

# **Past and Present Irrigation Strategies in Mango**

## **A Review of Literature and Identification of Future Research Needs**

PRESENTED BY  
DR. A.G. LEVIN\*  
FOR  
THE NATIONAL MANGO BOARD

\*Northern R&D-, Migal, Galilee Technology Center, P.O.Box 831, Kiryat' Shmona  
11016, Israel.

([adolfolevin@gmail.com](mailto:adolfolevin@gmail.com))

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## EXECUTIVE SUMMARY

Mangoes are produced in over 90 countries worldwide. Between 1996 and 2005, production grew at an average annual rate of 2.6%. The ten leading mango producers during the years 2003 – 2005 include Mexico (5.5%) in fourth place and Brazil (4.3%) in seventh place. In terms of distribution, Mexico, Brazil, Peru, Ecuador, Haiti and Guatemala supply the majority of mango imports to the North American market.

The most popular mango cultivars exported to the USA are Kent, Tommy Atkins, Haden, and Keitt, which have fruit with a red blush, and are less fibrous, firmer, and more suited for long-distance transportation than other cultivars. In recent years, cv. Ataulfo has been gaining popularity in the USA market, mainly within the Latin American population. Increasing production, focused on quantity and quality, as well as reducing alternate bearing, will promote a more stable marketing supply chain, ensuring higher quality products and better returns for mango producers in the main countries exporting mango to the USA.

The author has attempted to present key results from the main scientific studies conducted on mango worldwide in general and in Latin America in particular. This information should be useful to those planning to conduct research and extension activities in this field and/or in need of information on water requirements for mango production in countries exporting mango to the USA.

Studies on water usage and irrigation strategies evaluated in mango covered a number of important regions worldwide. However, the number of studies carried out on water and fertilizer requirements for mango under prevalent growing conditions in Latin American producing countries is quite limited.

The amount of fresh water available for agricultural use is decreasing worldwide. Climate change suggests a future increase in aridity and in the frequency of extreme events, such as lower rainfall, longer drought periods and higher temperatures, in many regions of the world. In addition, global climate change introduces uncertainty about the spatiotemporal distribution of precipitation. This scenario leads to an increasing demand for irrigation water and may cause many serious socioeconomic problems, reducing crop yield, limiting the sustainability of irrigated crops, and increasing the

cost of irrigation water. Therefore, the adoption of water saving strategies for agricultural purposes is becoming increasingly critical.

Mango exhibits some adaptive features, such as deep tap/sinker roots, long-lived, tough leaves with thick cuticles and resin ducts to reduce wilting that confer tolerance to drought. Which is why, this crop is considered to be drought resistant. These adaptive mechanisms increase its ability to survive drought seasons, while irrigation is required throughout the entire dry growing season to ensure commercial production.

A deficit irrigation strategy can be implemented in various ways, differing mainly in the irrigation rate distribution throughout the season. Particularly, sustained deficit irrigation (SDI) is based on a uniform water restriction, depending on the crop-water requirements, that can be applied at less susceptible phenological periods during the current production cycle. Regulated deficit irrigation (RDI) requires the water status to be maintained within a narrow tolerance range. Crop response to RDI depends on the timing and severity of the water deficits, with significant differences among species.

The irrigation requirements of mango have not been adequately investigated, and very few studies have been conducted on RDI strategies at different phenological stages. These studies have focused mainly on developing irrigation strategies for the entire fruiting period, rather than evaluating different water strategies at different phenological periods. Early reports in the previous century already showed the importance of irrigation for mango. The most recent studies regarding irrigation in mango focused mainly on developing different irrigation strategies to save water and increase water use efficiency, rather than maximizing crop production.

The nutrient demands of mango, expressed as the accumulated amounts of the elements found in different plant organs, vary according to factors such as genotype, soil, climate, presence of irrigation, water quality, plant health, phenological stage and expected crop load. The importance of fertilizing mango for commercial production has been emphasized by several authors, however, there are no clear recommendations in the scientific literature for a fertilizer strategy for mango under any growing conditions (climate, physical and chemical characteristics of the crop, production load, pests and diseases, etc).

The main objectives of this review were:

1. To evaluate the literature related to past and present outcomes of the different irrigation strategies which have been applied in mango cultivation and their impact on fruit quantity and quality in the short, medium and long terms and on the alternate bearing production of the trees.
2. To identify future research needs for improving fruit quantity and quality production, reduce alternate bearing and significantly improve water use efficiency for the main cultivars imported by the USA.

According to the evaluated literature, the influence of different irrigation strategies on productive parameters such as fruit weight, fruit number per tree, yield, vegetative growth and alternate bearing can be summarized as follows:

***Fruit weight:***

The impact of irrigation on fruit weight appears to be more dramatic in the final fruit growth (FFG) (cell expansion) phenological period rather than during the main fruit growth (MFG) (cell division) period.

***Fruit number:***

In general, irrigation at fruit set stage and during the MFG period has been reported to promote higher numbers of fruit at harvest.

***Vegetative growth and Yield:***

Yield in mango is better correlated with the number of fruits than fruit weight. As mangoes are a perennial crop, the carry-over effects of management practices from one season to another are important in the medium and longer term and they will have an impact on production, especially since the mango crop is produced mainly on the vegetative growth of the previous year (or season).

Deficit irrigation practices have reduced vegetative growth in several tree crops including mango. Contradictory reports can be found in the scientific literature regarding the impact of different irrigation strategies on yield. While some reports indicated a positive impact of deficit irrigation strategies on yield and consequently on water use efficiency (WUE), others found a negative impact of these strategies on yield, but not necessary on WUE.

### ***Alternate bearing***

Alternate bearing (also called biennial or uneven bearing) is the tendency of a fruit tree to produce a heavy crop (on-crop year) followed by a light crop or no crop (off-crop year). Alternate bearing can be a major problem in mango production, especially in subtropical regions. A number of studies demonstrated that yield in mango trees is affected by the irrigation regime. However, there are few, if any, long-term studies (five or more seasons) that have evaluated the impact of different irrigation regimes on alternate bearing in mango.

Although a significant number of studies have been conducted on mango regarding crop water requirements and water saving strategies, there is no clear consensus among researchers on the topic. With regards to the crop, the wide range of climatic and soil conditions under which mango is grown, for example, hinders efforts to develop an irrigation protocol that could be widely applicable. In addition, the vast number of different mango cultivars around the world, with great variation in genetic characteristics and consequent responses to environmental conditions and agricultural practices, make this task even more difficult.

## A. INTRODUCTION

Mangoes are produced in over 90 countries worldwide. Asia accounts for approximately 77% of global mango production, while the Americas and Africa account for approximately 13% and 9%, respectively (FAOSTAT, 2007). In 2005, world production of mango was estimated at 28.51 million metric tons. Between 1996 and 2005, production grew at an average annual rate of 2.6% (Evans, 2008). The ten leading mango producers during the years 2003 – 2005 include Mexico (5.5%) in fourth place and Brazil (4.3%) in seventh place (FAOSTAT, 2007). In terms of distribution, Mexico, Brazil, Peru, Ecuador, Haiti and Guatemala (Galán Saúco, 2004) supply the majority of mango imports to the North American market.

The most popular mango cultivars exported to the USA are Kent, Tommy Atkins, Haden, and Keitt, which have fruit with a red blush, and are less fibrous, firmer, and more suited for long-distance transportation than other types of cultivars (Galán Saúco, 2004). In recent years, cv. Ataulfo has been gaining popularity in the USA market, mainly, within the Latin American population (Dr. Leonardo Ortega, NMB, personal communication).

Although most of the commercially-traded mango cultivars have been developed in Florida, the USA is not a major mango producer. USA mango production remains fairly stable at just under 3,000 metric tons per year. However, the USA is the world's leading importer of fresh mangoes, accounting for 32.7% of total imports during the years 2003 – 2005 (FAOSTAT, 2007). During the last five years, Brazil, Peru, and Ecuador have become significant exporters to the USA, competing with Mexico at the beginning and end of the season.

In general, average mango production per hectare in the main Latin American countries which export to the USA does not exceed 12 t ha<sup>-1</sup>, except for Brazil, (personal observation). Increasing production with respect to quantity and quality, as well as reducing alternate bearing, will promote a more stable marketing supply chain, ensuring higher quality products and better returns for mango producers in the main countries that export mango to the USA. Better quality and a more stable supply chain mean better conditions for the American consumer with wider consumption options. Both factors can significantly increase mango consumption in North America. A comprehensive literature review to identify the main areas for future research that could

assist in the development of adequate irrigation strategies in the USA supplier countries, according to the needs of the producers and their limiting factors (ie. limited water resources, water quality, soil type, etc....) in order to deliver higher quality products in a sustainable way to consumers have been carried out.

The author has attempted to present the key results of the main scientific studies conducted on mango worldwide, in general, and in Latin America, in particular. This information should be useful to those planning to conduct research and extension activities in this field and/or in need of information on water requirements for mango production in countries that export mango to the USA. Studies on mango water use and irrigation have examined a number of important issues worldwide, including (but not confined to):

- Determining pre-harvest irrigation cessation and season-long reduced volume applications on fruit quality;
- Effects of irrigation at different phenological periods, including prior to flowering, and the effects of pre-flowering irrigation on trees receiving flowering-promoting treatments;
- The effect of age, season and cultivar on water use as determined by sapflow methods;
- Effects of different irrigation schedules on the efficiency of irrigation water use;
- Effects of irrigation practices among growers.

In contrast, the number of studies conducted on water and fertilizer requirements of mango under local growing conditions in Latin American countries is quite limited.



## **B. BACKGROUND**

The amount of fresh water available for agricultural use is decreasing worldwide (Jury and Vaux, 2005). Climate change research suggests a future increase in aridity and in the frequency of extreme events, such as lower rainfall, longer drought periods and higher temperatures, in many regions of the world (IPCC, 2001). In addition, global climate change introduces uncertainty about the spatiotemporal distribution of precipitation (Durán Zuazo et al. 2011a). This scenario leads to an increasing demand for irrigation water and may cause many serious socioeconomic problems, reducing crop yield, limiting the sustainability of irrigated crops, and increasing the cost of irrigation water. Therefore, the adoption of water saving strategies by agriculture is becoming increasingly critical, especially for fruit trees that require a certain amount of irrigation for survival and where growers do not have the option to skip a season when a water shortage is expected, in contrast to annual crops. This situation has stimulated the development and application of different water-saving irrigation strategies and technologies (such as regulated deficit irrigation or subsurface drip irrigation) in order to save water and increase water use efficiency (WUE) in crops under semiarid conditions (Romero et al. 2004a, b,c).

Mango is considered a drought-resistant crop and exhibits some adaptive features that confer drought tolerance, such as deep tap/sinker roots, long-lived, tough leaves with thick cuticles and resin ducts to reduce wilting (Bally, 2006). These adaptive mechanisms increase its ability to survive drought seasons, while irrigation is required throughout the entire dry growing season to ensure commercial production.

A deficit irrigation strategy can be implemented in various ways, differing mainly in the irrigation rate distribution throughout the season. Sustained deficit irrigation (SDI) is based on a uniform water restriction, depending on the crop-water requirements, that can be applied at less susceptible phenological periods within the production cycle. This approach allows the crop to adapt to the stressful situation.

In recent years, it has become clear that maintenance of a slight plant water deficit can improve the partitioning of carbohydrates of reproductive structures such as fruits and control excessive vegetative growth (Chalmers et al. 1981), giving rise to what has been termed by Chalmers et al. (1986) as ‘regulated deficit irrigation’ (RDI). Successful RDI requires the water status to be maintained within a narrow tolerance range in order to

obtain maximum benefit from RDI on one hand and to avoid excessive water stress that will result in decreased crop production and/or quality on the other hand. Crop response to RDI depends on the timing and severity of the water deficits, with significant differences among species (Feres and Soriano, 2007). Most studies have shown that mild water stress applied during the period of slow fruit growth could control excessive vegetative growth while maintaining or even increasing crop yield. These included studies on peach (*Prunus persica*) (Li et al. 1989; Williamson and Coston, 1990), European pear (*Pyrus communis*) (Mitchell et al. 1984; Brun et al. 1985a, 1985b; Chalmers et al. 1986; Mitchell et al. 1986, 1989), Asian pear (*Pyrus serotina*) (Caspari et al. 1994) and apple (*Malus domestica*) (Irving and Drost, 1987). In addition, water stress applied after harvest has been shown to reduce vegetative growth of early-maturing peach trees and nectarine (Larson et al. 1988; Johnson et al. 1992; Naor et al, 2005). Conversely, in citrus, it has been demonstrated that even moderate water stress applied during phase I (i.e., flowering and fruit set) normally compromises yield by increasing June fruit drop (Doorenbos and Kassam, 1979; Ginestar and Castel, 1996; Romero et al. 2006; García-Tejero et al. 2010), while water restrictions applied during the last phase of fruit growth and ripening might decrease yield by reducing the final fruit weight (González-Altozano and Castel, 1999; Pérez-Pérez et al. 2009; García-Tejero et al. 2010).

Tree crop level was found to affect tree water status in deciduous fruit trees (Naor, 2006) and olives (Naor et al. 2013). Fruit-bearing trees have higher stomatal conductance than non-fruiting trees (Hansen, 1971; Loveys and Kriedemann, 1974; Lenz, 1986; Downton et al. 1987). In nectarine, Naor et al. (2001) reported stem water potentials to decrease with increasing crop load, but other studies on apple found that crop load did not affect leaf water potential (Erf and Proctor, 1987).

Irrigation requirements of mango have still not been adequately investigated (Spreer et al. 2007), and very few studies have been conducted on RDI strategies. These studies have focused mainly on developing irrigation strategies for the entire fruiting period, rather than evaluating different water strategies at different phenological periods. One of the main reasons for the relatively small number of studies that have been conducted on this issue in mango compared to other fruit trees is probably the fact that most of the mango growing regions around the world are in tropical climates where the need for irrigation is lower and/or mainly supportive and restricted to the dry season.

Early reports in the previous century already showed the importance of irrigation for mango. Marloth (1947) observed a reduction in the current season's vegetative growth, on which the following season's crop is borne, due to water stress. Similarly, Yan and Chen (1980) found that vegetative growth and photosynthesis of potted mango trees decreased when soil moisture content dropped below 40%. Conversely, panicle development, fruit set, and fruit growth of mango increase with adequate soil moisture (Valmayor, 1962; Beutel, 1964; Young and Sauls, 1981). In Egypt, Azzouz and El-Nokrashy and Dahshan (1977) reported that mango fruit number and fruit size increased with increasing irrigation frequency. More recent studies report similar trends. Schaffer et al. (1994) observed that fruit drop from water-stressed trees was much greater than non-stressed trees. Tahir et al. (2003) reported that drought stress causes a great reduction in the emergence of new vegetative flushes in mango cv. Langra during the stress period. Number of leaves per flush, flush length and weight, leaf water content and root growth were also reduced due to drought stress.

The most recent studies regarding irrigation in mango focused mainly on developing different irrigation strategies to save water and increase WUE rather than maximizing crop production. de Acevedo et al. (2003) proposed a progressive crop coefficient ( $k_c$ ) ranging from 0.4 (flowering) to 0.8 (fruit growth) for calculating water crop requirement. In a four-year-old orchard of mango cultivar Kent, in South Africa, Pavel and Villiers (2004) observed a saving of 37 – 52% in water use under RDI treatments compared with the control, with a non-significant difference in productivity. Spreer et al. (2007) reported that by applying partial root zone drying (PRD) under production conditions in northern Thailand it is possible to substantially increase WUE in mango cultivar Chok Anan, compared to stress-avoidance irrigation, and at the same time significantly increase average fruit size. Durán Zuazo et al. (2011a) evaluated the impact of SDI on tree growth, mineral nutrition, fruit yield and quality of mango in Spain, over three years. The experimental treatments were SDI-1 (33% ET<sub>c</sub>), SDI-2 (50% ET<sub>c</sub>) and SDI-3 (75% ET<sub>c</sub>) and were compared with a control (C-100) irrigated at 100% ET<sub>c</sub>. The SDI-2 treatment resulted in the highest yield (18.4 t·ha<sup>-1</sup>) and the best WUE (7.14 kg·m<sup>-3</sup>). However, fruit were significantly larger (longer and wider) in SDI-3 and the control.

Mostert and Hoffman (1997), in their study, concluded that the water requirement for mature mango trees under optimal irrigation in South African growing conditions was

11,976 m<sup>3</sup> ha<sup>-1</sup>yr<sup>-1</sup>. Similar results (between 10,500 and 11,500 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>) were reported by Levin et al. (2015 b) for mature mango trees cv. Keith under optimal irrigation in the semi-arid region of Israel.

Pictures "a" and "b" showed mango trees irrigated by gravity/furrow irrigation, pictures "c", "d" and "e" mango trees irrigated by drip irrigation.

### **C. OBJECTIVES:**

1. To review the literature on past and present outcomes of the different irrigation strategies which have been applied in mango cultivation and their impact on fruit quantity and quality in the short, medium and long terms and on the alternate bearing production of the trees.
2. To identify future research needs to improve fruit quantity and quality production, reduce alternate bearing and significantly improve WUE for the main cultivars exported to the USA.

### **D. METHODOLOGY:**

In the first step I collected and reviewed all the available information about past and present irrigation strategies evaluated in mango, focusing mainly on the main export cultivars and countries exporting to the USA market. Second, I recommended past and/or new irrigation strategies which can be relevant for evaluation in some of the main exporting countries. In addition, I suggest potential partners in the relevant countries for evaluating such strategies, a step which is critical to the success of the project. Third, I prepared my report to the NMB.

### **E. MANGO IRRIGATION RESEARCH AROUND THE WORLD**

#### ***1. Main irrigation strategies evaluated in Mango and their impact on vegetative/fruit development, yield and quality around the world***

In the past 20 years, a number of strategies have been developed to improve the Water Use Efficiency (WUE) in agriculture in general (Anon 2002; Oster and Wichelns, 2003; Costa et al. 2007; Geerts and Raes, 2009) and in mango in particular (Spreer et al. 2007, da Silva et al. 2009; Spreer et al. 2009 a,b; Durán-Zuazo, et al. 2011, Levin, et al. 2015). One strategy is ‘deficit’ irrigation (DI). This is described as irrigation administered at

rates that are below the required water amount necessary for evapotranspiration (Costa et al. 2007; Geerts and Raes, 2009). The DI approach can be achieved by two different methods: 1. by applying water at a constant deficit throughout the dry season, or on a supplemental basis if irrigation occurs for a short period only, for example, during the rainy season. This method is defined as ‘Sustained Deficit Irrigation’ (SDI) and has been used in mango studies, e.g. replacing 70%, 80% or 90% evapotranspiration (ET<sub>o</sub>) throughout the irrigation season for crop coefficients of 0.75 or 0.8 (da Silva et al. 2009; Spreer et al. 2009 a, b). 2. by varying the degree of DI according to critical phenology. This is described as ‘Regulated Deficit Irrigation’ (RDI) (Costa et al. 2007) or as ‘drought stress differentiated by phenological stage’ (Geerts and Raes, 2009). An example is where different replacement volumes of crop factors are used for different phenological intervals. For example, in almonds, RDI was applied at 50% of ET<sub>o</sub> during the kernel-filling stage but 100% ET<sub>o</sub> throughout the remaining periods (Egea et al. 2009). Alternatively, different factors or coefficients can be used for different periods. This latter method, although identified as appropriate for mango trees (de Azevedo et al. 2003), has not been well investigated. This strategy requires comprehensive knowledge of the water requirements at each phenological stage (Goodwin and Boland, 2002; Costa et al. 2007). In comparison, SDI is easier to implement and requires less information, but is not tailored to the crop’s changing requirements through time. Another application method is that of ‘Partial Rootzone Drying’ (PRD) which splits water applications from one side of the tree to the other, with alternate drying of rootzones being the underlying principle. The volumes of application or scheduling are usually applied on a deficit-irrigation basis. This method has received widespread attention, for example, in grapes, in Spain (De la Hera et al. 2007), Australia (Dry et al. 1996; Dry and Loveys, 1998) and China (Du, et al. 2008) and in other high-value horticultural crops (Costa et al. 2007). However, a recent meta-analysis comparing RDI and PRD from a large number of studies for horticultural crops indicated that PRD resulted in only small increases in yield (average ~5%), when compared with RDI (Sadras, 2009). Also, while RDI uses existing irrigation systems, PRD requires a specialized configuration of irrigation lines and probably higher capital investment in irrigation hardware. The small difference in yield between RDI and PRD irrigation treatments may not support the additional investment required for PRD (Sadras, 2009). A comparison of RDI and PRD in mango production demonstrated no

clear advantage (Spreer et al. 2007). There is a need to evaluate RDI strategies once seasonal water use or crop coefficients become available.

We will now consider the main studies carried out on mango using the three different irrigation approaches and their impact on the main crop production variables: yield, fruit number, fruit size and vegetative growth. Table 1 summarizes some of the main studies evaluating different irrigation strategies on mango worldwide, in general, and in Latin America, in particular, and the suggested best treatment according to the results.

## ***2. Regulated Deficit Irrigation (RDI), Partial Rootzone Drying" (PRD) and Sustained Deficit Irrigation (SDI).***

Increased WUE in mango through DI has been reported by Pavel and de Villiers (2004) and Spreer et al. (2006) among others. PRD is thought to reduce plants' water consumption by enhancing abscisic acid (ABA) in the water stressed half of the roots, a hormonal signal controlling the stomatal aperture, hence reducing transpiration of the leaves (Davies et al. 2000, 2002). Hereby, the well-watered half of the root system ensures the maintenance of fruit growth, while vegetative growth is reduced (Dry et al. 1995, 2000). Conversely, dos Santos et al. (2003), Gu et al. (2004) and Pudney and McCartney (2004) reported that RDI, meaning evenly-distributed water stress to the whole root system, could achieve the same beneficial effect on water consumption.

## ***3. Mango response to RDI, PRD and SDI at different phenological stages:***

In order to evaluate the effect of different irrigation strategies on different tree parameters, a clear definition of the phenological period during which the treatments were applied is crucial. Phenological stages of mango have been proposed by Cull (1991). However, for irrigation purposes the following phenological stages can be considered:

- a.*** Post-harvest vegetative growth
- b.*** Flowering
- c.*** Fruit set
- d.*** Main Fruit Growth period (MFG-fruit set to pit hardening)
- e.*** Final Fruit Growth period (FFG-pit hardening to harvest)

Yield increase due to irrigation normally results from a higher crop load (number of fruit) rather than greater fruit size (Pavel and de Villiers, 2004; Spreer et al. 2009 b).

a. Post-harvest vegetative growth:

Vegetative growth in mango is never continuous, but exhibits periodic quiescence (Chacko, 1986). This cyclic growth pattern is usually called flushing, with each flush terminating when all new leaves are fully expanded (Whiley, 1993). One of the first reports on the impact of water quantities on vegetative growth in mango was done by Marloth (1947), who observed a reduction in the current season's vegetative growth, on which following season crop is borne, due to water stress. Yan and Chen (1980) found that vegetative growth and photosynthesis of potted mango trees were reduced when soil moisture content was below 40%. Tahir et al. (2003) reported a significant reduction of emergence of vegetative flushes by 46% in stressed trees compared to non-stressed trees. Similar results were reported by Levin et al. (2015 a, b) where post-harvest (PH) vegetative growth in mango cv. Keitt under Israeli growing conditions was significantly reduced when water application during the PH period was reduced by 50% compared to the standard farm water application (control), mainly after low production years. Also, reduced water application during the final fruit development (FFG) period had a significant impact on PH vegetative growth, mainly under high crop loads, even though all the trees received the same amount of water during PH (Levin et al. 2015b). Conversely, Larson et al. (1989) reported no difference in mean shoot growth in cv. Tommy Atkins under Florida growing conditions, among the three evaluated treatments (irrigation every 7, 14 days and no irrigation). Individual shoot growth varied greatly within treatments but was approximately 8.0 cm per shoot over the two-month period (Larson et al. 1989).

**a. 1. Response of Fruit Production and Vegetative Growth to different irrigation strategies during the Post-Harvest period (PH).**

I will preface this section by noting that the effects of irrigation treatments on crop yield attributes in the case of PH are expected in the subsequent season. The following results were reported by Levin et al. (2015a, b) in mango cv. Keitt irrigated with different water quantities at different phenological stages, in this case the PH period. Four treatments were evaluated during this period, from T-1, the least irrigated treatment, to T-4, the most irrigated treatment. The average irrigation values in the “On” seasons (Mango

trees producing heavy crop load) ranged from 2.8 mm in T-1 to 5.4 mm in T4; the actual Kc values ranged between 0.57 in T-1 to 1.09 in T-4; annual irrigation amounts ranged from 950 mm in T-1 to 1067 mm in T-4.

The crop yield in the experimental plot in 2010, before the beginning of the PH treatments was  $\sim 50 \text{ t ha}^{-1}$ . The number of fruits per tree in 2011 was slightly lower (8%, not significant) at T-1 than at T-4. Nevertheless, fruit weight at T-4 was significantly higher (30%;  $F = 5.8525$ ;  $P = 0.0068$ ) than at T-1. Consequently, the yield at T-4 increased significantly by almost 40% ( $F = 8.0784$ ;  $P = 0.0017$ ) compared to T-1 (62.8 and  $87.0 \text{ t ha}^{-1}$  for T-1 and T-4, respectively). It should be emphasized that during 2011 all treatments were subjected to the same irrigation regime from the beginning of the season to harvest.

There was a significant increase ( $F = 7.7947$ ;  $P = 0.0002$ ) in the number of new vegetative shoots with increasing irrigation in 2010. However, no significant difference in the length of the new flushes was observed among the treatments. In autumn 2011, after a highly productive year (around  $70 \text{ t ha}^{-1}$ ) no significant difference among the treatments was observed for either the number of new flushes or for their length. In autumn 2012, after a very light crop (around  $15 \text{ t ha}^{-1}$ ), a significant increase in the number ( $F = 13.0963$ ;  $P < 0.0001$ ) of new flushes and their length ( $F = 11.3649$ ;  $P < 0.0001$ ) was recorded with increasing irrigation (T-4 and T-3 significantly higher than T-2 and T-1). In autumn 2012, 2013 and 2014, the impact of the different irrigation levels during the second phenological period (pit hardening – harvest) on post-harvest vegetative growth was evaluated. In 2012, under low productivity conditions, a non-significant reduction in PH vegetative growth with increasing water quantities was recorded. However, in 2013 and 2014, under high crop production, there was a positive correlation between increasing water quantities during the FFG period and PH vegetative growth (significant in 2013). These results were achieved even though the amount of water applied during the PH period in these trees was the same for all treatments and T-4 had significantly higher crop production during these seasons compared to T-1.

Growers have practiced DI for decades. In the past, DI was restricted to the post-harvest period based on the belief that water stress does not cause problems during phenological stages when fruit are absent from the trees. However, the greatest impact of water stress



under Israeli growing conditions (sub-tropical) on mango tree performance was recorded during the post-harvest period. No reports on the impact of varying irrigation levels during the post-harvest period on tree performance have been found for mango under tropical or subtropical conditions. According to the above results, varying irrigation levels during the post-harvest period had a strong effect on autumnal vegetative growth in the following season. However, such an impact may interact with the current season's crop yield: the lower the crop yield, the stronger the influence of different irrigation levels on post-harvest vegetative growth. Among other factors strongly affecting autumnal vegetative growth are climatic conditions and harvesting time. Early harvest followed by a hotter and longer autumn season may allow the potential post-harvest vegetative growth to be achieved. According to the results of this study, the main impact of increasing irrigation levels during the PH period was to increase the number of new vegetative shoots. The increased production of new autumn vegetative shoots may influence yield in the following season; in this case the main effect was on fruit weight rather than fruit number. The amount of leaves or canopy per fruit was apparently higher at T-4 compared to T-1, indicating that carbohydrate availability may be higher in T-4 compared to T-1. These results are in agreement with previous studies (Chacko et al. 1982; Lechaudel et al. 2002; Reddy and Singh, 1991) that reported a positive association between fruit growth/size and number of leaves per fruit in mango cvs. Lirfa, Dashehari, Langra, Alphonso, Totapuri, Neelum and Kalapady.

#### **b. Flowering**

Flowering and fruit set are the most critical stages for determining the mango tree crop. In nature, mango trees may produce large numbers of flowers while only a small proportion set fruit. Understanding mango flowering in the tropics and subtropics is essential for efficient utilization of crop management systems such as irrigation and fertilization management, which may extend both the flowering and crop production seasons (Chacko, 1991; Whiley et al. 1991) and ensure a sustainable production system. Under sub-tropical conditions, temperatures of 15°C or below promotes mango flower induction (Lu and Chacko, 2000), while temperatures close to 20°C promote vegetative growth (Davenport and Nunez-Elisea, 1997). In the tropics where temperatures may remain too high for flower induction by cool nights, a dry period preceding flowering may be necessary to achieve a commercial crop (Chacko, 1986). Nevertheless, the

effect of plant water stress on flowering response is still a matter of controversy (Lu and Chacko, 2000).

Singh (1960) and Bally et al. (2000) reported floral morphogenesis initiation after mango cultivars were exposed to an extended period of mild water stress in the low-latitude tropics. However, according to Ramirez and Davenport (2010) water stress does not induce flowering. It is the age of the last flush impacted by the stress duration that drives flowering. Water stress prevents shoot initiation and maintains trees at rest until age accumulation in leaves takes place and trees flower due to the age-dependent reduction of the vegetative promoter (VP) (Ramirez and Davenport, 2010). The accumulating age of stems is greater in water-stressed trees than in trees maintained under well-watered conditions, which can flush more frequently (Davenport, 1993; Schaffer et al. 1994).

Mango tree responses to water stress during the pre-flowering period may be cultivar-dependent, mainly under tropical conditions. Lu and Chacko (2000) reported a different response of cvs. Nam Dok Mai, Irwin and Kensington Pride to water stress during the pre-flowering period. While cv. Nam Dok Mai did not need a strong floral stimulus such as that promoted by water stress, cv. Irwin appeared to have the strongest requirement of water stress for flowering, even more than cv. Kensington Pride.

Nuñez and Davenport (1994) reported on an experiment conducted in Homestead, Florida, to determine whether water stress induces floral morphogenesis in mango during July (mean minimum temperatures about 20°C, non-floral-inductive), and October and November (mean minimum temperatures about 15°C, floral-inductive) in cv. Tommy Atkins grown in containers. Water stress for 35 days during October advanced floral bud break by nearly 2 weeks in nearly 40% of the buds. In this experiment Nuñez and Davenport (1994a) conclude that low temperatures thus promoted floral induction of mango, whereas water stress promoted growth of florally-induced buds. Levin et al. (2015 a, b) reported that more severe water stress during the PH period, results in earlier flowering. Trees under deficit irrigation treatments (mainly T-1) flowered earlier than trees receiving T-3 or T-4 irrigation. However, the treatments did not affect flower intensity. These results are in agreement with those reported by Cuevas et al. (2008) for loquat (*Eriobotrya japonica* Lindl.), where deficit irrigation had a minor effect on flowering intensity. In contrast, water-stressed trees flowered

before controls (between 10 and 27 days, depending on treatment). However, no effect on flowering time was observed in the trees belonging to the second phenological period (pit hardening – harvest) due to different irrigation levels applied at that time of the season.

### **c. Fruit set**

Mango productivity throughout the tropics and subtropics is relatively low compared to its potential, due mainly to severe fruit drop especially during the initial 3-4-week growth period following anthesis (Dahsham and Habib, 1985; Chen et al. 1995; Searle et al. 1995). Yield depends on the number of fruits that progress through various growth and developmental stages from initial fruit set until maturity (Singh, et al. 2005). Fruit yields are depressed by water deficits during critical periods of the reproductive cycle (flowering, fruit growth and maturation) that impact fruit retention and size (Léchaudel and Joas 2007; Schaffer et al. 2009).

Pongsomboon (1991) reported that water stress induced heavy fruit drop during the first 30 days of fruit development but did not affect fruit photosynthesis. Similarly, Schaffer et al. (1994) reported that fruit abscission on trees was enhanced under severe drought stress. Larson et al. (1989) and Spreer et al. (2007) reported that fruit drop in mango at an early developmental stage was associated with low soil moisture. According to Larson et al. (1989) and Spreer et al. (2007) an excessive loss can be prevented by adequate irrigation, particularly during flowering and the first six weeks after fruit set.

In a study conducted in the Son La Province in northern Vietnam, Roemer (2011) reported that in 10-year-old trees of cv. Hôi and cv. Tron, irrigated with micro-sprinklers every 4 days for 2 hours with a nominal water rate of 120 l h<sup>-1</sup> from full bloom (15 February) until mid-May at the beginning of the rainy season, and in non-irrigated control trees, seasonal fruit drop was significantly affected by cultivar, however, irrigation treatment had no effect on final number of fruit per inflorescence. Levin et al. (2015 b) reported that the number of fruits per tree tended to increase (non-significantly) from 216 to 253 fruits per tree when tree irrigation increased from 2.8 to 5.4 mm/day, between fruit set and pit hardening.

**d. Main Fruit Growth period (MFG-fruit set to pit hardening)**

Lakshminarayana et al. (1970) reported that mango fruit growth followed a sigmoid curve. The MFG stage is characterized by rapid fruit expansion that is associated mainly with a high rate of cell division and expansion (Subramanyam, et al. 1975; Ram et al. 1983; Tharanathan et al. 2006). Approximately 80% of the final fruit size is achieved in the MFG stage (personal observations). Much of the published literature evaluating the effect of different water quantities on mango production considered the fruit growth period as a single event.

Levin et al. (2015 a,b) performed a study on the response of mango to deficit irrigation at different phenological periods in Israel between 2010 to 2014. The research was carried out in the context of a shortage of fresh water for agricultural use, very little rainfall during the growing season and previous extreme drought years. The main objective of this research was to evaluate the effect of deficit irrigation at different phenological periods on fruit quantity and quality of a late mango cultivar, Keitt, drip irrigated and under semi-arid conditions, in order to maximize the Irrigation Use Efficiency (IUE). The secondary objective was to build a tree response curve of the evaluated parameters to different water application levels at different phenological stages. The evaluated parameters were: total yield per hectare, number of fruits per tree, fruit size distribution, average fruit size, post-harvest vegetative growth, flowering timing and intensity.

The two main hypotheses of the study were: 1) The most sensitive phenological periods to drought conditions are fruit set and first fruit growing period (maximum rate of fruit growth by cell division). 2) Water saving, if necessary, should be done mainly after harvesting, when there is no fruit on the trees.

In order to evaluate our objectives and hypothesis, three independent experiments were conducted at three phenological stages. Differential irrigation levels were applied at each phenological stage, while commercial irrigation levels were applied during the rest of the season.

- Main Fruit Growth (MFG) - from fruit set to pit hardening (early May to early July.
- Final Fruit Growth (FFG) - from early July until harvest, in early September (~7/7-10/9). –

- Post-Harvest (PH) – after harvest until the first meaningful rain, from early September to mid-November (~11/9-15/11).

The first two phenological periods, related to the fruiting period, as described by Levin et.al. (2015a, b), agree with those proposed by Rajan et al. (2011) in their modified BBCH (Biologische Bundesantalt, Bundessortenamt and Chemische Industrie) scale allowing uniformity of growth stage descriptions and can be adopted widely for mango. Our MFG period corresponds to the 701-708 code of the BBCH scale; the FFG period corresponds to the 708-809 code of the same scale.

Levin et al. (2015a, b) reported that irrigation rates were similar in “On” (2011, 2013, 2014) seasons and were lower in the “Off” season of 2012. The average irrigation values in the “On” seasons ranged from 2.8 mm in T-1 to 5.4 mm in T-4; the actual Kc values ranged between 0.38 in T-1 to 0.80 in T-4; annual irrigation amounts ranged from 940 mm in T-1 to 1145 mm in T-4. During the "Off" season the water quantities were reduced by at least 15%.

The number of fruits per tree tended to increase (non-significantly) with increasing irrigation level by 16.8 – 19.3% between the T-1 and T-4 and T-3 treatments, respectively. Average fruit weight was not affected but there was a shift in fruit size distribution towards smaller fruit weight. The proportion of non-commercial fruit (less than 280 g) significantly increased ( $F= 7.4806$ ;  $P= 0.0024$ ) from 2.4% in T-1 to 6.0% in T-4. The amount of small fruit also increased (close to significant-  $F= 2.9797$ ;  $P= 0.0627$ ), from 24.6% in T2 to 33.1% in T-4, and the amount of large fruit tended to decrease (non-significantly) at higher irrigation levels, from 19.1% in T-1 to 10% in T-4. Despite the different trends in fruit number and differences in fruit size distribution between T-4 and T-1, similar average yield for the four years of the experiment was recorded in both treatments (68.5 and 70.6 t ha<sup>-1</sup> for T-1 and T-4, respectively). These results indicate that higher irrigation in the MFG period may increase the final number of fruits per tree, however, the fruit may be slightly smaller during this treatment, probably because the higher number of fruits will affect the water distribution, meaning proportionally less water per fruit with respect to the least amount of fruit in T-1.

Torrecillas et al. (2000) reported that deficit irrigation in the first stage of fruit growth (exponential growth) in apricot did not affect final fruit size. They claim that when irrigation was restored in the third stage of fruit growth, they observed compensatory

growth which allowed the fruit to reach a similar diameter as fruit from the control treatment. We assume that similar processes may occur in mango where the fruits in the low irrigation treatments, T-1 and T-2, during the MFG period (first stage in apricot) may have their fruit size recovery period during the FFG period (third stage in apricot).

Several previous studies showed a positive association between irrigation level and final fruit number. The irrigation level during fruit set was shown to be important for final fruit number (Bhambid et al. 1988). Singh et al. (2003) reported that final fruit numbers were also higher in trees maintained at tensions of -10 to -20 kPa, than at -20 to -30 or -50 to -60 kPa during the MFG period. Similary, Chandel and Singh (1992) reported higher fruit retention by trees irrigated at 20% or 40% available soil moisture (ASM) than trees irrigated at 60% available soil moisture during the main fruit growth period. Spreer et al. (2007) also reported that water deficit in the early stage of fruit development leads to increased fruit drop in mango. Thus, yield increase due to irrigation normally results from a higher crop load rather than higher fruit weight (Pavel and de Villiers, 2004; Spreer et al. 2007, 2009 a, b).

*e.* Final Fruit Growth period (FFG-pit hardening to harvest)

The FFG stage counts for approximately 20% of the final fruit size at harvesting (personal observations). Fruit growth at this stage is by cell enlargement only (Subramanyam et al. 1975; Tharanathan et al. 2006).

There are not many reports in the scientific literature regarding the impact of different irrigation strategies during the FFG period on mango productive parameters. In this section I present the results reported by Levin et al. (2015a, b) for the FFG period evaluated under Israeli growing conditions. In the following section "**MANGO IRRIGATION RESEARCH IN LATIN AMERICAN COUNTRIES**" some more reports regarding the impact of different irrigation treatments at different phenological stages, including FFG, on productive parameters of mango are also presented.

In their irrigation experiment, Levin et al. (2015a, b) reported that during the FFG period, the average irrigation values in the "On" seasons ranged from 3.8 mm in T-1 to 9.2 mm in T-4 under semi-arid conditions of Israel; the actual Kc values evaluated in the experiment ranged between 0.48 in T-1 to 1.17 in T4; annual irrigation amounts ranged from 875 in T1 to 1133 in T-4.

The FFG period was defined as the period of pit hardening to harvesting. According to Levin et al. (2015a, b) in this period, the average number of fruits for the experimental period was slightly higher in T-4 (8%, non-significantly) than in T-1. However, in 2013 for example, the number of fruits increased by 16% with increasing water quantities, from T-1 to T-4. Also, fruit size increased with increasing water quantities. In 2013, fruit size in T-4 was significantly greater by 10.3% than in T-1, even when the number of fruits in the former was 16% higher than in the latter. The average fruit size for the experimental period increased by 53g between T-1 (least irrigated) and T-4 (most irrigated). Fruit yield increased significantly with increasing water quantities by 27.1 and 46.9 in 2013 and 2014, respectively, from T-1 to T-4. During the experimental period (2010-2014) a cumulative effect of increasing water quantities, applied at the FFG phenological period, was observed on fruit yield. Despite the higher average number of fruits in T-4, fruit size distribution was skewed (non-significantly) towards larger fruit, especially for the highest fruit size group.

In this phenological period water quantity seems to be more relevant in productive “On” years rather than “Off” years. Under non-productive conditions such as the 2012 season, no relationship between production parameters (number of fruits, average fruit size and fruit size distribution) and irrigation level (data not shown) was found. The impact of increasing irrigation under heavy production ( $>50 \text{ t ha}^{-1}$  i.e. 2011 season) in the FFG phenological period was different to that observed in the MFG phenological period. While we observed a negative effect of increasing irrigation on fruit weight during the first phenological period, a positive (non-significant) relationship between irrigation level and fruit weight was recorded during the second period.

#### **4. *Water quality:***

Considering the scarcity of conventional water sources for agricultural use, there is an urgent need for alternative water sources in agriculture to replace the high-quality water required for human consumption (Marecos do Monte et al. 1996; Angelakis et al. 1999; Oron et al. 2001; Toze, 2006). The reuse of municipal wastewater or other water alternatives like saline water for irrigation could be a realistic way of reducing water shortage, as has been demonstrated in many countries in the Mediterranean region such as Israel, Cyprus, Jordan and Tunisia (Angelakis et al. 1999). In Israel, for example, treated sewage effluent is expected to be the main (70%) source of water for irrigation by

2040 (Haruvy et al. 1999). In many parts of the world, treated wastewater has been successfully used for irrigation, and many researchers have recognized its benefits (Asano and Levine, 1991; Levine and Asano, 2004). In Mediterranean countries, treated wastewater is increasingly used in areas with water scarcity and its application in agriculture is becoming an important addition to water supplies.

Several studies have shown the advantages and disadvantages of using wastewater for irrigation of various crops (Reboll et al. 2000). However, in the preparation of this chapter, no data were found regarding the impact of different water sources and quality (i.e. recycled water, saline water, etc.) on mango production parameters except for the research carried out by Durán Zuazo et al. (2004). These authors evaluated the impact of salinity on the fruit yield of mango cv. Osteen. The study was conducted over four growing seasons (1996–1999), in a mature mango orchard (12 years old) at the Experimental Station ‘El Zahori’ (at the Patronato de Cultivos Subtropicales de Almuñécar, SE Spain). Of the 24 evaluated trees, 12 were grafted to the Gomera-1 rootstock (G1) and 12 to the Gomera-3 rootstock (G3). The experiment comprised four saline irrigation treatments, using irrigation water available at the experimental station (representative of the region): water without added NaCl, but nevertheless with a certain baseline salinity, was used as the control ( $1.00 \text{ dS m}^{-1}$ ), while three increments of NaCl ( $1.50$ ,  $2.00$  and  $2.50 \text{ dS m}^{-1}$ ) comprised the other treatments. The experimental design was a randomized block with three replicates. A drip irrigation system of four emitters ( $4 \text{ l h}^{-1}$  each) per tree was used. During each irrigation event, surplus water was added to provide a leaching fraction (LF) of about  $0.18 - 0.20$ . The irrigation water applied in all treatments was equivalent to the evapotranspiration of the crop, estimated from a class-A evaporation pan. According to the reported results, the toxic effect of salinity on fruit yield was significant in all salt-stressed trees compared to the control. As salinity increased, yield diminished in both scion-rootstock combinations. Nevertheless, the intensity of the negative effect on yield was slightly greater in G3 than in G1, especially at the two highest saline treatments ( $2.00$  and  $2.50 \text{ dS m}^{-1}$ ). The number of fruits also was significantly reduced with increasing salt concentration.

Previous research by the same authors examined the effect of rootstocks on mineral nutrition of mango cv. Keitt, (Durán Zuazo et al. 2002), Salt tolerance of mango rootstock cv. Osteen, (Durán Zuazo et al. 2003) and the impact of salinity on macro-



and micronutrient uptake in mango cv. Osteen with different rootstocks (Durán Zuazo et al. 2004).

This lack of information, regarding the response of mango trees to varying water quality, opens a significant research field that may be very relevant for the mango industry in the near future.

## **F. MANGO IRRIGATION RESEARCH IN LATIN AMERICAN COUNTRIES**

Latin American countries show great potential for expanding their irrigated areas. Irrigation is important for strengthening local and regional economies in general and for the mango industry in particular. Latin America is relatively water-abundant at the national level and is not generally considered to be water-scarce. However, when viewed from the perspective of “economic water scarcity”, there is a notable need for investments in the water sector (Drechsel et al. 2015).

This section provides a description and summary of past research on irrigation in mango orchards in the main Latin American countries which export mango to the USA, with a focus on key results relating to water requirements and the impact of different irrigation strategies on mango performance. According to the reviewed literature, the main studies regarding mango water needs and/or response to different irrigation strategies were conducted in Brazil and to a lesser extent in Mexico.

- ***Brazil:***

Brazil is the major mango producing country in South America with a cultivated area of approximately 67,600 hectares and production of 970,000 metric tons (Pinto et al. 2004). Mango trees are found growing extensively in Brazil due to favorable soil and climate conditions. The main mango producing States are Bahia, Pernambuco, Sao Paulo, Minas Gerais and Ceará (IBGE, 2011). In Bahia, the main producing regions, where the use of irrigation is necessary, are the semiarid regions of Juazeiro, Livramento de Nossa Senhora, Rio Corrente, Itaberaba and Ceraíma/Estreito. According to Souza et al. (2002), southeast and northeast Brazil are the most important production areas with 34,600 and 28,800 hectares, respectively. These regions represent 51.4% and 42.6%, respectively, of the total cultivated mango area in Brazil.

According to Gomes et al., (2002) there is a wide range of irrigation systems being used in the Northeast mango orchards. Around 41% of the orchards are irrigated with a micro-sprinkle system, 21% with other irrigating systems (furrows, drip, basin etc.) and 33% do not use any type of irrigation.

The semi-arid northeast has become the largest mango producing area, accounting for 66.5% of Brazilian production in 2012 (1,175,000 metric tons). Exports, mainly from the state of Bahia that is the second largest producer, accounted for 54% of domestic production (IBGE, 2014), making this state the largest fruit exporter in Brazil (Anuário Brasileiro de fruticultura, 2013). Brazil's main cultivars are Tommy Atkins (85%), Ataulfo (8%), and Palmer (7%) (Anon. 2016). The majority of cultivated mango in the valley of São Francisco, Brazil, is Tommy Atkins, which represents approximately 95% of the mango crop (Lima Neto et al. 2010).

Irrigation management strategies concerning rational water use have been adopted even in regions where water is not a limiting factor for irrigation. In this scenario, irrigation techniques such as RDI and PRD dominate (Santos et al. 2014) the main studies conducted in Brazil.

- de Acevedo et al. (2003) studied the water requirements of irrigated mango orchards in northeast Brazil. This study was conducted at the Bebedouro Experimental Station of the Brazilian Organization for Agriculture and Animal Research (Embrapa semi-árido) in the semi-arid region of the middle reaches of San Francisco River Valley in Petrolina-PE, Brazil (latitude: 09°09'S; longitude: 40°22'W; altitude: 365.5 m a.s.l.). Field measurements were made during the productive cycle of a 7-year-old orchard of mango cv. Tommy Atkins, from June 10<sup>th</sup> to November 19<sup>th</sup>, 1999. The orchard trees were planted at a spacing of 8.0 m between rows and 5.0 m between trees (8.0 m × 5.0 m). The 1999 productive cycle started with flowering induction (application of a 4% solution of potassium and calcium nitrate) and was divided into the following phenological stages: flowering (20 days: from July 13<sup>th</sup> to August 2<sup>nd</sup>); fruit fall (40 days: from August 3<sup>rd</sup> to September 12<sup>th</sup>); fruit formation (40 days: from September 13<sup>th</sup> to October 22<sup>nd</sup>); fruit maturation (20 days: from October 23<sup>rd</sup> to November 12<sup>th</sup>). Evapotranspiration from individual mango trees was obtained by two methods: Bowen ratio-energy balance (BREB) and soil water balance (SWB). Daily mango orchard evapotranspiration increased slowly from 3.1 mm per day at the beginning of the

experimental period to 4.9 mm per day at the maximum growth period of the fruit, then decreased to approximately 4.1 mm per day at full maturation. The accumulated mango orchard water consumption for the whole productive cycle was 551.6 mm and 555.1 mm by the soil water and Bowen ratio-energy balance methods, respectively.

- Coelho Filho and Coelho (2005) reported on 4-year-old mango trees cv. Tommy Atkins, irrigated by micro-sprinklers, with RDI treatments comprising water deficits at three stages of fruit growth, using 50%, 70% and 85% of crop evapotranspiration (ET<sub>c</sub>). The treatments were applied during each one of the three phenological stages of fruit production. No significant differences in productivity, number of fruits per plant or average fruit weight among the treatments were reported.
- da Silva et al. (2009) evaluated water-use efficiency and evapotranspiration of a mango orchard grown in northeastern Brazil. The study was conducted at the commercial mango farm located in middle reaches São Francisco River region, Petrolina, PE, Brazil (latitude: 09°09' S; longitude: 40°22' W; altitude: 365.5 m a.s.l.) during two consecutive crop production years. Field experiments were performed at a 12-year-old cv. Tommy Atkins orchard, planted with a spacing of 10 m × 5 m, resulting in a density of 200 trees ha<sup>-1</sup>. A sprinkler irrigation system was used with one sprinkler per plant and a water discharge rate of 60 l h<sup>-1</sup>. da Silva et al. (2009) found a significant yield reduction when irrigated at 100% of reference evapotranspiration (ET<sub>o</sub>) compared to 70%, 80% and 90%. They also found that WUE was influenced by soil water content and it was improved by programming irrigation with 90% ET<sub>o</sub>.
- Coelho Filho et al. (2009), evaluated irrigation management with PRD irrigation in a mango orchard cv. Kent under semi-arid conditions. The study was conducted at Fazenda Boa Vista (Iaçu Agropastoril Ltda) in a 6 years old orchard of mango cv. Kent, with a spacing of 8 m × 5 m. The orchard was irrigated by drip irrigation, with two lateral lines per plant row, and ten flow drippers at 3.75 l h<sup>-1</sup> per dripper. The experimental design was in randomized blocks with five replications, where each replicate comprised three plants. For each treatment production parameters, including fruit weight, number of fruits and productivity, were evaluated. The five treatments represented three different types of irrigation: Treatment without deficit, i.e. irrigation based on water quantities applied at the farm, (507 mm), with irrigation performed using two lines of drippers running simultaneously (T1); water application at 50% of

T1 as PRD irrigation (Deficit – IP), with five emitters working only on one side of the plant each time (T2); deficit (IP) applied alternately, with IP-7, alternating every 7 days (T3); IP-14, alternating every 14 days (T4); and IP-21, alternating every 21 days (T5). The treatments were applied at the beginning of flowering (July 2007) and extended until harvest (October 2007). Productivity without deficit (T1) was significantly higher than under IP (PRD treatment) but not significant from IP-14 and IP-21; the same trend was observed for fruit number. There were no differences among IP-7, IP-14 and IP-21 for yield, fruit number or fruit weight.

- Cotrim et al. (2011) evaluated the effect of RDI on cv. Tommy Atkins under micro-sprinklers in the semi-arid region of Brazil. The study was conducted in a 9-year-old mango orchard cv. Tommy Atkins, with a spacing of 8 m × 8 m in the Ceraíma Irrigated Perimeter, city of Guanambi, in southwestern Bahia, at latitude 14°13'30" S and longitude 42°46'53" W, and at an altitude of 525 m.a.s.l. (meters above sea level). The characteristic climate of the region is semi-arid with an average annual rainfall of 664 mm. The experiment was conducted during two consecutive crop production cycles, where experiment 1 was set up in 2006 and experiment 2 in 2007. In both cases, the treatments were applied in phases I (onset of flowering to fruit fixation), II (fruit expansion) and III (end of growth and fruit maturation) of mango fruit development, after the period of floral induction, for uniform flowering of approximately 80% of the branches. This experimental system was irrigated using micro-sprinklers, with an emitter rate of 56 l h<sup>-1</sup> per plant. Irrigation treatments comprising combinations of 30%, 40%, 60%, 80% and 100% of ET<sub>c</sub> were applied by varying the irrigation time of the different registers. The irrigation level for a specific period was determined based on crop coefficients (K<sub>c</sub>) ranging from 0.45 to 0.87, from flowering to fruit ripening, according to Coelho et al. (2002).

During the first productive cycle (2006) the experimental design was completely randomized, with ten treatments and three replicates in plots comprising a single mango plant. The treatments were: T0 - full irrigation at all phases of fruit development (100% ET<sub>c</sub>); T1 - full irrigation (100% ET<sub>c</sub>) in Phases II and III and 40% ET<sub>c</sub> in Phase I; T2 - full irrigation (100% ET<sub>c</sub>) in Phases I and III and 40% ET<sub>c</sub> in Phase II; T3 - full irrigation (100% ET<sub>c</sub>) in Phases I and II and 40% ET<sub>c</sub> in Phase III; T4 - full irrigation (100% ET<sub>c</sub>) in Phases II and III and 60% ET<sub>c</sub> in Phase I; T5 - full irrigation (100% ET<sub>c</sub>) in Phases I and III and 60% ET<sub>c</sub> in Phase II; T6 - full irrigation (100% ET<sub>c</sub>) in

Phases I and II and 60% ETc in Phase III; T7 - full irrigation (100% ETc) in Phases II and III and 80% ETc in Phase I; T8 - full irrigation (100% ETc) in Phases I and III and 80% ETc in Phase II; T9 - full irrigation in phases I and II and 80% ETc in Phase III.

During the second productive cycle (2007) the experimental design was also completely randomized, with eight treatments and three replicates, in plots comprising a single mango plant. The treatments were: T1 - without irrigation; T2 - full irrigation at all phases of fruit development (100% ETc); T3 - full irrigation (100% ETc) in Phases II and III and 60% ETc in Phase I; T4 - 100% ETc in the Phases I and III and 60% ETc in Phase II; T5 - 100% ETc in Phases I and II and 60% ETc in Phase III; T6 - 100% ETc in Phases II and III and 30% ETc in Phase I; T7 - 100% ETc in Phases I and III and 30% ETc in Phase II; T8 - 100% ETc in Phases I and II and 30% ETc in Phase III.

The results recorded during the first production cycle (2006) revealed no significant effects of applied irrigation treatments on productivity, number of fruits per plant, average fruit weight and efficiency of water use. Similarly, in 2007 there were no significant effects of treatments on the variables studied. Although productivity of T3 was almost double that of T1, the averages did not differ significantly from each other, possibly due to the high heterogeneity of production between plants in the same treatment.

- Santos and Martines (2013) evaluated soil water distribution and extraction by mango trees cv. Tommy Atkins under different irrigation regimes. The study was conducted in the experimental field of Companhia de Desenvolvimento dos Vales do São Francisco e Parnaíba (Company for the Development of Sao Francisco and Parnaiba River Basins – CODEVASF), located in the irrigated perimeter of Ceraíma, in Guanambi, Southwestern Bahia, Brazil (latitude: 14°17'27'' S, longitude: 42°46'53'' W, altitude: 537m.a.s.l., average annual rainfall: 680 mm, average annual temperature: 25.6 °C). Three irrigation regimes were evaluated: RDI, full irrigation, and no irrigation, and their influences on water distribution and extraction by mango cv. Tommy Atkins were studied from blooming to fruit maturation. The orchard was 11-12 years old; trees were planted at a spacing of 8 m × 8 m. Plants were irrigated with micro sprinklers, one per plant, and received 50 l h<sup>-1</sup> water at 200 kPa. The treatments were: T1 – irrigation supplying 100% ETc from flowering to fruit harvest; T2 – 50% ETc from the onset of flowering to the beginning of fruit expansion followed by 100%

ETc to physiological maturity; T3 – 100% ETc from the onset of flowering to the beginning of fruit growth, 50% ETc from the beginning of expansion to the beginning of physiological maturation and 100% during physiological maturation of the fruit; T4 – 100% ETc from the onset of flowering to fruit expansion and 50% ETc during physiological maturation; T5 – No irrigation. The different irrigation regimes caused different profiles of distribution and extraction of water by the mango tree. The extraction of water regardless of the treatment is primarily due to a distance less than 1.50 m from the plant, and to a depth of 0.50 m.

- Santos et al. (2014) evaluated the impact of RDI treatments at different phenological stages. The study was conducted in an experimental area of CODEVASF, located in the irrigated perimeter of Ceraíma, in Guanambi, Southwestern Bahia (latitude: 14°17'27" S, longitude: 42°46'53" W, and altitude: 537 m a.s.l.). RDI was used on mango cv. Tommy Atkins from flowering to fruit ripening during two productive cycles, 2010 and 2011. RDI treatments were applied during three development phases according to Cotrim et al. (2011): phase I – from early flowering (EF) to fruit set (FS), ca. 65 days; phase II – (fruit expansion) from FS to ca. 95 days after EF, and phase III – (late growth and physiological fruit ripening) from the end of phase II to nearly 120 days after EF. Five irrigation treatments with six replications were applied in phases I, II and III after the blossoming induction period, as follows: 1) 100% ETc from flowering to fruit harvest; 2) 50% ETc from early flowering to early fruit expansion, followed by 100% ETc until harvest; 3) 100% ETc from early flowering to early fruit expansion, followed by 50% ETc to early physiological ripening and then 100% ETc during fruit physiological ripening; 4) 100% ETc from early flowering to late fruit expansion and 50% ETc during physiological ripening; 5) no irrigation. WUE for cv. Tommy Atkins in this study was influenced by the use of RDI. The best WUE for the crop was when RDI at 50% ETc was adopted in the third phase of tree production corresponding to final fruit growth (FFG). These results contrast with those of Levin et al. (2015a, b), who reported that final yield was significantly increased by increasing water quantities during the same phenological period. The use of RDI at 50% ETc in the fruit set phase caused yield reduction and, as a consequence, reductions in WUE.

- Santos et al. (2015) studied yield, WUE and physiological characteristics of mango cv. Tommy Atkins under a PRD system. The study was based on the use of PRD

in a 12-year-old orchard of mango cv. Tommy Atkins, from flowering in August 2011 to fruit ripening in December 2011. It was conducted in an orchard located at Ceraíma, in Guanambi, Southwestern Bahia, Brazil, with plants at a spacing of 8 m × 4 m. Plants were watered by drip irrigation with six emitters per plant, where each emitter had a flow rate of 8 l h<sup>-1</sup>. Five treatments were applied from the onset of flowering to harvesting of mango, using drip irrigation: 1) full irrigation, 100% ETc; 2) 100% ETc, alternation of the irrigation side (FA) every 15 days; 3) 80% ETc with FA of 15 days; 4) 60% ETc with FA of 15 days and 5) 40% ETc with FA of 15 days. A randomized block design was used, with six replicates, and each plant represented an experimental plot. Treatments were applied by varying irrigation time through control valves, where each valve referred to a different treatment. The irrigation amounts were based on the reference evapotranspiration (ET<sub>o</sub>) that was determined daily by the Penman-Monteith method, FAO standard method (Allen et al. 1988). They found that the use of PRD caused no significant reduction in the production (number of fruits per hectare and yield) of mango cv. Tommy Atkins compared to full irrigation. The study demonstrated that PRD with 40% ETc and alternation of the watered side every 15 days increased WUE ( $P < 0.05$  by Tukey test), without causing a significant reduction in productivity.

- Faria et al. (2016) evaluated the effects of irrigation management on floral induction of mango cv. Tommy Atkins in the semiarid region of Bahia. The experiment was conducted during the 2012 and 2013 seasons in a 16-year-old orchard of mango cv. Tommy Atkins, grown with a spacing of 8 m x 8 m on a eutrophic fluvic Neosol – Brazilian Soil Classification system - (Entisol - Soil Taxonomy-). The experimental site was in the experimental area of CODEVASF, located in the Irrigated Perimeter of Ceraíma, in Guanambi, Southwestern Bahia (latitude: 14°17'26" S; longitude: 42°42'50" W, altitude: 530 m a.s.l.). Irrigation management strategies adopting controlled water stress at floral induction and 100% return at the fruiting period, during two production cycles, 2012 and 2013. Irrigation was carried out via a localized system, using one micro sprinkler per plant at a flow rate of 48 l h<sup>-1</sup> and 150 KPa pressure. Treatments comprised five irrigation levels based on crop evapotranspiration (ETc): T1 – 0% ETc without irrigation in the flowering induction period (FI) and 100% ETc in the fruiting phase (FII), T2 – 25% ETc in FI and 100% ETc in FII, T3 – 50% ETc in FI and 100% ETc in FII, T4 – 75% ETc in FI and 100% ETc in FII and T5 – 100% ETc in FI and FII. They were arranged in a randomized block design with six replications

and one useful plant per experimental plot. Water level reduction was obtained by alterations in irrigation time by controlling a valve inserted into each treatment dripline. These levels were obtained from the reference evaporation data ( $E_{To}$ ), crop coefficient ( $K_c$ ) and landscape coefficient ( $K_l$ ). The reported results showed that there was no interaction ( $p > 0.05$ ) among the different irrigation reduction levels based on  $E_{Tc}$ , or between the evaluated production cycles on mango cv. Tommy Atkins production characteristics. In the first and second evaluated cycles (2012 and 2013) the average number of fruits per tree was significantly higher in 2012 than in 2013 (197 and 59 fruits per tree, respectively). Fruit weight per plant was 106 and 26.5 kg, respectively. Only the cycles ( $p < 0.05$ ) influenced productive characteristics, regardless of the irrigation strategies used for floral induction. High alternate bearing was observed in these trees.

- Santos et al. (2016) evaluated the effect of irrigation deficit strategies on physiological and productive parameters of mango. Two experiments were conducted, with PRD implemented in one and RDI in the other. The experiments were conducted in an 18-year-old orchard of mango cv. Tommy Atkins, with a spacing of 10 m x 8 m, located in the Irrigated Perimeter of Ceraima, in Guanambi, Southwestern Bahia, Brazil (latitude: 14°17'03" S, longitude: 42° 43'57" W and altitude: 530 m a.s.l.).

The experimental design was randomized block, with seven RDI treatments under micro-sprinklers and five PRD treatments under drip irrigation. The RDI treatments consisted of applications of 100, 75 and 50%  $E_{Tc}$  at each one of the three stages: S1 – onset of flowering to fruit set, S2 – fruit development and S3 – fruit physiological maturation. The PRD treatments consisted of applications of 100, 80, 60 and 40%  $E_{Tc}$ , during the same three stages, alternating the irrigation side every 15 days. PRD irrigation at 80%, 60% and 40%  $E_{Tc}$  caused a reduction in production of mango cv. Tommy Atkins compared to full irrigation (FI), and PRD at 80%  $E_{Tc}$  led to lower WUE. There were deficit effects with PRD at 50%  $E_{Tc}$  and 75%  $E_{Tc}$ , applied at different production stages, however, there was no effect on WUE. Application of RDI at 50%  $E_{Tc}$  at the fruit set and development stages caused a drop in production, while RDI at 75%  $E_{Tc}$  caused a reduction in production when applied only to the fruit set stage. Yields in this study tended to be greater when the deficit was applied at maturation and lower when applied at the fruit set stage, even with no difference between the yields when considering only the level of RDI.



- de Souza et al. (2016) evaluated the water requirement estimate for the reproductive period of mango orchards in the northeast of the State of Pará. The aim of this study was to estimate the water consumption of a mango orchard during each phenological stage. For this purpose, an equipped micrometeorological tower was installed in a 22-year-old orchard of mango cv. Tommy Atkins, with data collected during the crops of 2010/2011 and 2011/2012. The actual crop evapotranspiration was estimated from the energy balance using the Bowen ratio technique. The study was carried out in a mango orchard located at the experimental ranch of Cuilarana of the Federal Rural University of Amazonia (FRUA), city of Salinópolis, Pará, Brazil (latitude: 00°39'50.50" S, longitude: 47°17'4.10" W, altitude: 17 m a.s.l.). The trees were planted at a spacing of 10 m x 10 m (100 plants ha<sup>-1</sup>). The phenological stages were monitored according to Rodrigues et al. (2013) and represented by a normalized thermal range, depending on the accumulated degree-days, obtaining the normalized thermal time (NTT) (COSTA et al. 2009), where each NTT index represented a phenological phase from flowering (NTT = 0), onset of fruit drop (NTT = 1), fruit formation (NTT = 2), fruit maturation (NTT = 3) and harvest (NTT = 4). From the results obtained they calculated the actual crop evapotranspiration during its reproductive period as ranging between 402.9 and 420 mm with an average daily water consumption of 3.8 mm at flowering, 4.25 mm at fruit drop, 3.56 mm at fruit formation, 3.0 mm at fruit maturation and 3.73 mm for the whole period.

- ***Ecuador:***

Ecuador has about 5,300 hectares of mango producing land for export, irrigated predominantly by micro sprinklers (Mr. Johnny Jara Arteaga, Director Ejecutivo Fundación Mango del Ecuador, personal communication). In general, the Ecuadorian season begins in September and extends until January. Ecuador's main cultivars are Tommy Atkins (65%), Kent (18%), and Ataulfo (15%) (Anon. 2016). Unfortunately, no research regarding mango water needs under Ecuadorian growing conditions were found in the relevant scientific literature.

- ***Guatemala:***

The mango industry in Guatemala has been growing dramatically since 1990, when the Ministry of Agriculture began to support the fruit industry in Guatemala and developed

a unique program designed to promote new fruit crops. Since that time the productive area has increased from 900 ha to 7000 ha (Granados-Friely and Escobar, 2000). According to Mr. Eddy Martinez (“Gerente de Operaciones”, Agrotropics, personal communication) 5,000 ha of mango for export are currently planted in Guatemala, of which 40% are irrigated, mainly by micro sprinklers. Approximately 100 ha are irrigated by drip irrigation; the remaining hectares are rain-fed. The main cultivars are: Tommy Atkins (4000 ha), Ataulfo (500 ha), Kent (300 ha) and Keitt (200 ha). In the past five years exports have been close to 5 million boxes, 90% to the USA market and 10% to the European market. Unfortunately, no research regarding mango water needs or responses to different irrigation strategies under Guatemalan growing conditions were found in the relevant scientific literature.

- ***Mexico:***

Mexico has been one of the main producers and consumers of mango, and a leading exporter worldwide (Hanemann et al. 2008, USAID, microreport). Mexico is globally the leading exporter and third in rank as a producer and is by far the main supplier for the North American market, followed at some distance by Brazil, Ecuador, Peru, Haiti and Guatemala (Hanemann et al. 2008; Galán Saúco, 2004). Mexico’s main varieties are Tommy Atkins (38%), Ataulfo (26%), Kent (20%), Haden (7%), Keitt (8%) and others (1%) (Anon. 2016).

The main mango producing areas are located in the Pacific regions and production moves up the coast during the course of the season, which extends from January to September, reaching a climax during June and July (Hanemann et al. 2008). Irrigation is available in just under 30% of the Ataulfo mango orchards in the Soconusco region. The most common irrigation method, however, is flooding, which leads to soil erosion, deficient water distribution and water loss by evaporation (Magallanes-Cedeño, 2004). The president of the Oaxaca Mango Product System Council, Roberto Nivon Velasquez, said that producers in the San Pedro Tapanatepec, Santo Domingo Zanatepec, Reforma de Pineda, San Francisco Ixhuatán, San Francisco del Mar and Chahuities regions experienced great losses in the current crop due to the lack of rains last year. He also stated that, even though they had exported 56,400 tons of Tommy, Ataulfo, and Gold mango cultivars to the United States, Canada, and Europe, the drought had caused a 40% decrease in production (Source: [elsoldelitsmo.com.mx](http://elsoldelitsmo.com.mx), Publication date: 5/17/2016. <http://www.freshplaza.com/article/157797/Mexico->

[Mango-production-in-the-Isthmus-down-due-to-drought](http://www.freshplaza.com/article/157797/Mexico-Mango-production-in-the-Isthmus-down-due-to-drought)). Unfortunately, he said, approximately 80% of the orchards need the rains because they do not have irrigation systems. Hence, those orchards, mainly the adult ones, are dying because of climate change. (Source: [elsoldelitsmo.com.mx](http://elsoldelitsmo.com.mx), Publication date: 5/17/2016. <http://www.freshplaza.com/article/157797/Mexico-Mango-production-in-the-Isthmus-down-due-to-drought>).

The above facts, presented by Mr. Velasquez, represent the actual situation of the mango industry in Mexico in general and in Oaxaca State in particular, where the vast majority of the mango growers do not have a proper irrigation system (Medina-Urrutia et al. 2011), or irrigate by gravity (ie. in the Sinaloa region), in the best-case scenario (personal observations). Unfortunately, no research regarding mango water needs or responses to different irrigation strategies under Mexican growing conditions was found in the relevant scientific literature.

- ***Peru:***

The total planted area in Peru is 27,000 hectares, of which 95% is flood irrigated. In Peru, sprinklers are favored over drip irrigation whenever an irrigation system is installed in a mango farm (Mr. Juan Carlos Rivera, Gerente Asociación Peruana de Productores y Exportadores de Mango – APEM, personal communication and personal observation). Mango production in Peru has increased dramatically in the past ten years with production figures almost tripling since 2000. Today Peru produces around 300,000 tons annually. Due to the economic crisis, production dropped significantly in 2009, to almost fully recover in the first five months of 2010. Because of its suitable climatic conditions, the northern region of Piura is by far the leading mango-producing region (Anon. 2011). The most common mango cultivar exported by Peru is Kent. Of the exports from the two main mango producing regions in the country – Piura and Lambayeque – the Kent cultivar comprises 82% of all mangos grown and 88% of all exported. Other mango cultivars exported by Peru are Haden, Tommy Atkins and Keitt (Anon. 2011). Unfortunately, no research regarding mango water needs or responses to different irrigation strategies under Peruvian growing conditions was found in the relevant scientific literature.

## **G. MANGO FERTILIZER RESEARCH AROUND THE WORLD IN GENERAL, AND IN LATIN AMERICAN COUNTRIES, IN PARTICULAR**

Although this review focuses on irrigation strategies that have been evaluated in mango, I will now present a short review of some of the fertilizer strategies evaluated in mango worldwide in general and in Latin American mango producer countries in particular. The subject of macro- and micro-nutrient deficiency symptoms in mango will not be presented here, however, information about specific deficiency symptoms in mango will be highlighted where necessary. For characteristic mineral deficiency symptoms in mango it is recommended to consult the chapter "Crop Production: Mineral nutrition" by Bally (2009) in "The mango: botany, production and uses" and Prado et al. (unpublished day) Macronutrient and micronutrient deficiency symptoms in mango.

The nutrient demands of mango, expressed as the accumulated amounts of the elements found in different plant organs, vary according to factors such as genotype, soil, climate, use of irrigation, water quality, plant health, phenological stage and expected crop load. Understanding and visualizing nutrient deficiency symptoms would enable improvement of fertilization programs and increases in yield. In mango, visual examination of the plants, as well as soil and leaf analysis, is an important additional tool since it permits modifications in the fertilization program during the same cropping year (Prado, 2004). Thus, it becomes possible to intervene in a situation of nutritional disorders within a short period of time and as a consequence to guaranteeing more fruits with better quality (Prado, 2004). The symptoms exhibited by a plant have a direct relationship with the functions the corresponding nutrient plays in the plant metabolism (Bally, 2009). So, after the occurrence of the biological events, the symptoms will be related to the specific nutrient causing the disorder (Prado, 2004).

The importance of fertilizing mango for commercial production was emphasized previously by Young and Koo (1974). They reported a significant yield increase in cvs. Parvin and Kent grown in the sandy soils of Lakewood, Florida, USA, when nitrogen (N) fertilization was increased threefold for the four-year average. Increasing potassium (K) fertilization threefold increased yield of Parvin significantly in the second and fourth years, and for the four-year average. For the three years immediately prior to the experiment, they were fertilized with mixtures which supplied approximately 0.6 pound

of N and 0.8 pound of K<sub>2</sub>O per tree per year to Parvin trees and 0.9 pound of N and 1.2 pounds of K<sub>2</sub>O per tree per year to Kent trees. There was no irrigation or cultivation. Highest yields in Parvin were obtained with high rates of both N and K fertilization. Potassium rates had no significant effect on yield of Kent. The same authors also reported a generally good correlation between treatment and leaf concentration of N and K. They observed that a heavy crop tended to decrease the level of N and K in leaves.

Recommendations for N supply for example, indicate that 400 g N per tree per year are needed for acceptable commercial yields (Chia et al. 1988; Wanitprapha et al. 1991; Xiuchong et al. 2001). Crane and Campbell (1994) suggested that N amounts could be increased according to tree size and site conditions. In sandy soils, fertilization practices may raise environmental concerns about rapid N leaching to ground waters. The recommended fertilizer levels (N:P: K) in Brazil for the mango crop vary according to the expected productivity (from <10 to >50 t fruit ha<sup>-1</sup>), the nutrient content of the leaf, the element itself, and whether or not the trees are irrigated (Pinto et al. 2007). The timing and proportions of the total annual application also vary according to whether the crop is rain-fed or irrigated. Raji et al. (1996) recommended maximum nutrient inputs of up to 50 kg N ha<sup>-1</sup>, 80 kg P ha<sup>-1</sup> and 80 kg K ha<sup>-1</sup>, for a rain-fed crop with high expected yield (>20 t-ha<sup>-1</sup>) and low leaf mineral concentration and/or low nutrient availability from the soil (mainly N-P-K). For an irrigated crop these figures are increased to 120 kg N ha<sup>-1</sup>, 150 kg P ha<sup>-1</sup> and 250 kg K ha<sup>-1</sup> (Silva et al. 2002). 'Fertigation' is encouraged with drip or micro-sprinklers. In Brazil, yields of up to 40 t ha<sup>-1</sup> are possible with irrigation. However, average yields under rain-fed conditions are in the range 8–12 t ha<sup>-1</sup> (Carr, 2014).

Ooshuyse (1997) reported increased fruit set and retention in cv. Tommy Atkins due to one single spray of 4% KNO<sub>3</sub> during flowering period under South African growing conditions. In the case of cv. Heidi, two applications at 4% were necessary to get similar results while in cv. Kent two applications at 2% were sufficient. Tree yield increased for both cultivars. In contrast, Nguyen et al. (2004) evaluated the effect of nitrogen on the skin color and other quality attributes of ripe fruit of mango cv. Kensington Pride. The effect of N application on skin color and other quality attributes was investigated in three orchards, one with a high green (HG) skin problem and two with a low green (LG) skin problem. N was applied at pre-flowering and at panicle emergence at the rate

of 0, 75, 150, 300 g per tree (soil applied) or 50 g per tree as foliar N for the HG orchard, and 0, 150, 300, 450 g per tree (soil applied) or 50 g per tree (foliar) for the LG orchards. In all orchards the proportion of green color on the ripe fruit was significantly ( $P<0.05$ ) higher with soil applications of 150 g N or more per tree. Foliar sprays resulted in a higher proportion of green color than the highest soil treatment in the HG orchard, but not in the LG orchards. Anthracnose disease severity was significantly ( $P<0.05$ ) higher with 300 g of N per tree or foliar treatment in the HG orchard, compared with no additional N. The authors concluded that N can reduce mango fruit quality by increasing green color and anthracnose disease in ripe fruit.

Morales and Rivas (2004) evaluated the efficiency use of fertilization and its effects on mango yields in the Mara municipality in the Zulia state, Venezuela (rain-fed orchard is assumed). The experiment was conducted on four-year-old trees of cv. Haden. The treatments were distributed within a completely randomized  $3 \times 3$  factorial arrangement, five trees per treatment and three replications. Fertilization was applied using three combination doses (D): D1 – 13,043 g urea + 869.5 g ammonium phosphate + 500 g potassium chlorate per plant; D2 – 50% of D1; and D3 – 50% of D2 and three frequencies of application (E): E0 – 100% before flowering, E1 – 50% + 50% for three months each and E2 – 30% + 70% for six months each. Highly significant differences were observed for dose (D), frequency of application (E) and the interaction  $E \times D$ . The average yield for E0 was 37.22 kg tree<sup>-1</sup> with an efficiency of 681 kg, for E1 the yield was 42.72 kg tree<sup>-1</sup> with an efficiency of 781 kg, and for E2 yield decreased to 42.54 kg tree<sup>-1</sup> with an efficiency of 777 kg. The D3 dose combined to E1 and E2 application methods led to significantly higher yield than D1 and D2 combined to the E0 application method. Similarly, frequency of application E1 and E2 led to significantly higher yield than E0.

Tropical soils, characteristic of many mango production areas worldwide, are usually highly acidic and this may impede suitable mango tree nutrition, and as a consequence, commercial production. de Almeida et al. (2012) reported on mango tree response to lime applied during the production phase. The experiment was conducted from May 2005 through February 2008 in an orchard of mango cv. Haden, grafted on rootstock of cv. Co-quinho. The soil was a dystrophic Red Oxisol (Typic Haplustox), of clayish texture, located in the ex-experimental farm of the Selviria campus of the São Paulo State University (UNESP), at latitude 20°14' S, longitude 51°10' W and an altitude of

335 m a.s.l. (meters above sea level) The amount of lime applied was calculated to achieve 80% base saturation. The lime treatments were determined with respect to the calculated reference lime dose required to achieve 80% base saturation at a depth of 0 - 20 cm. The reference dose was 3.1 t ha<sup>-1</sup> and the treatments were as follows: T1: no lime, T2: half the reference dose, T3: the reference dose, T4: 1.5 times the reference dose, T5: twice the reference dose, calculated as 0, 1.55, 3.10, 4.65, and 6.20 t lime per hectare. Soil liming improved soil reaction chemistry, leading to higher pH, and lower H and Al. Concentrations of Ca and Mg also increased, leading to increases in both sum of bases and base saturation. The liming procedure did not affect fruit number ( $F=0.37$ , ns) or production ( $F=0.54$ , ns) in the first year of the study. However, in the second year, soil liming promoted an increment in fruit number with a quadratic adjustment and influenced fruit production. The highest fruit yield was achieved with a lime dose of 4.6 t ha<sup>-1</sup> at which point soil base saturation was 72%.

Prakash et al. (2015) evaluated the effect of drip irrigation regimes and fertigation levels on yield and quality of mango cv. Alphonso under ultra-high-density planting. The study was conducted during 2009-2010 at JISL Farm, Elayamuthur, Udumalpet. The trees were planted with a spacing of 3 m × 2 m. There were three irrigation regimes in main plots: I1 (16 l day<sup>-1</sup> plant<sup>-1</sup>), I2 (20 l day<sup>-1</sup> plant<sup>-1</sup>) and I3 (24 l day<sup>-1</sup> plant<sup>-1</sup>) and four fertigation levels in subplots, F1 (50% of recommended dosage fertilizer (RDF) – 60.0/37.5/50.0 g NPK), F2 (75% RDF - 90.0/56.5/75.0 g NPK), F3 (100% RDF - 120.0/75.0/100.0 g NPK) and F4 (125% RDF - 150.0/93.75/125.0 g NPK), replicated three times in a split plot design. In main plots, irrigation treatments were applied daily and in subplots, fertigation treatments were applied at weekly intervals. Thus, there were twelve treatment combinations with irrigation and fertigation. Irrigation regimes were applied through a drip irrigation system as per the treatment schedule at daily intervals, excluding the month of December to induce stress for flowering. Fertigation was applied immediately after harvest (July, August and September), pre-flowering (October, November and December), flowering to fruit set (January, February and March) and fruit development stages (April and May) at weekly intervals as per the above schedule. In the present study, application of 24 l of water per day per plant produced a significantly higher percentage fruit set, fruit weight and number of fruits per tree. Application of 100% RDF significantly increased percentage fruit set, number of fruits and fruit yield. The interaction between water regimes and nutrient level

revealed that I3F3 i.e., applying 24 l day<sup>-1</sup> per plant through a drip and supplying 100% RDF is required to obtain the highest yield. Regarding fruit quality Prakash et al. (2015) reported that the highest TSS, total sugars, carotenoids and ascorbic acid contents were recorded for application of 24 l of water per day per plant (I3) whereas the lowest levels of these traits were recorded in the treatment providing 16 l of water per day per plant (I1).

Salazar-García et al. (2016) studied the influence of fertilization treatments in the presence of parthenocarpic fruit in mango cv. Ataulfo, in Mexico. The study was conducted at Nayarit, Mexico, in cv. Ataulfo, in which high production of parthenocarpic fruit had been observed. One of the objectives of their study was to evaluate the influence of soil fertilization on the presence of parthenocarpic fruit. The research was conducted in two commercial orchards of cv. Ataulfo located in a warm humid climate on the coast of Nayarit. Two levels of balanced fertilizer (N, P, K, Ca, Mg, Fe, Mn, Zn and B) were evaluated, based on nutritional requirements and nutritional status of the tree, soil fertility and fertilization efficiency. The control trees did not receive fertilizer. Fertilization treatments did not affect the proportion of parthenocarpic mango that reached harvest maturity.

***a. Organic fertilization:***

Organic agriculture (OA) has been recently defined as a production system that sustains the health of soil, ecosystems and people. According to "The International Federation of Organic Agricultural Movements (IFOAM)" it relies on ecological processes, biodiversity and cycles adapted to local conditions rather than on the use of artificial inputs with adverse effects on the environment and potentially on human health (IFOAM, 2009). Eight percent (8%) of the total mango planted area in Mexico are in the process of conversion from conventional to organic systems, mainly in the Pacific Coast under tropical dry and wet conditions. Mango cultivars in organic systems are Tommy Atkins, Kent, Ataulfo, and are demanded by market for their early or late harvest season (Medina-Urrutia et al. 2011). According to Medina-Urrutia et al. (2011) mango cultivars for organic production in Mexico are selected according to a range of characteristics:

- 1) harvest season (early or late);
- 2) adaptability to the environment;



- 3) water requirements;
- 4) tree size (dwarf to semi dwarf);
- 5) better tree and fruit tolerance to pests and diseases;
- 6) fruit quality and marketability;
- 7) proximity to markets.

Fertilization studies in Mexico to determine optimum nutrient dosages on mature mango trees did not show yield differences between treated and control trees (Ireta-Ojeda, pers. comuna. In: Medina-Urrutia et al. 2011). Conversely, Avilan (1983) reported increased yield and vegetative growth as a consequence of organic fertilizer application. Also, Das et al. (2009) reported improved flowering and yield when chemical fertilizer was combined with organic fertilizer. To date, fertilizer use in Mexican mangoes is based on technical reports adapted from studies in external countries (Vazquez-Valdivia et al. 2006; Ireta-Ojeda and Estrada-Guzman, 2002). Diversity of physical and chemical soil conditions, rootstocks and water availability are more important factors interacting with tree nutrition. Under these conditions, organic nutrition is chosen according to a diversity of local formulations prepared by growers using local resources as a result of their own accumulated experience (Medina-Urrutia et al. 2011).

Silva et al. (2013) evaluated the impact of three different organic composts (A, B and C) at three different concentrations (0, 5 and 10 t ha<sup>-1</sup>), on soil chemical characteristics, nutrient contents in leaves and production level of mango crops grown in the organic system under the semi-arid conditions of northeastern Brazil. The experiment was conducted in a 3 × 3 factorial (3 composts x 3 levels) randomized block design, with three replications. The organic composts were prepared from animal and vegetable waste, enriched with castor bean, MB4® and thermo phosphate. The enrichment was efficient in increasing the nutrient content of the composts. The organic composts increased the levels of soil organic matter (SOM), especially compost C, whose soil analysis showed higher levels of total P, K, Ca, Mg, B, Cu, Mn and Zn. The SOM increased linearly with increasing compost levels. Production and fruit number per plant were higher when using the B and C composts, which showed higher total nutrient contents. N leaf content increased linearly with the compost level. The production of

fruit ( $\text{kg ha}^{-1}$ ) and fruit number per plant showed a quadratic increase with compost concentration, without reaching a maximum.

Peralta-Antonio et al. (2014) evaluated responses to organic fertilization in the mango cultivars: Manila, Tommy Atkins and Ataulfo. The research was conducted during four consecutive years (2009-2012) in the Cotaxtla Experimental Field (INIFAP) ( $18^{\circ} 56' 13'' \text{ N}$ ;  $96^{\circ} 11' 38'' \text{ W}$ ), Veracruz, Mexico. The soil in the experimental place was a pelic vertisol, with a clay texture (30 %) at a depth of 1 m and slightly acid (pH 6.5). Three organic fertilizers were used: vermicompost (V), bokashi (B), and chicken manure (CM), at doses of 5 and  $10 \text{ t ha}^{-1}$  (equivalent to 7.5 and  $15 \text{ kg tree}^{-1}$ ). These organic fertilizers were compared to two mineral doses recommended by Mosqueda et al. (1996): 230-0-300 and 230-0-0 g NPK  $\text{tree}^{-1}$ , and a control; they were applied in September 2009. During that year, the applications were made in the periphery of the canopy, for which trenches were dug, approximately 20 cm wide by 10 cm deep, where the fertilizers were placed and covered. From 2010, the fertilizers were uniformly distributed throughout the entire area under the canopy, to a depth of 10 cm and covered with soil. During the dry season (December to May), sheets of 54 mm furrow irrigation were applied every 20 days. The design was completely random for soil variables. For growth, flowering and fruit yield variables, a completely random, split-plot design was used, where the mango cultivar was the large plot, and the fertilizer source, the split plot, with three replications, considering one tree as an experimental unit. No statistically significant differences among fertilizer treatments were found for soil pH and soil organic matter at 0-20 and 20-40 cm depth. Regarding macronutrients, statistically significant differences ( $p \leq 0.05$ ) were found only for N, K and Ca content, in the first 20 cm depth. Differences in trunk diameter were observed between cultivars. Flowering differed significantly among cultivars and fertilizers. Regarding yield in 2010, only Tommy Atkins fruit were harvested, showing differences between fertilizers and control. In 2011 there were differences among cultivars and fertilizers, where chicken manure and mineral fertilizers outperformed the control. In 2012, Tommy Atkins outperformed Ataulfo. It was concluded that chicken manure at  $10 \text{ t ha}^{-1}$ , had a similar effect to the mineral doses on soil contents of N, K, Cu and Zn; fertilizer did not affect trunk diameter; bokashi and chicken manure at  $10 \text{ t ha}^{-1}$  had a similar effect to the mineral doses on flowering and yield.

## H. DISCUSSION

The aim of this section is to summarize and highlight the main results found in this review with respect to the different irrigation and fertilization strategies evaluated or any additional relevant information found in the scientific literature that provides information to support improved WUE, mango production chain and fruit quality for mango growers in the Latin American countries who currently export mango to the USA or may do so in the future. This section will focus mainly on the influence of the different irrigation strategies on the following productive parameters: fruit weight, fruit number per tree, yield, vegetative growth and alternate bearing.

### *Fruit weight:*

The impact of irrigation on fruit weight appears to be more dramatic during the final fruit growth (FFG) (cell expansion) phenological period than during the main fruit growth (MFG) (cell division) period. Diczbalis et al. (1993) reported a significant impact on fruit weight when irrigation ceased two to three weeks before harvest, with average individual fruit weight reduced by 45 g at a site with sandy soil in the Northern Territory, Australia. In a similar study, on a loam soil, ceasing irrigation four weeks prior to harvest reduced fruit weight by 35 and 50 g, respectively, compared with fruit from trees irrigated up to two weeks or only one week before harvest (Diczbalis 1994a). Levin et al. (2015 a,b) reported a reduction in the percentage of large fruit (4-6 size) from 19.4% to 9.4% and in the final fruit size by 34.5 g, when water restriction was imposed during the FFG period (irrigation 3.8 mm/day compared to 9.2 mm/day). Also, Kuppelwiesser (1990) reported a reduction of fruit weight by 52 to 69 g in trees where the irrigation was ceased five weeks before harvest. Simmons et al. (1998) reported similar results in cv. Kensington Pride trees in Bowen, Australia. Fruit weight from trees where irrigation ceased 7.5 weeks before harvest (350 g) was significantly reduced compared with fruit weight from trees irrigated until 1.5 weeks before harvest or irrigated up to harvest (479 and 513 g, respectively).

In contrast, Spreer et al. (2007, 2009 a, b) reported that both PRD and RDI had a better fruit size distribution than the fully irrigated control with nearly 60% fruits over 250 g. The authors explained the results as being a consequence of the interaction between fruit size and crop load (less fruit was harvested from the PRD and RDI treatment with respect to the control treatment). In addition, recent studies indicate that cessation of

irrigation one to two weeks before harvest may not reduce fruit weight (Bithell et al. 2010). Simmons et al. (1995) observed that if irrigation ceased between flowering and the first half of the fruit growing period, water stress occurred and affected fruit growth rate and final fruit size. However, no effect on fruit size was observed for a water shortage close to harvest (1.5 weeks before harvest, for example). Simmons et al. (1995) also reported that when water was withheld during the second month of fruit development, final fruit size was 34% smaller than from non-stressed trees.

Interaction between water quantity and quality, and environmental and soil conditions, may accentuate the effects of irrigation cessation on fruit weight. Light sandy soils, present in many of the mango growing areas around the world, may be affected more rapidly and deeply by irrigation cessation during the FFG period (Diczbalis and Bowman 1991; Diczbalis et al. 1995b). In addition, the early cessation of irrigation for up to a month prior to harvest, depending on the flowering date of the crop, may occur during months when pan evaporation values are at a peak (Bithell et al. 2010). Thus, environmental demands at particular times combined with light soils, for example, may contribute to reduced fruit fill and hence reduced fruit weights.

In contrast, water restrictions during the MFG period may not affect final fruit size, especially if watering is restored during the FFG period. Torrecillas et al. (2000) reported that when deficit irrigation was applied at the first stage of fruit growth (exponential growth) in apricot (similar to MFG period in mango) final fruit size was not affected. In their study, when irrigation was restored in the third stage of fruit growth (similar to FFG period in mango), compensatory growth was observed, allowing the fruit to reach a similar diameter as fruit from the control treatment.

Water quantity can directly affect final fruit size, as presented above, or have an indirect impact via improvement of the leaf:fruit ratio for example. Léchaudel et al. (2005) reported that increasing the leaf:fruit ratio strongly increased fresh weight in mango trees in cv. Lirfa in Reunion Island. Similar results were also reported by Simmons et al. (1998) in North Queensland, Australia in cv. Kensington Pride where fruit size increased with number of leaves per fruit. Levin et al. (2015b) reported an increase in the number of new vegetative flushes with increasing water quantity during the post-harvest (PH) period. The following season tree yield correlated well with the number of new vegetative growth flushes from the previous PH season (i.e. the leaf:fruit ratio

was improved), even though the trees were watered uniformly during the period of fruit development.

### ***Fruit number:***

In general, irrigation at fruit set and during the FFG period has been reported to promote a greater number of fruits at harvest. Pavel and de Villiers (2004) reported a (non-significant) reduction in yield due to application of RDI and PRD treatments compared to the full irrigated treatment. Yield differences between treatments were apparently related mainly to fruit number, indicating that the reduced irrigation treatments might have affected growing conditions before flowering or during the early stages of fruit growth rather than growth later in the season. Spreer et al. (2007, 2009 a,b) reported highest yield and average amount of fruit per tree in the control treatment (fully irrigated) compared to the RDI and PRD treatments, which was possibly caused by the absence of fruit drop in the early fruit development stage. Similar results on the effect of increasing water quantity on the final number of fruits per tree at harvest were reported by Irving and Drost (1987), Sanchez-Blanco et al. (1989) and Mitchell et al. (1989) in several fruit crops. Levin et al. (2015a, b) reported that the recorded (non-significant) differences in yield among treatments during the MFG period (fruit set to pit hardening) were based mainly on number of fruits rather than on fruit size. Conversely, Durán- Zuazo et al. (2011 a) reported that SDI (50% ET<sub>C</sub>) consistently resulted in higher numbers of fruits than other treatments including the most irrigated one (control). In a mulch and irrigation study, Kumar et al. (2008) reported that organic mulching coupled with a drip irrigation schedule of 50% pan evaporation significantly improved final fruit number in mango trees by 130 and 40 fruit/tree, respectively, when compared with mulching combined with a drip irrigation schedule of 75% or 25% pan evaporation. In a Brazilian study, trees receiving 100% potential evapotranspiration replacement yielded 2 to 3 t ha<sup>-1</sup> less than trees irrigated at 70%, 80% or 90% potential evapotranspiration replacement (da Silva et al. 2009).

Irrigation timing may affect fruit set and number of fruits per tree. Levin et al. (2015a) reported that in autumn 2012, after a very light crop (ca. 15 t ha<sup>-1</sup>), a significant increase in the number ( $F=13.0963$ ;  $P< 0.0001$ ) of new flushes and their length ( $F=11.3649$ ;  $P< 0.0001$ ) was recorded with increasing irrigation quantity during the PH period (T-4 respect to T-1 treatment). The following season, the average number of fruits per tree

in the most irrigated treatment (T-4) increased by 20.4% with respect to the least irrigated treatment (T-1) (Levin et al. 2015b). In a study carried out in the Northern Territory, in Australia, the proportion of fruit set was significantly and negatively reduced by pre-flowering irrigation in non-paclobutrazol-treated trees at both low and high rates (e.g. 13 and 50 mm/week) (Diczbalis and Wicks 1996).

### ***Vegetative growth and yield:***

Yield in mango is better correlated with number of fruits rather than fruit weight (Spreer et al. 2009 a). As mangoes are a perennial crop, the carry-over effects of management practices from one season to another are important in the medium and long term and they will have an impact on production. The mango crop is produced mainly on vegetative growth from the previous year (or season) Marloth (1947).

Deficit irrigation practices have reduced vegetative growth in a number of tree crops (Romero et al. 2004 a,b,c; Romero et al. 2006; Cui et al. 2009; Iniesta et al. 2009). These effects may be viewed positively in crops such as pear, where severe and moderate water deficit at bud-burst to leafing and flowering to fruit set decreased new shoot length, new shoot diameter and panicle length (Cui et al. 2009). Such levels of water deficit during these periods also reduced leaf area index (LAI) and pruning, however, they enhanced water use efficiency at the yield level (WUEY, defined as ratio of fruit yield to total water use) by 17.3 - 41.4%. In contrast, Romero et al. (2004c) reported a negative impact of post-harvest deficit (50% of ETP) applications in an arid environment that led to smaller almond trees and reduced yields over four years.

Results from several studies conducted under tropical conditions indicate that the primary impact of water stress on mango was to prevent vegetative flushing during the pre-flowering stress period (Tahir et al. 2003), in order to promote intensive and homogeneous flowering. Levin et al. (2015b) reported a significant impact of increasing water quantity during the final fruit growth (FFG) period in cv. Keith on post-harvest vegetative (PH) growth, under semi-arid conditions, even though these trees received the same amount of water during the PH period and the most highly irrigated trees during the FFG period produced significantly larger crops in the same season. However, in the same trees under low production conditions (less than 15 t ha<sup>-1</sup>) the same treatment caused a negative impact on the PH vegetative growth. In this same four-year experiment, Levin et al. (2015b) also reported that the difference in yield between the

least and the most irrigated treatment each year increased, from no difference in yield level in the first experimental year (2010) to a 46% difference in the last year (2014). These results highlight the carry-over effect of water at a critical phenological period where the physiological demand for water may be high during the FFG period under heavy load crop conditions and significantly lower under light load crop production. In the same experiment, Levin et al. (2015b) reported a significant increase in PH vegetative growth with increasing water quantity during the PH period. During three out of four seasons (two of them significant) the yield increased by 19.3 – 38.3 % even though these trees received the same amount the water during the fruiting period.

Spreer et al. (2007) reported that PRD yielded less than the fully-irrigated control treatment, nearly doubling WUE, although the differences were not significant. Pavel and de Villiers (2004) reported that progressively reduced irrigation (PRI-1 [20%], PRI-2 [35%], RDI [water was withheld for four weeks each during May/Jun 2000 and during Dec 2000/Jan 2001]) significantly reduced vegetative growth in comparison to the farm control (FC). Differences in yield between treatments were not significant, although trees in the control treatment (85% of FC) apparently showed the highest yield among all treatments followed by the RDI treatment and the farm control. Negative yield responses to over-irrigation have been cited for a number of crops (Geerts and Raes 2009).

### ***Alternate bearing***

Alternate bearing (also called biennial or uneven bearing) is the tendency of a fruit tree to produce a heavy crop (on-crop year) followed by a light crop or no crop (off-crop year) (Verreyne and Lovatt, 2009). The phenomenon is widespread, occurring in deciduous and evergreen trees (Monselise and Goldschmidt, 1982). Alternate bearing may occur over an entire region or block of trees, in an individual tree, part of a tree, or even one branch (Monselise and Goldschmidt, 1982). Alternate bearing is initiated by an environmental trigger that is favorable or unfavorable to crop production, resulting in excessive fruit set or extreme thinning of reproductive structures, respectively (Hield and Hilgeman, 1969). Alternate bearing can be a major problem in mango production, mainly in subtropical areas.

A number of studies demonstrated that yield in mango trees is affected by the irrigation regime. However, there are few, if any, long-term studies (five or more seasons) needed

to evaluate the impact of different irrigation regimes on alternate bearing in mango. Spreer et al. (2009 a) reported that fruit yield varied considerably between years. Between 38 and 75% of the trees demonstrated alternate bearing, meaning that a high crop load in one year negatively affected flowering and fruit set in the following year. Even though the phenomenon of alternate bearing could be observed throughout the orchard, it was not possible to identify a direct effect of treatments or yields in the previous seasons on current crop load. Alternate bearing imposes a strong limitation on fruit yield. No effect of irrigation treatment on flowering in the subsequent season was observed, neither were long-term effects of non-irrigation and deficit irrigation. Similarly, Levin et al. (2015b) evaluated the impact of four different irrigation treatments applied at three different phenological stages (12 treatments) on alternate bearing of cv. Keitt under Israeli semi-arid conditions for four consecutive seasons (2011 to 2014). No significant difference among the treatments was found at the three different phenological stages. The alternate index values for the four-year experiment ranged between 0.44 and 0.53 without any relationship with treatments and/or phenological stages.

## **I. CONCLUSIONS**

Although a significant number of studies have been conducted on mango with respect to crop water requirements and water saving strategies, there is no clear consensus among researchers on the topic. With regards to the crop, the wide range of climatic and soil conditions under which mango is grown, for example, hinders efforts to develop an irrigation protocol that could be widely applicable. In addition, the vast number of different mango cultivars around the world, with great variation in genetic characteristics, and consequent responses to environmental conditions and agricultural practices, make this task even more difficult.

One of the main constraints highlighted by the studies considered for this review is the fact that the vast majority of these studies were conducted over only two seasons. In order to evaluate the impact of different irrigation strategies, especially if the objective is to develop an irrigation and/or fertilizer protocol, a minimum of four to five production seasons are needed. Carry-over effects from some of the irrigation



treatments, mainly deficit irrigation, may have been overlooked in such a short period of time, especially in studies that were conducted on heavy soils.

Another questionable point found in many of these studies is the fact the fruiting period was considered as a single event, assuming that the fruit response to different irrigation strategies is evenly distributed along the fruit development and maturation periods. Ram et al. (1983) reported that the mango fruit growth curve is a typical sigmoid type where two fruit growing periods can be clearly distinguished: 1) exponential growth by rapid cell division and cell enlargement; 2) slow growth by cell enlargement only. The few studies found for this review in which the fruiting period was separated into two different phenological periods proved this assumption wrong. In addition, the main objective of many studies regarding potential irrigation strategies for mango was related to water saving, rather than crop water requirements for maximizing fruit production, with respect to quantity and quality, in the short, medium and long terms. Finally, the number of publications in the relevant international scientific literature, of irrigation studies conducted on mango in Latin American countries, except for Brazil, is negligible.

## **J. RECOMMENDATIONS**

The recommended research fields relate mainly to Latin American mango-producing countries. This review of research conducted on past and present irrigation strategies in mango demonstrates a need to continue working in a number of fields, to determine:

1. Mango water requirements under lysimeter conditions. (Quantitative research).
2. Impact of different crop loads on water requirements under lysimeter conditions. (Quantitative research).
3. Mango mineral consumption under different crop loads under lysimeter conditions. (Quantitative research).
4. Impact of different crop loads on mango water requirements under particular growing conditions. (Qualitative research).

5. Mango water requirements for maximizing production in the short, medium and long term, with respect to quantity and quality, under different climate and soil conditions. (Qualitative and quantitative research).
6. Long-term response of mango (at least four seasons) to different water quantities, including deficit irrigation, on mango vegetative growth and associated yield at each phenological stage in an environment with no effective rainfall during the irrigation season and its impact on fruit post-harvest behavior in the main cultivars exported to the USA. (Qualitative research).
7. Irrigation practices required for supporting optimal fruit numbers following the use of paclobutrazol or other flowering treatments for the main mango cultivars exported to the USA under different soil conditions. (Qualitative research)
8. Impact of irrigation with different water qualities on production parameters such as number of fruits, fruit size distribution, fruit quality (chemical), total yield, vegetative growth, alternate bearing and fruit post-harvest behavior, under different soil and climate conditions. (Qualitative research)
9. Impact of irrigation frequency, compared to water quantities, under different soil conditions, on fruit post-harvest behavior of different cultivars. (Qualitative research).
10. Short-, medium- and long-term impact of different irrigation methods (gravity, sprinkles, and drip irrigation), under different soil conditions, on fruit post-harvest behavior of different cultivars. (Qualitative research).
11. Effect of different irrigation strategies compared to a fully-automated one (i.e. Growth-based irrigation or GBI, based on plant, soil and weather sensors).
12. Usefulness of different foliar spray fertilizer strategies, with an emphasis on small- and medium-size mango producers without proper irrigation systems in place, as alternative or complementary to manual soil fertilization. (Qualitative research).

The above proposed studies are recommended to be conducted for a minimum of three to five production seasons in order to properly evaluate the impact of different irrigation

and/or fertilization strategies on relevant production variables (including alternate bearing) pertinent for the mango growers. Also, it is recommended to conduct these evaluations or part of them at the farms of growers who are interested in taking part in such projects. This can facilitate subsequent dissemination of the information among the mango growers, locally and internationally, in a more effective way.

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Table 1. Evaluated irrigation strategies on mango worldwide in general and in Latin America in particular and the suggested best treatment according to the results.

N°	Author	year	Evaluated technique*				number of treatments	Evaluated years	Cultivar	Orchard Place	Outstanding treatment	Evaluated phenological period**				
			SDI	RDI	PRD	Other						F-FS	MFG	FFG	EFPP	(PH)
1	Chandel and Singh	1992	X				4	1	Dasbehari	Himachal Pradesh India	20% available soil moisture (ASM)	-	-	-	X	-
2	Pavel and de Villiers	2004		X			5	1	Kent	Hoedspruit, S. Africa	Co (85% from farm control)	-	-	-	X	-
3	Durán Zuazo et al.	2004				Salinity	4	4	Osteen	El Zahori-Spain	Control= dSm-1	-	-	-	X	-
4	Spreer and et al.	2006	X		X		4-5	2	Chok Anan	Chiang Mai, Thailand	D1-75% and PRD 50% of Etc	-	-	-	X	-
5	Spreer et al.	2007		X	X		4	2	Chok Anan	Chiang Mai, Thailand	partial root zone drying (PRD = 50% of ETC, applied to alternating sides of the root zone)	-	-	-	X	-
6	da Silva et al.	2009		X			4	2	Tommy Atkins	Semi-Arid Brazil	T3 = 90% of reference evapotranspiration - Eto	-	-	-	X	-
7	Spreer and et al.	2009		X	X		4	2	Chok Anan	Chiang Mai, Thailand	c) PRD with 50% of ETC (PRD)	-	-	-	X	-
8	Coelho Filho, et al.	2009			X		5	1	Kent	Fazenda Boa Vista-Brazil	T-1= Treatment without deficit	-	-	-	X	-
9	Cotrim et al.	2011		X			10 and 8	2	Tommy Atkins	Semi-Arid Brazil	T1 -full irrigation (100% ETC) in phases II and III and 40% of ETC in Phase I (NS)	X	X	X	-	-
10	Durán Zuazo, et al.	2011	X				4	3	Osteen	El Zahori-Spain	SDI-2=50% of Etc	-	-	-	X	-
11	Santos et al.	2014		X			5	2	Tommy Atkins	Semi-Arid Brazil	T4=100% of ETC from early flowering to late fruit expansion and 50% of ETC during physiologic ripening	x	x	x	-	-
12	Levin et al. a,b	2015		X			12	4	Keitt	Israel	T-4 in FFG and PH= 9.2 and 5.4 mm/day, respectively.	-	x	x	-	x
13	Santos et al.	2015			X		5	1	Tommy Atkins	Ceraíma, Guanambi, Bahia, Brazil	5) 40% of ETC with alt. irrig. side of 15 days	-	-	-	X	-
14	Faria et al.	2016		X			5	2	Tommy Atkins	Vales do São Francisco-Brazil	T1 (0% of ETC without irrigation in flowering induction period (FI) and 100% in fruiting phase (FII)), T2 (25% of ETC in FI and 100% in FII)	X	-	-	X	-
15	Santos et al.	2016		x	x		12	2	Tommy Atkins	Ceraíma, Bahia, Brazil	RDI50S3 - full irrigation, 100% of ETC in stages I and II and 50% of ETC in stage III- (RDI at fruit maturation only)	X	X	X	-	-

\*SDI= sustained deficit irrigation; RDI= regulated deficit irrigation; PRD= partial rootzone drying.

\*\*F-FS= flowering-fruit set; MFG= main fruit growth; FFG= final fruit growth; EFPP= entire fruit production period; PH= post-harvest.

Pictures "a" and "b": mango trees irrigated by gravity/furrow irrigation. Pictures "c", "d" and "e" mango trees irrigated by drip irrigation.



