DEFICIT IRRIGATION CONTRIBUTION TO IMPROVE WATER USE EFFICIENCY IN WATER SUPPLY AND UTILIZATION CHAIN

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ABSTRACT

One of the main requisite for having sustainable agriculture is establishing equilibrium between resources which are consumed in crop production procedure. Water is always the primary limiting element in crop production cycle in most of the regions in the world where rainfall amount is not enough to supply plant water requirement. In this research, the effect of deficit irrigation on total water use efficiency in water supply and utilization chain has been computed. A systematic and quantitative approach was applied to determine water use efficiency. Water supply system for crop production could start with pumping from deep well, Or taking water from diversion channel from irrigation network canal. How to distribute water to the field is important practice to determine total water use efficiency in field system. Deficit irrigation strategies are used when farmers have less water than the maximum evapotranspiration (ET), and have to irrigate their fields at levels below full ET. At first glance, we just use less water than usual, so the application efficiency would be increased because most or all of the applied water remains in the root zone. But in fact, we also altered some inherent behaviors of plant compared to normal condition. Studies showed that the final product specification and quality indices are improved by applying deficit irrigation strategies.

This fact relies on the role of deficit irrigation in changing the resource partitioning pattern in photosynthesis and plant metabolism. Total water use efficiency is calculated as final product mass divided by total volume of water delivered to the field. Due to the multiplying feature of improvement in efficiencies chain in each step for calculating the overall efficiency, it is important to know how improvements in the efficiency of the steps affect the overall efficiency. For example it is demonstrated in studies that deficit irrigation during specific growth period of plants could control the excessive vegetative growth in some plants. And consequently yield efficiency would be increased. Also in plants that secondary metabolites such as essential oils are used as final product, it is proved that deficit irrigation can alter the metabolism to produce more essential oil.

In this study, the peppermint plants were subjected to regulated deficit irrigation and partial root-zone drying. Peppermint was cultivated under full irrigation (FI, control) and regulated deficit irrigation treatments including RDI85, RDI70, RDI55 and RDI40 receiving 85, 70, 55 and 40% of FI treatment, respectively; Partial root zone drying techniques including PRD70, PRD55 and PRD40 receiving 70, 55 and 40% of FI treatment in one side of root zone at each irrigation event, respectively. Four components of total wet biomass, dried biomass, leave weight and essential oil as final product were investigated. Improvements in efficiency of each step were calculated. The highest improvement in efficiency in wet biomass stage, which has not significant difference with highest yield, was corresponded to PRD70 treatment (18.6% improvement). In dried biomass section, the highest improvement in the

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section considering not having significant difference with highest yield was made by PRD40 treatment (27.7% improvement). The highest improvement in efficiency in leaves weight, which has not significant difference with highest yield, was found in case of RDI55 treatment (9.94% improvement). In essential oil yield step, as final procedure, highest improvements observed in PRD55 treatment with 91.95% improvement in efficiency compared to control treatment. According to the results and calculating overall efficiency, PRD55 treatment improved water use efficiency by 173% compared to the control treatment. By applying such investigations, weaknesses and strengths of deficit irrigation strategies could be revealed and actions and measures could be implemented to improve water use efficiency as much as possible.

Keywords: drought, food security, water productivity, irrigation management.

1. INTRODUCTION

Sustainable agriculture is establishing equilibrium between resources which are consumed in crop production procedure in a way that beside reasonable yield, the production also remain sustainable. Water is definitely the most important fraction of resources which plays essential role in production cycle. Due to the limited availability of freshwater, there are a lot of pressures on the agricultural sector as the largest consumer of water to improve water use efficiency (WUE). Food production using water as a key input is usually complicated process which is influenced by management decisions and environmental criteria. To inspect where the inefficiency lies, to evaluate the potential improvements, and most importantly of all, to discover how to allocate available resource to maximize the enhancement in water productivity, a systematic and quantitative approach is needed (Hsiao et al. 2007).
One of the methods to increase WUE, is irrigation management practices based on understanding the effects of water deficit. Water stress, affects plant growth and productivity in many ways.

Most of the reactions have a negative effect on production but plants have different and often multiplex mechanisms to react to water shortages. Regulated Deficit Irrigation (RDI) and Partial root zone drying (PRD) is the strategy of reducing irrigation rates and managing how and where to irrigate during a specific period of growth and development, with the objective of conserving water and managing plant growth while maintaining yield and quality. RDI has frequently proved to be an efficient tool to optimize water-use efficiency (WUE) of different crops such as grapes, pears, citrus and etc. (Romero et al 2013, Cui et al. 2008, and Panigrahi et al. 2014). In addition to the possible water savings, some investigations have also shown that deficit irrigation during plant growth period also may have a positive effect on quality (Faci et al. 2014, Cui et al. 2008, Hueso and Cuevas 2008).

By alternately wetting and drying part of root zone, PRD may allow the induction of the abscisic acid (ABA)-based root-to-shoot chemical signaling to regulate growth and water use (Wang et al. 2012). Across several crop species, PRD has shown a potential in saving water and increasing WUE (Wang et al. 2012, Kang et al. 2001, Guang-Cheng et al. 2008, Wakrim et al. 2005, Savic et al. 2009, Stikic et al. 2003, Tang et al. 2010). The impact of partial root zone drying on quality has been investigated for some plant species. In many cases, a positive influence on quality was reported such as Mango (Spreer et al. 2007), potato (Shahnazari et al. 2007), tomato (Stikic et al. 2003) and ‘Golden Delicious’ apples (Zegbe et al. 2011).

2. Concept of chain of efficiency steps:

1. When the production of a product is complicated and the starting resource input goes through many processing steps sequentially ending in the product, a simple approach is available to quantify the overall efficiency of the whole in terms of the efficiency of each of the component steps (Hsiao et al. 2007). Because the processing steps are in sequence and comes one after another, the output of the first step is the input of the second step, and the output of the second step is the input of the third step, etc. In equation form:

$$\mathrm{Output_i} = \mathrm{Input_{i+1}}$$
$$E_i = \frac{output_i}{Input_i} = \frac{Output_i}{Output_{i-1}}$$

2. This gives rise, inevitably, the following relationship between the efficiency of individual steps and the overall efficiency:

$$E_{all} = \frac{output_1}{Input_1} \times \frac{Output_2}{Output_1} \times \frac{Output_3}{Output_2} \times \ldots \times \frac{Output_i}{Output_{i-1}} = \frac{Output_i}{Input_1}$$

3. Deficit irrigation could improve WUE by adjusting water application efficiency and harvest index (yield efficiency). Improvements achieved by applying deficit irrigation strategies could be formulated by equations below:

$$E_{i,new} = (1 + \Delta_i) E_{i,Orginal}$$
$$\cdots$$
$$E_{all,new} = E_{all,Orginal} \times \prod_i (1 + \Delta_i)$$

Various plants are different in efficiency of irrigation water use.

4. Medicinal plants, as a collection of plants with high economic value, can produce more capital than other plants in terms of water use. Peppermint herb as a plant with high economic value which widely used in medicines, hygiene and oral medications, was selected for this experiment. Peppermint is grown for commercial production of essential oil, dry leaves and fresh herb market. Peppermint essential oil is a major aromatic agent used extensively in chewing gum, toothpaste, mouth washes, pharmaceuticals and confectionary and aromatherapy products (zheljakov 2010). It has long been evident that conditions of limited soil moisture can alter the content and yield of secondary metabolites in medicinal and aromatic plants. Results with peppermint, however, have not been conclusive. Nakawuka et al. (2014) investigated the effect of deficit irrigation on yield, quality and costs of the production of native spearmint.

5. Their field experiment included four irrigation levels; 40, 54, 80, and 100% of ETc. they indicated that applying up to 60% less water to native spearmint plants can yield oil of similar quantity and quality to that obtained from fully irrigated plants. They also reported that water stress in native spearmint can increase WUE and reduce the total production costs. The objective of this study was to determine the efficiency of each step from fresh herb yield to essential oil of peppermint and WUE with regulated deficit irrigation and partial root-zone drying in field condition. To the best of our knowledge, the effects of partial root zone drying on medicinal plants and specially peppermint, have not yet been investigated.

3. METHODS

The field experiments were carried out in 2013 at the research farm of Sari Agricultural Sciences and Natural Resources University, Sari, Iran. Weather data was collected at a nearby climate station (12km). Fig. 1 A and B illustrates precipitation and air temperature during growing season. The soil texture was clay loam with PH 7.4, containing 0.98% organic carbon, 100 ppm available potassium, 1.8 ppm available phosphors. Soil moisture (volumetric water content) at field capacity (FC) in the plant root zone was 30% and bulk density 1.36 g/cm^3. The experimental area was divided into 32 plots of 3 × 2 m^2 (length × width). Plots of peppermint were planted in May 7, 2013. Each plot consisted of five rows with 3 m length, 40 cm between rows and a distance of 20 cm between plants in the rows.

The experimental design was a randomized complete block with four replications and eight irrigation treatment. Irrigation treatments consisted of full irrigation (FI) that received 100% of evaporation demand; regulated deficit irrigation (RDI) treatments including RDI85, RDI70, RDI55 and RDI40 receiving 85, 70, 55 and 40% of FI treatments at each irrigation event, respectively; Partial root zone drying (PRD) techniques including PRD70, PRD55 and PRD40 receiving 70, 55 and 40% of FI treatments in one side of root zone at each irrigation event, respectively. Plant water use (evapotranspiration) was estimated by monitoring water balance components in the soil. Net irrigation requirement (I_n. mm) was determined based on equation as follows:

$$I_n = \sum_{i=1}^{n} (\theta_{Fc} - \theta_{Bi}) D_i / E_a$$

Where θ_{Fc} and θ_{Bi} are volumetric soil water content at field capacity and before irrigation (%), respectively; D_i is soil layer depth (mm); i is layer number and n is number of layers; E_a is irrigation efficiency (90%). θ_{Fc} was measured in the field and laboratory before planting time. θ_{Bi} was measured by Time Domain Reflectometer sensors (TDR), before each irrigation event. IDRG SMS T-2 TDR probes were installed in two layers, measuring the soil moisture variations in 10 cm intervals. There was no significant rainfall during applying deficit irrigation treatments. A drip irrigation system with two parallel drip line with emitters of every 20cm for each row in plot was used to applying irrigation treatments. All plots were irrigated in same amount to set up uniform stands across all plots. Deficit irrigation treatments were implemented 40 days after planting. The volume of irrigation applied to each plot was measured by flow meters.

Plants were harvested in mid-flowering stage, 92 days after planting after removal of two adjacent rows of plants and 30 cm from each side in the 06 august, 2013. Plants were weighed for fresh herbage yield and then air dried in shade for one week and then they were weighed for biological yield. Flowers and aerial parts essential oil contents were determined using a Clevenger apparatus. Air-dried flowers and leaves were finely ground and eighty grams subjected to 500 ml water distillation and run for 3 hours using Clevenger apparatus.

According to efficiency chain, the first step would be the water used for producing fresh herbage yield. Then we got the dried yield. After that we extract essential oil from leaves and aerial parts. So we would have a chain of efficiencies like below:

$$E_1 \times E_2 \times E_3 \times E_4 = E_{overall} \quad (6)$$

$$\frac{Fresh\ \ herbage\ yiled}{water\ delivered} \times \frac{Dried\ yield}{Fresh\ herbage\ yield} \times \frac{Leaves\ and\ aerial\ parts}{Dried\ yield} \times \frac{Essential\ oil}{Leaves\ and\ aerial\ parts} = \frac{Essential\ oil}{Water\ delivered} \quad (7)$$

To calculate improvements achieved in each step and for each treatment, below equation were applied.

$$\left(\frac{Fresh\ \ herbage\ yiled}{water\ delivered}\right)_{New} = (1+\Delta_1)\left(\frac{Fresh\ \ herbage\ yiled}{water\ delivered}\right) \quad (8)$$

$$\ldots$$

$$\left(\frac{Essential\ oil}{Water\ delivered}\right)_{New} = (1+\Delta_{Overall})\left(\frac{Essential\ oil}{Water\ delivered}\right)$$

Data were subjected to analysis of variance using SPSS statistical package (version 21). Each treatment measured parameters means were compared using Duncan multiple range test ($p < 0.01$).

4. RESULTS AND DISCUSSION

Yield and yield components and essential oil yield are summarized in table 1. Irrigation treatments had significant effect on all yield parameters except leaves and aerial parts. Fresh herbage yield increased with increasing the depth of applied water. Maximum fresh herbage yield was corresponded to FI treatment (9427 kg.ha^{-1}) whereas the lowest one was observed in RDI40 treatment (5729 kg.ha^{-1}). Significant reduction in fresh herbage yield as a result of water deficit also reported by Ghanbari et al. (2013) in peppermint, Okwany et al. (2012) and Meskelu et al (2014) in spearmint, Khalil et al. (2010) and Ekren et al. (2012) in basil and Ozturk et al. (2004) in lemon balm.

There was no significant difference between FI and RDI85 and PRD70. PRD treatments outperformed RDI treatments in term of fresh herbage yield. Biological yield significantly decreased by implementing deficit irrigation practices. Similar to the results of fresh herbage yield, the highest biological yield achieved in FI treatment (1942 kg.ha-1) and the lowest one observed in RDI40 treatment (1288 kg.ha-1). There was no significant difference between FI, PRD and RDI treatments except RDI40 in biological yield. In herbaceous plants, yield components consists of leaves and stem. As seen in table 1, there was no significant difference in leaves weight and stem and wooden parts weight between treatments. But there is downward trend in both PRD and RDI treatments which cause significant reduction in fresh herbage yield and biological yield. Significant reduction in leaves weight and dried herb yield reported by Ekren et al. (2012) in purple basil and Ghanbari and Ariafar, (2013) in peppermint.

According to the table 1, the highest oil yield achieved in PRD70 treatment (23.67 kg/ha) and lowest one obtained in RDI40 treatment (11 kg/ha). Despite decreasing irrigation regimes, there was no significant difference between RDI and FI treatments. In RDI treatments, essential oil yield indicated upward trend to RDI70 treatment and after that, it decreased with applying more water deficit level. Applying PRD70 and PRD55 significantly increased oil yield. PRD treatments outperformed RDI treatments in term of oil yield and also it was more than full irrigation treatment. The upward trend and significant increase in essential oil ratio in medicinal and aromatic plants affected by water deficit has also been documented by Nakawuka et al (2014) in spearmint, Ghanbari and Ariafar (2013) and Charles et al (1990) in peppermint, Ozturk et al (2004) in lemon balm, Ekren et al (2012) in purple basil, Rahmani et al (2012) in marigold. Ghanbari and Ariafar (2013) reported that highest value for oil ratio was observed in 30% FC and highest shoot yield belonged to 70% FC but the highest oil yield was observed in 50% FC in peppermint. They believe that the drought stress increases the essential oil percentage of more medicinal and aromatic plants, because in case of stress, more metabolites are produced in the plants and substances prevent from oxidization in the cell.

Rahmani et al (2012) also support this idea that increase in essential oil ratio is response to water deficit in order to reducing the intercellular oxidative damages in marigold plant. Charles et al (1990) demonstrated that water deficit may have affected essential oil accumulation indirectly through its effects on either net assimilation or the partitioning of assimilates among growth and differentiation processes. The reduction in growth induced by lower soil moisture may have resulted in a new pattern of resource partitioning, perhaps providing additional carbon skeletons for terpene biosynthesis and accumulation (Charles et al 1990). Selmar and Kleinwachter (2013) stated that stress-induced enhancement of natural products can be explained as follows: because of the stomata closure due to the incipient water deficiency, the uptake of CO^2 markedly decreases.

As a result, the consumption of reduction equivalents ($NADPH^+H^+$) for the CO^2-fixation via Calvin cycle declines considerably, generating a massive oversupply of $NADPH^+H^+$. As consequence, metabolic processes are pushed toward the synthesis of highly reduced compounds, like isoprenoids, phenols or alkaloids.

Table1. Effect of deficit irrigation management on Fresh herbage yield, dried yield, leaves and aerial parts weight and essential oil yield of Peppermint.

Treatment	Fresh herbage yield ($Kg.ha^{-1}$)	Dried yield ($Kg.ha^{-1}$)	Leaves and aerial parts ($Kg.ha^{-1}$)	Essential oil ($Kg.ha^{-1}$)
FI	9428 a*	1942 ^{a}	1104	14.14 ^{c}
RDI_{85}	8315 ^{ab}	1908 ^{ab}	1077	14.52 ^{c}
RDI_{70}	7122 ^{bcd}	1726 ^{ab}	925	15.36 ^{bc}
RDI_{55}	5729 ^{cd}	1536 ^{bc}	897	14.74 ^{c}
RDI_{40}	5290 ^{d}	1288 ^{c}	805	11.00 ^{c}
PRD_{70}	7824 ^{abc}	1833 ^{ab}	991	23.67 ^{a}
PRD_{55}	6554 ^{bcd}	1581 ^{abc}	866	21.29 ^{ab}
PRD_{40}	5961 ^{cd}	1568 ^{abc}	935	14.57 ^{c}
ANOVA	**	**	ns	**

*For a given variable, mean values not sharing common letters are significantly different ($P \leq 0.01$), Duncan test.

Table 2 and 3 demonstrate the results related to the efficiency of each step in essential oil production process and improvements achieved in each step. The highest efficiency in fresh herb yield consumed water achieved in RDI_{40}which was expectable. Highest efficiency without significant difference with highest yield achieved in PRD_{70} as much as 6.37 and 18.6% improvement compared to FI treatment. The highest efficiency in fresh herb yield conversion to dried yield was achieved in RDI_{55}. Highest efficiency without significant difference with highest yield was achieved in PRD_{40} as much as 0.26 and 27.7% improvement compared to FI treatment. According to non-significant difference among leave and aerial parts, highest efficacy and improvement, both was observed in PRD_{40} as much as 0.63 and 9.94% compared to FI treatment. In bottommost stage, which is essential oil yield from leaves and aerial parts, highest improvement in efficiency achieved in PRD_{55} about 91.95% compared to FI treatment.

Table 2. Efficiency of each step in essential oil production process

Treatment	$\frac{Freshherbageyiled}{waterdelivered}$	$\frac{Driedyield}{Freshherbageyie}$	$\frac{Leavesandaerialpa}{Driedyield}$	$\frac{Essentialoil}{Leavesandaerialpa}$	$\frac{Essentialoil}{Waterdelivered}$
FI	5.38	0.21	0.57	0.0128	0.0081
RDI_{85}	5.58	0.23	0.56	0.0135	0.0097
RDI_{70}	5.8	0.24	0.54	0.0166	0.0125
RDI_{55}	5.94	0.27	0.58	0.0164	0.0153
RDI_{40}	7.54	0.24	0.63	0.0137	0.0157
PRD_{70}	6.37	0.23	0.54	0.0239	0.0193
PRD_{55}	6.79	0.24	0.55	0.0246	0.0221
PRD_{40}	8.5	0.26	0.6	0.0156	0.0208

Table 3. Percentage of improvement in efficiency of each step in essential oil production process

Treatment	Δ_1	Δ_2	Δ_3	Δ_4
RDI_{85}/FI	3.758517	11.40033	-0.70726	5.261748
RDI_{70}/FI	7.915631	17.65467	-5.72835	29.64899
RDI_{55}/FI	10.48328	30.16156	2.726237	28.29942
RDI_{40}/FI	40.27365	18.20356	9.941123	6.68822
PRD_{70}/FI	18.55264	13.73758	-4.89763	86.48516
PRD_{55}/FI	26.39334	17.11049	-3.64679	91.94528
PRD_{40}/FI	58.0664	27.70188	4.892806	21.66554

According to Fig 1, WUE of essential oil production as main phase, in PRD_{55} treatment had highest improvement as much as 173% compared to FI treatment which was had not significant difference with PRD_{70} treatment in oil yield. According to table 3T the stage with lowest efficiency in essential oil production was leave and aerial parts from dried yield. Regarding formula 3 and chain feature of efficiencies, farm management strategies should be applied to improve efficiency of this step. Sherma and kanjilala (1999) showed that changing plant density would cause increasing leaves to stem ratio. Also, Alsafar and Alhasan (2009) demonstrated that optimizing fertilizer use rate has positive effect on peppermint leaves yield. Applying these management approaches alongside deficit irrigation practices will induce the efficiency of this step which because of multiplication property of efficiencies, has great influence on WUE of essential oil production.

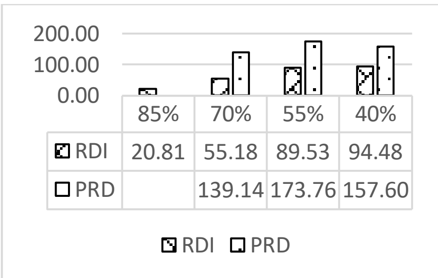

Fig 1. Percentage of improvements in overall WUE of essential oil production

5. CONCLUSIONS

High values of overall efficiencies of oil production in Table 2 and Fig 2 in PRD treatments compared to FI and RDI treatments, shows high performance of this deficit irrigation strategy. Results in recent studies on WUE of essential oil production process, show that WUEs observed in FI and RDI treatments in this study was in same range with other findings. With studying WUE of essential oil production in peppermint with chain features included, the phase with lowest efficiency could be recognized that could be adjusted with specific management plan. In this study, Leaves and aerial parts production as main source of essential oil had weakest function which should be optimized to adjust and gain more efficiency.

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