (mm)	Wind speed (m/s)	Radia-tion (MJ/m^2)	Sun hours	Cold hours	ETo (mm)
1	12	17.9	07.1	63.8	82.2	42.9	10.1	3.9	9.2	8.02	67.5	1.4
2	9.4	15.6	04.2	49.4	69.6	28.2	05.9	5.1	13.5	9.14	232.5	2.1
3	13.6	19.8	07.9	59.8	81.4	35.9	39.5	4.5	18.1	10.39	28	2.9
4	16.4	22.3	11.1	57.8	79.9	34.9	29.8	5.6	19.8	11.2	0	3.9
5	20.8	26.6	15.1	55.2	78.2	33.0	0	4.8	26.1	12.28	0	5.1
6	25.5	31.3	19.9	59.2	83.6	35.6	02.8	4.8	26.6	12.54	0	5.8
7	26.3	31.1	21.6	63.3	82.3	42.4	0	5.2	25.5	12.66	0	5.7
8	27.9	33.3	23.0	65.8	86.9	41.6	01.3	4.9	21.9	11.88	0	5.2
9	23.5	28.7	18.7	63.9	83.1	40.7	83.7	4.9	17.8	10.56	0	3.9
10	19.6	25.3	14.8	68.6	88.2	44.2	43.0	4.2	13.6	9.33	0.5	2.5
11	14.9	19.2	11.4	74.3	86.6	55.5	57.9	4.2	07.7	6.96	2	1.4
12	12.5	18.2	07.6	62.8	80.3	42.2	0.30	4.5	08.0	7.47	50	1.3

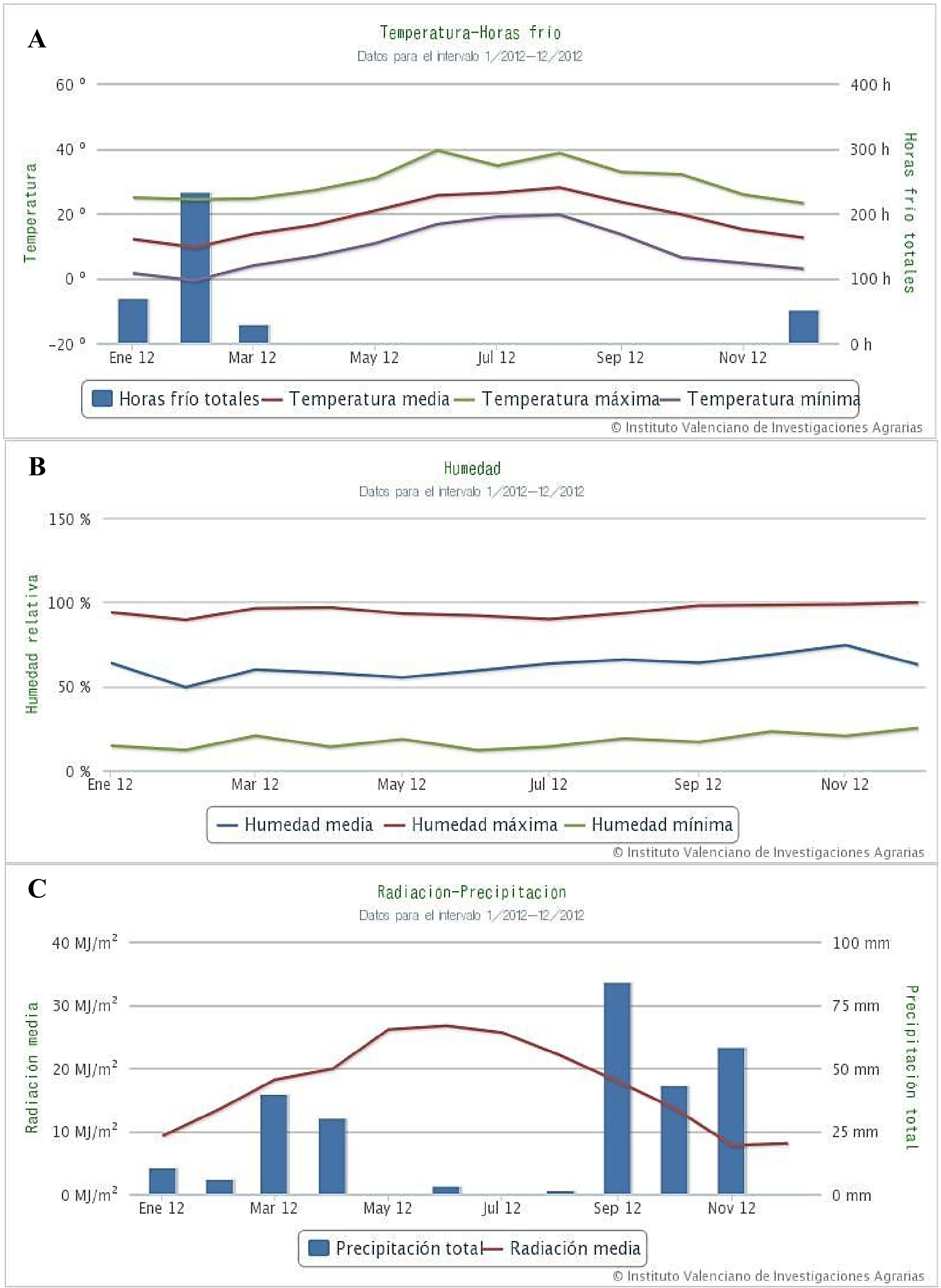

Figure 13. Climate data of season 2012 in Elche A) Temperature and Cold hours, B) Humidity and C) Perception and Radiation.

6. Tools installation

6.1. Black nets: Nets were put under the trees (Fig.14) to keep the dropped flowers in the tree area until collected and counted.

Figure 14. Installation of nets under pomegranate trees.

6.2. Soil sensors: Soil water content (SWC) was monitored by using two multi-sensor capacitance probes C-Probe (Agrilink Inc., Adelaida, Australia), installed in two blocks of the Control treatment. Each probe had four sensors located at 10, 30, 50 and 70 cm (Fig. 15) depth inside a PVC tube (for a tight contact between the soil and the probe) located at a distance of 10–15 cm from the emitter and 1.5–2.0 m from the tree trunk. Data were obtained every 15 minute and could be visualized using the manufacturer software addVANTAGE Pro 5.1.

Figure 15. Installation of soil sensors.

6.3. Programming units and Flow meters

Programming units were installed in control head of irrigation system (Fig.16) in the experimental plot to set the irrigation program for all treatments (duration and intervals). Flow meters were put at the head of irrigation line for each replicate of all treatments to measure and check water amount used for irrigation.

Figure 16. Installation of Programming units and Flow meters.

7. Irrigation system

Drip irrigation was applied with eight emitters per tree (flow rate of emitter) 4.0 L / h and located in a single line parallel to the tree row. The structure of irrigation control unit is presented in Fig.17.

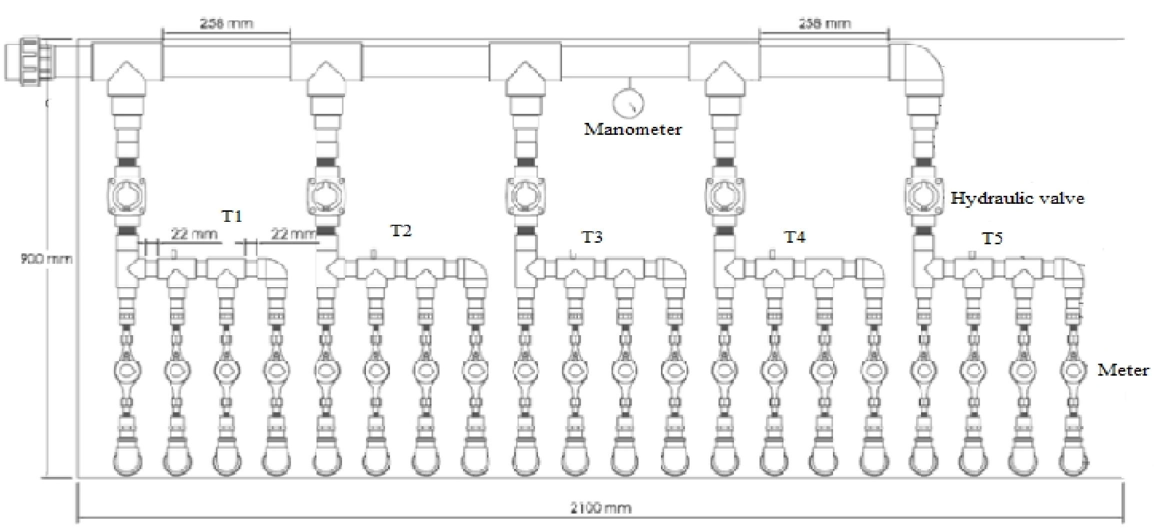

Figure 17. Diagram of irrigation control unit of experimental plot.

8. Water requirements calculation

The irrigation water requirements were calculated by using (ITS) Irrigation technology service (http://riegos.ivia.es/calculo-de-necesidades-de-riego) introduced by IVIA (Centro para el Desarrollo de la Agricultura Sostenible) as in Fig.18 depended on: Climate data, Crop information (Kc – Canopy diameter – Planting spaces), Irrigation system (drippers number / plant – dripper flow rate – system efficiency) and Irrigation water salinity. ETo was calculated with hourly values by the Penman-Monteith formula as in Allen et al. (1998). The Kc values employed were based on results in the same experimental orchard reported by Intrigliolo *et al*. (2011).

Figure 18. Water requirements calculation by Irrigation technology service introduced by IVIA website.

9. Treatments

This experiment based on exposing the trees to water stress in certain periods related to phenological stages of the pomegranate trees (Table 6).

Table 6. Phenological stages of pomegranate trees under experimental conditions.

Stage	Period
Vegetative growth	7 Feb – 14 April
Main flowering period	15 April – 1 July
Fruit set	15 May – 10 July
Fruit growth	20 June – 30 August
Fruit ripening	1 Sep – 5 Oct

The treatments were depended on estimated crop evapotranspiration (ETc) by using reference evapotranspiration (ETo) and crop coefficient (Kc) as described in table 7:

Table 7. Irrigation treatments.

Treatment	Irrigation regime
T1 (Control)	100% of ETc during growing season (March to November)
T2 (SDI)	Water stress was applied at 50% of ETc during growing season (March to November)
T3 (RDI_1)	Water stress was applied at 50% of ETc during main flowering and fruit set stage and 100 % ETc rest of the season
T4 (RDI_2)	Water stress was applied at 50% of ETc during fruit growth stage and 100 % ETc rest of the season
T5 (RDI_3)	Water stress was applied at 50% of ETc during fruit ripening stage and 100 % ETc rest of the season.

Stress for T3, T4 and T5 was applied by decreasing the amount of irrigation water during the deficits through reducing irrigation duration, while frequency of irrigation was always the same for all treatments. Irrigation frequency changed over the season from twice a week in April reaching to six times a week during summer.

10. Experimental Design

The experimental design was completely randomized block, with four replicates per treatment. Each replicate was consisting of three adjacent tree rows with 8 trees per row. The inner trees of the middle row was used for data collection which were uniform in appearance (leaf area, trunk diameter, height ground shaded area, etc.) while the other trees in the same row and the other rows served as border trees (Fig.19).

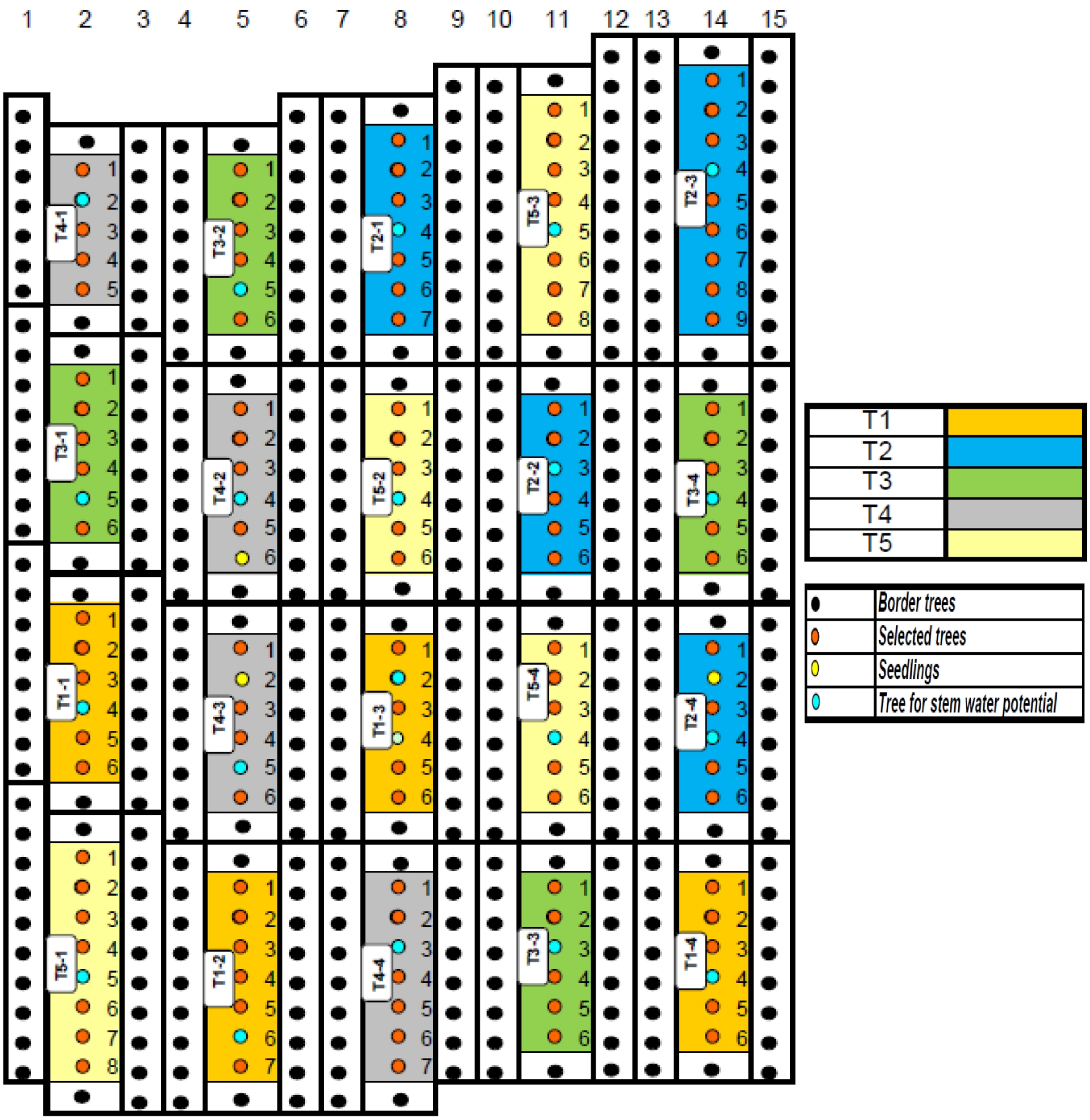

Figure 19. Experimental Design.

11. Measurements

11.1. Stem water potential

Midday stem water potential (Ψ_{stem}) was measured by using a pressure chamber (Soil Moisture Equip. Corp. mod. 5100A, Santa Barbara, CA, USA), following procedures as recommended by Turner (1981). Determinations were carried out in 4 trees per treatment, each tree located in a different experimental plot. Two mature leaves per tree, from the north side near the trunk, were enclosed in plastic bags covered with silver foil (Fig.20) at least 2 hours before beginning of measurements, which were done between 12:30 and 14:00 h solar time. Measurements of Ψ_{stem} were carried out approximately every week from May to October.

Figure 20. Stem water potential measurement, leaves covered with silver plastic bags (left) and pressure chamber used for measurement.

11.2. Vegetative growth rate

Vegetative growth was evaluated by two measures:

11.2.1. Relative trunk growth (%): Trunk perimeter was measured twice at the beginning (Initial) and at the end of the experiment (Final) at approximately 0.2 m above the ground. Determinations were carried out in all experimental trees. Trunk growth was calculated as (Final–Initial) / Initial.

11.2.2. Tree canopy volume: Tree canopy volume was estimated in all experimental trees by measuring at the end of each growing season (i.e., November, before leaf fall), the canopy diameter and height at three locations within a tree. Tree canopy volume (V_c) was calculated according to (Hutchinson, 1978) as $V_c = (\text{width}^2 \text{ x height})/2$.

11.3. Flowering and fruiting parameters

11.3.1. Flowers drop: every week dropped flowers were collected from the nets under the trees, counted and classified to hermaphrodite or male flowers (Fig. 21).

11.3.2. Initial fruit set (%): Fruit set percentage was calculated by the following equation:

Initial Fruit set % = number of set flowers / hermaphrodite flowers x 100

11.3.3. Fruit set drop: Every week dropped fruits were collected from the nets under the trees and counted (Fig. 21).

11.3.4. Final fruit set (%): Final fruit set was calculated by using the following equation: Final Fruit set % = Initial Fruit set - Fruit set drop x 100.

Figure 21. Classification of dropped flowers.

11.4. Yield and its components

11.4.1. Yield per tree: Harvesting process was in two waves on 8th and 19th October, fruits were picked for each tree of all treatments, counted, weighted and classified as commercial and non-commercial which include (small, cracked fruits and sunburned fruits).

11.4.2. Yield value: Yield values for fruit oriented to fresh markets were calculated considering the relative weight of fruits and the prices received by growers for each commercial category set by the cooperative of the area.

Figure 22. Harvesting process of pomegranate fruits.

11.5. Fruit characteristics

Pomegranate fruits were harvested at commercial maturity. Fruit samples was taken and transported to the Centro de Tecnología Poscosecha in IVIA where pomegranates were selected free of physical damage then fruits were kept at 5 °C and 90–95% RH until the next day, when fruits were prepared to evaluate the quality attributes**.**

11.5.1. Fruit weight (g): Fruits were weighted by using a precision balance (Mettler Toledo, Switzerland, ± 0.01g).

11.5.2. Fruit diameter (mm): Fruit diameter was measured by using a digital calliper (Mitutoyo, Series 500). The measurement was done in the equator of pomegranates, taking 3 measurements per fruit.

11.5.3. Cortex thickness (mm): Cortex thickness was measured by using a digital calliper (Mitutoyo, Series 500).

11.5.4. Fruit colour: External colour was assessed in 30 fruits per treatment were randomly divided into three replicates of 10 fruits on opposite cheeks of healthy pomegranate fruits using standard CIELab colour space coordinates and expressed as L*, a* and b* colour values provided by a colorimeter (Minolta, model CR-400, Osaka, Japan- Fig. 21).

The maximum value for L* is 100, which represents a perfect reflecting diffuser. The minimum for L* is zero, which represents black. Positive a* values represents red colour, while negative is green while positive b* is yellow and negative b* is blue.

11.5.5. Fruit juice (%): Pomegranate fruits were hand-peeled then the arils were homogenized in a commercial blender, the juice weighted and the yield was expressed as percentage.

11.5.6. Juice Total Soluble Solids (TSS): TSS was measured using a digital refractometer (model PR1; Atago Co. Ltd, Japan – Fig. 21) and values were expressed as ◦Brix.

11.5.7. The titratable acidity (TA) of the juice: TA was determined by titrating 5 mL of juice sample with 0.1 mol L^{-1} sodium hydroxide to an end point of pH 8.1 and expressed as percentage of citric acid (Titrator T50 Mettler Toledo, Switzerland – Fig. 21).

11.5.8. Juice pH: The pH was measure with the automatic titrator (Mettler Toledo T50, Switzerland – Fig. 21).

11.5.9. Juice colour: Juice was prepared in three replicates of 5 fruits per treatment. The color was measured using standard CIELab colour space coordinates and expressed as L*, a*, b*, and hue colour values provided by a colorimeter (Minolta, model CR-400, Osaka, Japan – Fig. 21).

11.5.10. The maturity index (MI): MI was calculated as the TSS/TA ratio.

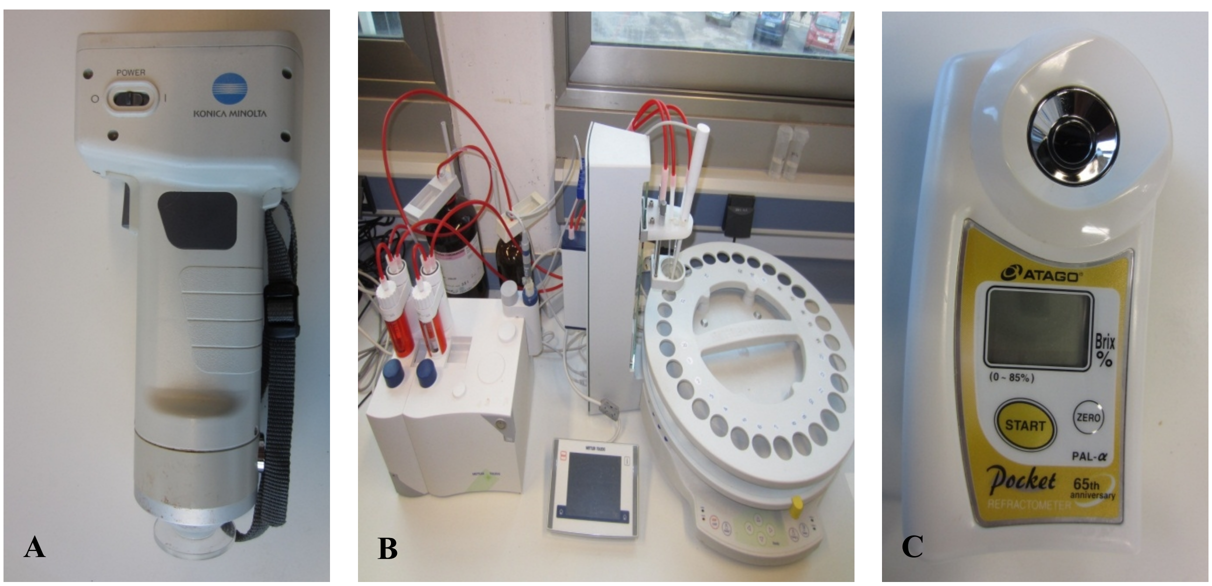

Figure 23. Fruits analysis devices A) Colorimeter (Minolta, model CR-400, Osaka, Japan), B) Titrator (T50 Mettler Toledo, Switzerland) and C) Digital refractometer (model PR1; Atago Co. Ltd, Japan)

11.6. Irrigation measurements

11.6.1. Water amount (m^3): Water used for irrigation during growing season was measured using flow meters.

11.6.2. Water use efficiency (Kg / m^3): Water use efficiency was calculated as yield divided on water quantity used for area unit and expressed as (Kg / m^3).

11.6.3. Water productivity (€/m^3): Water productivity was calculated according to Fereres and Soriano (2007) as the yield value divided by irrigation applied.

12. Statistical analysis

The data were analyzed by analysis of variance (ANOVA) using the general linear models ‘‘GLM’’ procedure of the SAS software (version 9.0; SAS Institute, Cary, NC). Significant differences between treatments were assessed by means of multiple Duncan range tests (Duncan, 1955).

Results

1. Stem water potential (Ψ_{stem})

In control trees, there was a general trend to a decrease in Ψ_{stem} values as the season progressed (Fig. 24). In fact, midday Ψ_{stem} of the control trees dropped from -0.54 MPa to -1.31 MPa, the large variations in the Ψ_{stem} values could be related to differences in the climatic conditions among days. SDI trees had a trend throughout the season to maintain lower Ψ_{stem} values than control and RDI treatments most of the season with range - 0.68: -1.94 MPa (Fig. 24). In RDI_1, differences with respect to the control trees appeared mainly in the middle of deficit irrigation cycle and continued until the end of the cycle reaching to −1.52 MPa (Fig. 24), differences were of -0.02 to -0.5 MPa. On the other hand, in RDI_2, differences in Ψ_{stem} compared with the control trees appeared just 2–3 weeks after restrictions started (Fig. 24). The maximum Ψ_{stem} recorded in RDI_2 was of -1.49 MPa. A similar degree of plant water stress was also achieved in RDI_3 (Fig. 24). In this treatment, Ψ_{stem} was around -1.0 to -1.60 MPa during most of the end of the season, the differences were clear in the middle of the deficit irrigation cycle. With RDI treatments, when water returned to full usage, plants recovered quickly their optimum water status.

2. Vegetative growth rate

SDI trees significantly reduced trunk growth with a decrease of 30% compared to the control trees (Table 8). The same with canopy volume that was only affected by water restrictions applied during the whole season (SDI) compared with control trees; the reduction in canopy volume in SDI trees was as high as 22.7% (Table 8). There were no significant differences between RDI treatments and control trees, giving an indicator that deficit irrigation strategies did not affect the vegetative growth rate of pomegranate trees.

Table 8. Effects of irrigation treatments on relative trunk growth and canopy volume of pomegranate trees.

Treatments	Relative trunk growth (%)	Canopy volume (m^3)
Control	$5.0^{a} \pm 0.9$	$11.22^{a} \pm 0.8$
SDI	$3.5^{b} \pm 0.3$	$08.67^{b} \pm 0.4$
RDI_1	$5.4^{a} \pm 1.6$	$11.64^{a} \pm 1.4$
RDI_2	$5.3^{a} \pm 0.6$	$10.81^{a} \pm 0.9$
RDI_3	$5.3^{a} \pm 0.9$	$11.20^{a} \pm 0.6$

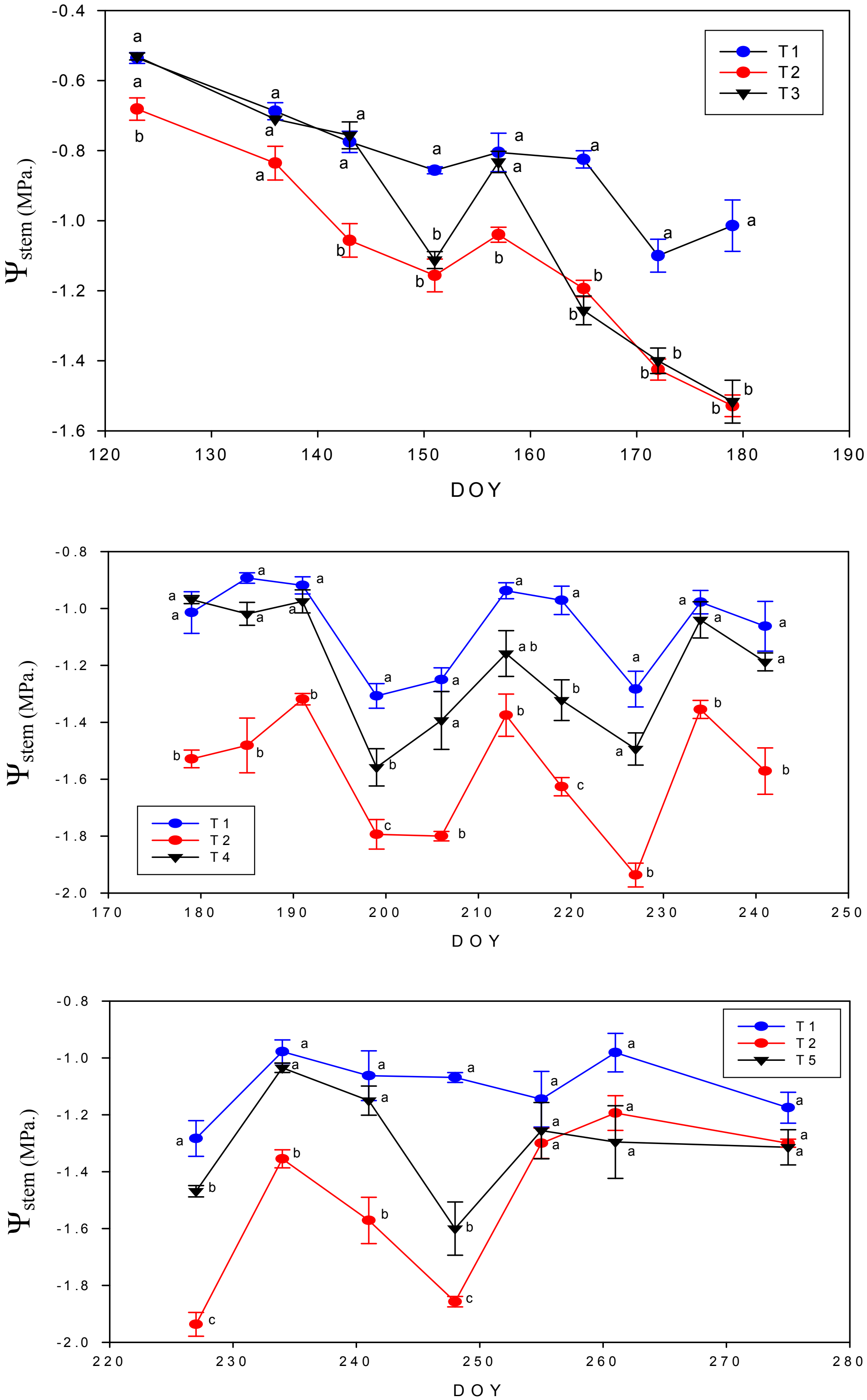

Figure 24: Midday stem water potential (Ψ_{stem}) in the different irrigation treatments. Error bars represent the standard error. DOY = day of the year.

3. Flowering and Fruiting parameters

There were no significant differences between RDI_1 and control trees in total flowers, (hermaphrodite and male flowers number) and sex ratio. SDI reduced male flowers production of 32% compared with control trees but there were no differences in H flowers number resulted in high sex ratio % of SDI which represented the highest value of 29.7% compared with control 22% (Table 9). The drop of H flowers was significantly decreased in the SDI treatment, since 63% of H flowers remained on the tree in this treatment, about 13-22% more than in the other treatments. On the other hand, there were no clear differences in the drop of H flowers between RDI_1 and control trees.

SDI trees recorded high percentage of fruit set of 63% compared with 54.3% for control, there were no differences between SDI and control trees in number of H flowers that succeeded in fruit set process but after the drop wave of during fruit set stage; SDI represented the highest value of final fruit set number with 68% of initial number, about 8-12% more than in the other treatments. SDI trees showed the lowest value of fruit set drop percentage of 31.8% compared with control trees of 38.9%. There are no significant differences between RDI_1 and control trees in fruit set % and fruit set drop %.

Table 9. Effects of irrigation treatments on flowering and fruit set parameters.

Treatment	Total Flowers	Male flowers	H Flowers	Sex ratio (%)
Control	$2296.7^{a} \pm 211.1$	$1790.3^{a} \pm 161.3$	$506.5^{a} \pm 73.6$	$22.0^{c} \pm 2.1$
SDI	$1722.0^{b} \pm 197.5$	$1215.5^{b} \pm 198.4$	$506.7^{a} \pm 13.1$	$29.7^{a} \pm 3.4$
RDI_1	$2406.5^{a} \pm 433.2$	$1846.5^{a} \pm 396.6$	$560.5^{a} \pm 76.3$	$23.6^{bc} \pm 3.3$

	H Flowers drop	H Flowers drop (%)
Control	$232.5^{ab} \pm 51.9$	$45.7^{a} \pm 6.5$
SDI	$187.3^{b} \pm 17.3$	$37.0^{b} \pm 3.6$
RDI_1	$288.5^{a} \pm 63.2$	$51.0^{a} \pm 4.3$

	Fruit set (%)	Initial fruit set	Final fruit set	Fruit set drop	Fruit set drop (%)
Control	$54.3^{ab} \pm 6.5$	$274.0^{a} \pm 46.1$	$166.0^{b} \pm 16.4$	$108.0^{a} \pm 31.3$	$38.9^{ab} \pm 4.6$
SDI	$63.0^{a} \pm 3.6$	$319.5^{a} \pm 22.3$	$217.8^{a} \pm 15.9$	$101.7^{a} \pm 14.6$	$31.8^{b} \pm 3.2$
RDI_1	$49.0^{b} \pm 4.3$	$272.5^{a} \pm 19.6$	$154.5^{b} \pm 05.8$	$118.3^{a} \pm 24.4$	$42.9^{a} \pm 6.1$

4. Yield components

SDI trees had a significant and consistent increase of collected fruits per tree; but with a significant decrease in yield (Kg/tree), about 15% less than control trees (Table 10). There were no significant differences between RDI treatments and control trees in number of collected fruits per tree; however RDI_1 and RDI_2 showed a significant decrease in yield (Kg/tree) about 10.3% and 8.3% respectively less than control trees while there were no significant differences between RDI_3 and control trees in yield (Table 10). For yield components, sun-burned fruits and cracked fruits percentage increased significantly in SDI which represented the highest values 14.8% and 14.3% respectively resulted in decrease of the commercial fruit, about 15% less than control trees. RDI treatments had no differences with control trees in yield components.. The yield value was significantly reduced by SDI; the decrease in yield value with respect to control trees was of 21%, while no differences were found between RDI treatments and control trees except with RDI_1 which showed a decrease of 11% (Table 10).

Table 10. Effects of irrigation treatments on yield and its components.

Treatments	Fruits/tree	Yield (Kg /tree)	Yield value (€/tree)	Yield (t / ha)
Control	$153.7^{b} \pm 9.0$	$55.3^{a} \pm 1.0$	$35.8^{a} \pm 1.3$	$27.6^{a} \pm 0.5$
SDI	$187.3^{a} \pm 7.3$	$47.0^{c} \pm 1.2$	$28.2^{c} \pm 1.2$	$23.5^{c} \pm 0.6$
RDI_1	$141.0^{b} \pm 2.0$	$49.6^{bc} \pm 1.2$	$31.7^{b} \pm 1.0$	$24.8^{bc} \pm 0.6$
RDI_2	$147.3^{b} \pm 7.5$	$50.7^{b} \pm 3.7$	$32.4^{ab`} \pm 2.4$	$25.4^{bc} \pm 1.8$
RDI_3	$147.3^{b} \pm 5.7$	$52.2^{ab} \pm 0.6$	$33.9^{ab} \pm 1.5$	$26.1^{ab} \pm 0.3$

	Commercial fruits (%)	Cracked fruits (%)	Sun-burned Fruits (%)
Control	$83.3^{a} \pm 3.7$	$7.6^{b} \pm 2.5$	$9.2^{b} \pm 1.9$
SDI	$70.8^{b} \pm 2.5$	$14.3^{a} \pm 2.6$	$14.8^{a} \pm 0.3$
RDI_1	$81.3^{a} \pm 3.9$	$8.8^{b} \pm 1.7$	$10.0^{ab} \pm 3.8$
RDI_2	$82.5^{a} \pm 2.4$	$8.6^{b} \pm 2.1$	$8.8^{b} \pm 0.8$
RDI_3	$83.8^{a} \pm 6.9$	$7.2^{b} \pm 3.7$	$8.9^{b} \pm 4.0$

5. Fruit characteristics

Fruit weight was not affected by RDI treatments compared to the control trees, while the effect of deficit irrigation on fruit weight was observed in the SDI treatment, with a 30.3% reduction than the control trees (Table 11-I). The same results were noticed with cortex thickness, as there were no significant differences between RDI treatments and control trees, cortex thickness significantly reduced by SDI treatment with a 17.5% compared to control trees (Table 11-I).

Table 11-I. Effects of irrigation treatments on fruit characteristics.

Treatments	Fruit weight (g)	Cortex thickness (mm)
Control	$360.8^{a} \pm 24.8$	$5.7^{ab} \pm 0.2$
SDI	$251.4^{b} \pm 15.6$	$4.7^{c} \pm 0.3$
RDI_1	$351.9^{a} \pm 04.5$	$5.6^{ab} \pm 0.5$
RDI_2	$344.3^{a} \pm 26.2$	$6.1^{a} \pm 0.1$
RDI_3	$354.6^{a} \pm 11.9$	$5.3^{bc} \pm 0.6$

Deficit irrigation during fruit growth (RDI_2) and fruit ripening (RDI_3) had a clear effect on juice content of pomegranate fruits, juice percentage was significantly increased by 15.8% and 25.3%, respectively, while deficit irrigation during flowering and fruit set period (RDI_1) had no influence on juice content (Table 11-II). Also there were no significant differences between SDI treatment and control trees. TSS ranged between 15.6 and 16.7 °Brix. Pomegranate fruits subjected to SDI and RDI_3 water restrictions had the highest TSS values, whereas control and RDI_1 fruits had the lowest (Table 11-II).

Table 11-II. Effects of irrigation treatments on fruit characteristics.

Treatment	Juice (%)	TSS (ºBrix)	TA (% C.A)	MI (%)	pH
Control	$41.6^{c} \pm 3.0$	$15.8^{bc} \pm 0.1$	$0.17^{a} \pm 0.01$	$94.8^{a} \pm 2.9$	$4.30^{a} \pm 0.10$
SDI	$41.9^{c} \pm 3.0$	$16.5^{a} \pm 0.2$	$0.16^{a} \pm 0.01$	$94.7^{a} \pm 2.6$	$4.19^{a} \pm 0.01$
RDI_1	$41.6^{c} \pm 2.4$	$15.6^{c} \pm 0.4$	$0.17^{a} \pm 0.01$	$91.0^{a} \pm 2.5$	$4.20^{a} \pm 0.06$
RDI_2	$49.4^{b} \pm 2.8$	$16.3^{ab} \pm 0.6$	$0.17^{a} \pm 0.00$	$94.3^{a} \pm 3.4$	$4.20^{a} \pm 0.03$
RDI_3	$55.7^{a} \pm 2.5$	$16.7^{a} \pm 0.3$	$0.18^{a} \pm 0.00$	$90.2^{a} \pm 1.3$	$4.15^{a} \pm 0.04$

Deficit irrigation had no effects on other fruit characteristics like TA, MI and pH, as there were no significant differences between DI treatments and control trees (Table 11-II).

The irrigation treatments had a significant effect on skin colour (external), pomegranate fruits subjected to SDI had the highest a* value followed by RDI_3 and showed lower values of L*and b* (Fig. 25). Therefore, SDI treatment resulted in redder and darker fruits. Juice colour (Internal) was differently affected by deficit irrigation, RDI_2 fruits recorded the highest of a* value while SDI the lowest. RDI_3 fruits which subjected to water stress during ripening phase showed negative value of b* resulted in darker juice colour.

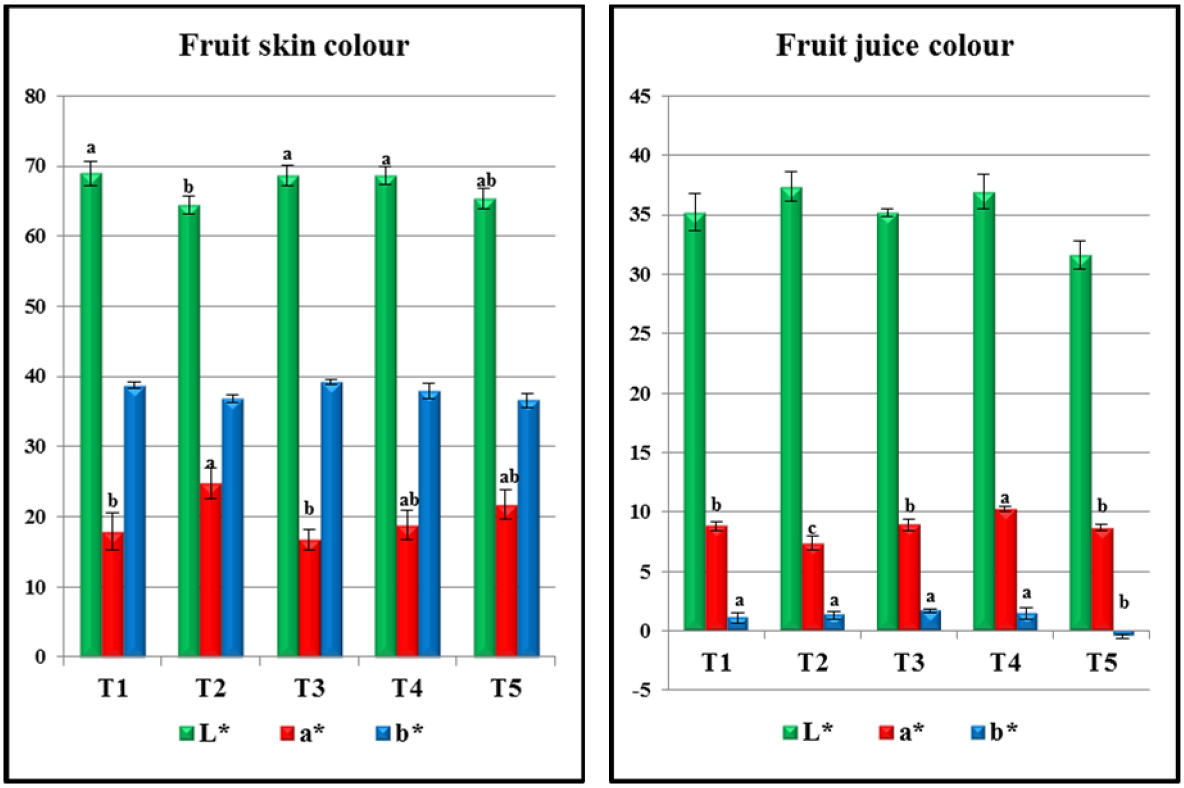

Figure 25: Skin and Juice colour (CIELab parameters) of pomegranate fruits at harvest as effect of different irrigation treatments. Error bars represent the standard error.

6. Water use efficiency and productivity

Water saving obtained by SDI treatment was around 44% compared to the control trees (Table 12), While RDI_2 recorded the highest water saving between the different RDI treatments, about 25% (water stress was applied during the period of higher irrigation requirements due to the high evaporative demand), followed by RDI_3 with water saving about 15% and the lowest water saving (7%) compared to the control treatment by RDI_1 (Table 12).

However, all deficit irrigation treatments resulted in increasing water use efficiency. SDI trees had the best WUE (6.9 kg/m^3), followed by RDI_2 (5.6 kg/m^3) and RDI_3 (5 kg/m^3) with respect to the control treatment (4.5 kg/m^3) as shown in Table 12. There were no significant differences between RDI_1 and control trees in water use efficiency.

As a consequence, water productivity was higher in the SDI treatment about 28.8% more than in control trees. Also RDI_2 increased water productivity with 17.6% compared to control trees (Table 12). There were no significant differences between the other RDI treatments and control trees in water productivity.

Table 12. Effects of irrigation treatments on water use efficiency and productivity.

Treatments	Water amount (m^3/tree and season)	WUE (Kg/m^3)	Water productivity (€/m^3)
Control	$12.18^{a} \pm 0.30$	$4.54^{d} \pm 0.2$	$2.94^{cd} \pm 0.09$
SDI	$06.83^{e} \pm 0.01$	$6.88^{a} \pm 0.2$	$4.13^{a} \pm 0.18$
RDI_1	$11.33^{b} \pm 0.10$	$4.37^{d} \pm 0.1$	$2.79^{d} \pm 0.10$
RDI_2	$09.09^{d} \pm 0.06$	$5.58^{b} \pm 0.4$	$3.57^{b} \pm 0.28$
RDI_3	$10.33^{c} \pm 0.30$	$5.00^{c} \pm 0.1$	$3.28^{bc} \pm 0.12$

Discussion

The obtained results support the general idea about the ability of pomegranate trees to handle with water stress. In this concept, it is remarkable that pomegranate trees under different deficit irrigation treatments could maintain yield level with better fruit quality and enhancing water use efficiency and water productivity compared to control trees.

The present results show that Ψ_{stem} measurements can be used for scheduling successful irrigation programs, since Ψ_{stem} allows predicting the optimum water status of pomegranate trees. Recently, using Ψ_{stem} (Shackel *et al*., 1997) has been adopted as a water stress indicator (McCutchan and Shackel, 1992) and its predictive potential of response to deficit irrigation (Naor, 2000). In fruit trees Ψ_{stem} has been used to adjust the irrigation regime, to avoid reaching to severe water stress (Lampinen *et al*., 2001). However, it has been stated that in drought tolerant species, midday plant water status might be similar in well watered and stressed plants if water stress resulted in clear reduction of stomatal and vegetative growth (Tardieu and Simonneau, 1998). The SDI trees maintained during the season the lowest Ψ_{stem} values, reaching a minimum value of -1.94 MPa. In general, the RDI trees had lower plant water status than the control; the differences were clear in the middle of the deficit irrigation cycle (Fig. 24). With RDI treatments, when water returned to full usage, plants recovered quickly their optimum water status, the same results were found by Mellisho *et al*. (2012) and Intrigliolo *et al*., (2013). The obtained results indicate that pomegranate trees can regulate their water status showing a sort of isohydric behaviour (Tardieu and Simonneau, 1998) which is a drought mechanism characterized with strong stomatal control of transpiration rate which prevents Ψ_{stem} from dropping below a critical threshold under water stress conditions (Tyree and Sperry, 1989; Franks *et al*., 2007). In any case, still clear differences in Ψ_{stem} among the tested irrigation regimes could be observed.

SDI had negative effects of on vegetative growth with a decrease of 22.7% in canopy volume than control trees; while the results of the other treatments indicate that RDI strategies did not affect the vegetative growth rate (Table 8), Intrigliolo *et al*., (2013) found the same effects of different deficit irrigation on pomegranate trees. Other authors (Abo-Taleb et al., 1998, Abou El-Wafa, 2002, Ibrahim and Abd El-Samad, 2009, Khattab *et al*., 2011) observed that water stress led to decrease in vegetative growth represented in shoot length, number of leaves per shoot and leaf area of pomegranate transplants or adult trees. Vegetative growth reduction under water stress conditions could be due to lower photosynthetic rate and stomatal conductance (Mpelasoka *et al*., 2001a). It is clear that the SDI irrigation regime led to a shift in the carbon allocation patterns, favoring reproductive growth over vegetative tree growth increasing plant productivity in case of water scarcity through applying of deficit irrigation strategies (Intrigliolo *et al*., 2013).

The effect of deficit irrigation on flowering was clear in SDI treatment as sex ratio increased by 26% and decreased H flowers drop about 19% resulted in high value of fruit set with 13% more than control trees (Table 9) and increased number of fruit collected per tree (18% more than control trees). This effect might be a consequence of a reduction in vegetative growth resulted in lower competition between vegetative growth and reproductive organs. Water stress during flowering and fruit set (RDI_1) did not affect sex ratio but increased H flowers drop by 10.4% and decreased fruit set about 9.7% compared to control trees, but Intrigliolo *et al*., (2013) found in one season of the experiment that applying mild water stress during flowering and fruit set decreased reproductive organs drop resulted in increasing number of collected fruits at harvest. Khattab *et al*., (2011) observed that decreasing irrigation water lead to reduce fruit set % and increase Fruit drop % of pomegranate trees. Similarly in Citrus trees, water stress during flowering and fruit set decreases tree crop level (González-Altozano and Castel 1999). In other fruit trees, water stress also modifies tree bearing habits and reproductive organs drop (Ruiz Sánchez *et al*. 2010). Flowering and fruit set stages in some stone fruit species are not consider as a critical period for water stress. In apricot, Pérez-Pastor *et al*. (2009) and Pérez-Sarmiento *et al*. (2010) developed RDI strategies (reductions in water irrigation of 25–40%) without affecting yield. In peach trees, Girona *et al*. (2003) found that the deficit irrigation applied during the hardening stage increase fruit loads at harvest due to reduction in fruit drop. In loquat species, an RDI treatment during the flower induction and flower initiation resulted in notable water saving without affecting yield and advancing full bloom 10–20 days leading to more valuable yield with precocity harvest (Hueso and Cuevas 2008).

SDI trees had higher number of collected fruits per tree about 18% more than the control (Table 10); the increase in crop level obtained by SDI treatment could have been due to high fruit set % and a reduction in reproductive organs drop (Table 9). The SDI trees were irrigated at 50% of ETc from the beginning of the season; it seems that they adapted to early season water stress and affected fruit drop. However, SDI trees recorded lower yield weight (Kg/tree) about 15% less than control trees (Table 10) due to reduce fruit weight of 30% less than control trees (Table 11-I) , which could result in lower yield value as the larger fruit diameter grades have higher commercial value in fresh markets. RDI_1 trees with water stress applied during flowering and fruit set stage decreased number of collected fruits due to increase of H flowers drop by 10.4% more than control trees (Table 9), while RDI_2 and RDI_3 did not affect tree crop level as water restrictions were basically applied when physiological drop finished. The reduction in yield of SDI and RDI_1 trees resulted in decreasing yield value compared to control trees by 21% and 11%, respectively. The same effects of SDI treatment on yield of pomegranate trees were observed by Intrigliolo *et al*., (2013).

Fruit cracking and Sun-burn are the major disorders fruit for pomegranate trees. SDI was the only treatment that increased significantly number of cracked and sunburned fruits resulted in decreasing of the commercial fruit % and yield value (Table 10). Beside changes in plant-water relations, SDI treatment reduced the tree canopy volume, so the pomegranate fruits exposed directly to sunlight without the protection of vegetative growth caused an increasing the percentage of sun-burned fruits. Exposure to direct sunlight lead to an irregular growth in the part of fruit cortex causing imbalance in the internal pressure, in addition, SDI treatment reduced the cortex thickness with 17.5% less the control (Table 11-I) resulted in decreasing cortex resistance to internal pressure causing fruits cracking (Prasad *et al*., 2003).

Deficit irrigation during fruit growth (RDI_2) and fruit ripening (RDI_3) had a clear effect on juice content of pomegranate fruits, juice percentage was significantly increased by 15.8% and 25.3%, respectively with respect to control trees (Table 11-II). In contrast, Laribi *et al*., (2013) found that deficit irrigation had no effects on juice content of pomegranate fruits, while Khattab *et al*., (2011) observed that juice % is directly proportional to the amount of irrigation water. Pomegranate fruits subjected to SDI and RDI_3 water restrictions had the highest TSS values (Table 11-II). The differences in TSS were important as 1°Brix is considered a meaningful increment in the perception of fruit flavour (Scandella *et al*., 1997). Previous studies supported these results as observed an increase in the soluble solids concentration in apple and peach fruits in response to deficit irrigation (Proebsting *et al*., 1984; Irving and Drost, 1987; Li *et al*., 1989; Ebel *et al*., 1993; Crisosto *et al*., 1994; Mpelasoka *et al*., 2001b; Marsal *et al*., 2012). It is important to highlight that during water stress most fruits act as strong sinks of photosynthates (Cohen and Goell, 1984; Caspari *et al*., 1994; Mills *et al*., 1996). Water stress improved starch conversion to sugar (Kramer, 1983) and could have caused high sugars accumulation in the fruit as a result of deficit irrigation (Laribi *et al*., 2013). The effect of deficit irrigation on TA is less clear as no differences between deficit irrigation treatments and control. Laribi *et al*., (2013) found that SDI and RDI (water stress during ripening) increased TA of pomegranate fruits. Other studies investigated irrigation effects on fruit composition at harvest have presented a reduction of TA in response to deficit irrigation (Drake *et al*., 1981; Proebsting *et al*., 1984), others have found no effect (Irving and Drost, 1987; Kilili *et al*., 1996; Papenfuss and Black, 2010; Intrigliolo and Castel, 2011; Marsal *et al*., 2012).

It is important to highlight that fruit external (peel) and internal (juice) colour were differently affected by deficit irrigation. Fruit skin colouration was increased by SDI and RDI_3 treatments, SDI resulted in redder and darker fruit at harvest, while RDI_2 treatment affected juice colour by increasing positive a* values which responsible for red colour degree (Fig. 25). Laribi *et al*., (2013) found the same results and explained that RDI with water stress during ripening induced the highest amount of juice anthocyanins, so it seems that the timing of water stress determined anthocyanin accumulation in skin and aril tissues. SDI and RDI_3 treatments had the highest TSS values (Table 11-II), which could explain the increase in red colouration as sugars are known to have an important role in anthocyanin synthesis (Saure, 1990), and skin colouration in pomegranates is indeed dependent on the level of anthocyanins (Du *et al*., 1975). In addition, SDI trees had reduced vegetative growth (Intrigliolo et al., 2013); this effect might improve fruit exposure to sun-light resulting in better fruit red colour appearance as mentioned in other studies in peach trees (Li *et al*., 1989; Gelly *et al*., 2003). Mellisho *et al*. (2012) also found that in "Mollar de Elche" pomegranates, moderate deficit irrigation applied during fruit growth and ripening increased peel luminosity and red saturation. Dixon (1993) found a negative correlation between lightness and pigment content; pigments level is increased as result of absorption more light with lower values of luminosity are recorded. In 'Mollar de Elche' pomegranates, six different anthocyanins have been determined as responsible for pomegranate juice colour (Du *et al*., 1975). Application of RDI during fruit growth phase increased the total anthocyanin content (Laribi *et al*., 2013).

Water deficits increased significantly expression of some genes responsible for anthocyanin synthesis (Deluc *et al*., 2009). Harvesting of "Mollar de Elche" pomegranate fruits is based on fruit skin colouration, increase in red skin colour will allow precocity harvest, which affect the yield value since the first fruit reaching the market have in general higher commercial prices. SDI and RDI_3 can be used as tools to accelerate fruit ripening due to earlier maturity colour and sugar accumulation (Laribi *et al*., 2013).

Water saving obtained by SDI treatment was around 44% resulting in an increase of WUE of 34% and water productivity increase of 28.8% more than control trees (Table 12) indicating that irrigation water was used more efficiently. However, growers are more concerned about irrigation strategy effects on the commercial yield value and SDI treatment led to an important reduction in the yield value. It was calculated that SDI regime could become as economically profitable as the control regime if water prices are higher than 1.6 €/m^3. RDI_2 recorded the highest water saving between the different RDI treatments (25%), since water stress was applied during the period of high water requirements due to a higher evaporative demand, led to an increase of WUE with 19.6% and water productivity with 17.6% more than control trees (Table 12), indicated that irrigation water was used more efficiently. Intrigliolo *et al*., (2013) found the same effects of SDI and RDI (water stress during fruit growth) treatments on water use efficiency and productivity.

Conclusion

Deficit irrigation should be applied in commercial orchard as a practice to maintain yield and enhance fruit quality, Ψ_{stem} measurements can be used for scheduling successful irrigation programs, since Ψ_{stem} allows predicting the optimum water status of pomegranate trees. Pomegranate trees can be irrigated at around 50% of the water requirements during the entire growing season resulting in important water saving and increasing WUE and water productivity. However, due to the negative impact on the yield value for fresh fruit markets, the SDI strategy can be recommended if prices for irrigation (water + energy) are high and for juice industry purpose where fresh fruit weight is not important as determining factor of yield value. Regulated deficit irrigation (RDI) appears to be a promising technique to save water while maintaining or even enhancing production of marketable product, successful RDI depends on inducing stress during periods of slow vegetative and reproductive growth. RDI treatments also led to increase WUE and water productivity with maintaining the yield value at similar levels to the control with no effects on average fresh fruit weight. RDI_2 treatment (water stress applied during fruit growth) resulted in water saving (25%), increasing juice % and improving juice colouration. RDI_3 treatment (water stress applied during fruit ripening) improved fruit commercial quality represented in increasing fruit skin colouration, juice % and TSS content. It is concluded that deficit irrigation can be used according to the desired goals (control harvest precocity (fruit ripening) and improve pomegranate fruit quality) and water availability (as a method to handle with water scarcity and high water prices) depending on the phenological stage when water stress is applied.

In order to face challenges of global water scarcity problem, research strategies needs to be reoriented. More work is needed to design irrigation programs aimed to decrease irrigation water consumed by crops without affecting yield and fruit quality. In case of pomegranate, it is known as drought tolerant plant, so it is important to investigate the mechanisms that pomegranate trees followed to handle with water stress. More researches must be done to know the impact of irrigation regimes on regulation of pomegranate trees flowering stage (flower induction, initiation and development), sex ratio and fruit set %.

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