IS PARTIAL ROOT ZONE DRYING IRRIGATION A FEASIBLE WATER SAVING STRATEGY IN AFRICAN LEAFY VEGETABLE PRODUCTION? A REVIEW.

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Abstract

Kenya is considered a water deficit country with an annual water recharge of 640 m^3 per capita. Water saving irrigation technologies such as partial root zone drying (PRD) are important means to sustainably produce high yield and quality African leafy vegetables under water-limited conditions. PRD is a novel and innovative approach in which half of the root zone is irrigated interchangeably in a planned irrigation schedule. Several researchers in developed countries, particularly those from arid and semi-arid, have extensively evaluated PRD as a water saving irrigation strategy on field and horticultural crops without significant influence on both crop yield and quality. PRD actually improves product quality in several crop species as partial root zone drying exploits the drought induced abscisic acid root- to-shoot signalling to limit stomatal conductance which ultimately saves water. In this paper we review PRD results on various field and horticultural crops around the globe with the view of assessing the potential of its implementation in production of African leafy vegetables in urban and peri-urban areas in Kenya.

Keywords: Deificit irrigation, water use efficiency, abscisic acid, drought stress, plant signalling.

Introduction

African leafy vegetables (ALV) are important sources of human nutrients and household incomes (Arnold et al., 1985, Neven et al., 2009, Uusiku et al., 2010, Weinberger et al., 2011). This has led to promotion of their production and consumption. In Kenya, there was an increase in demand of ALV by 213% between 2001 and 2006 (Irungu et al., 2007). Water shortage between rainy seasons is the major constraint that limits their production in urban and peri-urban areas in Kenya (Jaetzold et al., 2007). With the increasing demand of ALV in such areas, there is need to come up with water saving strategies that would enable their continuous production to meet the consumers' demand. Efficient irrigation and water saving technologies are becoming increasingly important in vegetable production. Agronomic practices such as conservation tillage and mulching can reduce irrigation demand thereby improving water use efficiency (WUE).

Partial root zone drying (PRD) is a novel and innovative water-saving irrigation strategy that has been developed and tested in field crops, fruit crops and lately vegetable crops such as hot pepper (Kang et al., 2001) canola (Mousavi et al., 2010), eggplant (Dasgan and Kirda, 2007) and tomatoes (Zegbe et al., 2004). The objective of this paper is to review PRD as a water saving strategy and it's prospective for improving AIV production in urban and peri-urban areas in Kenya.

Deficit Irrigation (DI) and PRD have been applied to many crop species. DI is defined as an irrigation method in which the entire root zone is irrigated with a smaller amount of water than the prospective evapotranspiration (English and Raja (1996). The stress that develops has minimal effects on the ultimate yield of the crop. PRD is therefore a modification of DI whereby half of the root zone is irrigated while the other half is allowed to dry out. In alternate partial root zone drying irrigation (APRDI), the treatment is then reversed during the next irrigation cycle depending on the soil and climatic conditions, so that the formerly wetted part of the root system is allowed to dry to a predefined soil moisture content and the dry part is allowed to be irrigated (Stoll et al., 2000). In fixed partial root zone drying irrigation (FPRDI) the irrigation water is applied to a fixed root side during the entire growing season while keeping the other side in a dry condition. A pronounced proportion of research has been carried out to study the effects of PRD on yield, water use efficiency, quality and production of different crops ranging from field crops, trees to exotic vegetables. PRD has been widely researched on a number of field, tree and vegetable crops such as pear (Kang et al., 2002), grapevine (Stoll et al., 2000, De la Hera et al., 2007, Dos Santos et al., 2003), hot pepper (Kang et al., 2001), cucumber (Mao et al., 2003), maize (Kang et al., 1998), apple (Leib et al., 2006), cotton (Kaman et al., 2006), potato (Shahnazari et al., 2007, Shahnazari et al., 2008), eggplant (Dasgan and Kirda, 2007) and tomato (Bertin et al., 2000, Kaman et al., 2006, Kirda et al., 2004, Stikic et al., 2003, Zegbe et al., 2004, Zegbe-Domınguez et al., 2003), but no research or review has been focused out on any ALV.

Plant response to partial root zone drying irrigation

When PRD as a water saving strategy is used in crop production, the root to shoot signalling system that operates in water deficient soils is altered, causing the half dry part of the root system to produce abscisic acid (ABA). The fully hydrated part of the roots maintains a favourable water status all through to the aboveground parts of the plant. ABA is a plant hormone that can be produced by the roots as a result of dry spell in the soil. Once ABA is accumulated in the roots, it is transported by transpiration flow in the xylem to the shoot to regulate the shoot physiology (Kang and Zhang, 2004). In PRD roots sense the soil drying and induce ABA that decrease leaf expansion and stomatal conductance while at the same time the roots in wet soil absorb adequate water to retain a high water status in shoot (Liu et al., 2006) and (Zegbe et al., 2004). This resulted in saving water by the crop while at the same time increasing water use efficiency. It is noteworthy, a decrease in stomatal conductance impedes transpiration rate than it reduces intercellular Carbon dioxide concentration for photosynthesis in the early stages of water stress (Liu et al., 2005) . Shao et al. (2008) further indicated PRD resulted in a reduction in leaf water potential, decrease in stomatal conductance to carbon dioxide and loss of turgor and osmotic adjustment in severe water stress cases.

In PRD experiment where potato was grown in an automatic rain-out-shelter; leaf area index was reduced slightly in PRD than in full irrigation. In contrast, the tuber biomass for both PRD and FI were not significantly different in the last harvest (Liu et al., 2005), and (Liu et al., 2006). They further noted xylem sap abscisic acid concentration increased exponentially with a reduction in root water potential. According to Saeed et al. (2008), the period for wetting and drying depends on crop species; growing stage; evaporative demands; soil texture; and soil water balance.

Root development and water uptake in partial root zone drying irrigation

Wang et al. (2008) observed that root development and distribution were affected by spatial and temporal soil water distribution which in turn affects both, water and nutrient uptake from the soil in order to maintain the physiological activities of the above ground part of the maize crop. Earlier studies in maize have shown that controlled APRDI resulted in better root development and distribution is as a result of high root to shoot ratio (Kang et al., 1998). In essence better root proliferation will signify better water uptake by plants.

Water use and water use efficiency in partial root zone drying irrigation

Water use efficiency (WUE) can be defined in productivity term, i.e. the output of crop per unit of water (Jones, 2004). Water use efficiency have been reported to increase significantly under PRD irrigation when compared to conventional irrigation. The increase in irrigation water use efficiency has been reported in mango (Spreer et al., 2007), apple (Zegbe and Serna-Pérez, 2011), pear (Kang et al., 2002), grape (De la Hera et al., 2007), cotton (Tang et al., 2010), maize (Kang et al., 1998), tomato (Kirda et al., 2004), potato (Liu et al., 2006), canola (Mousavi et al., 2010) and hot pepper (Dorji et al., 2005). The output for mango was defined as the ratio of total fruit yields in tons per hectare to amount of irrigation water used during the experimental period (Spreer et al., 2007). Liu et al. (2006) defined WUE as an increment of the tuber biomass divided by the plant water use during the treatment period. According to Kirda et al. (2004) output of the tomatoes was determined as a ratio of total tomato fruits yield per Kg ha^{-1} to seasonal- irrigation water (mm) applied in different irrigation treatments.

Mousavi et al. (2010) defined Irrigation water use efficiency (IWUE, in kg m^{-3}) as the ratio of grain yield by the amount of water applied during the growing season. In hot pepper experiment, Dorji et al. (2005) determined crop output by dividing the total fresh mass of fruit by the volume of irrigation water (litres) applied to the individual plant. WUE according to (Kang et al., 1998) , was determined as the biomass production (grams) per unit amount of water consumed (Kilograms) by the crop during the experiment. PRD investigation on pear using flood irrigation system showed a water savings of 52% under FPRDI and 23% under APRDI without much reduction in fruit yield (Kang et al., 2002). When PRD was used in maize production, there was a reduction in water use by 35% with a resulting reduction in crop biomass of 6-11% when compared to fully watered plants (Kang and Zhang (2004). Another experiment by Kang et al. (2001) using hot pepper showed that PRD reduced water use by 40% while at the same time it maintained the same yields as in fully watered plants (Table 1). Similarly, Dorji et al. (2005) reported an increase in water use efficiency for hot pepper grown under PRD by 66.7% compared to commercial irrigation (CI) with a reduction in fruits number by 20% and biomass by 19%. Compared with full irrigation (FI), PRD irrigation saved 30% of irrigation water in potato production under field conditions while at the same time maintaining tuber yield, resulting in a 61% increase in irrigation water use efficiency (Shahnazari et al. (2007).

In field potato and tomato experiments, PRD saved 20–30% of the water used in fully irrigated plants and improved marketable yield significantly by 15% (Jensen et al. (2010). In processing tomatoes, PRD saved water by 50% and increased irrigation water use efficiency by 92% or 70% (furrow and drip irrigations, respectively) when compared to fully irrigated tomatoes (Zegbe et al. (2004). Drip irrigated PRD did not only increase irrigation water use efficiency but also kept the photosynthetic rate and leaf water potential equivalent to fully drip irrigated tomatoes. Mousavi et al. (2010) established that PRD increased irrigated water use efficiency for canola produced under greenhouse conditions. Similar results showed that PRD increased irrigation water use efficiency were reported in tomato (Kaman et al., 2006), apples (Leib et al., 2006), and maize (Li et al., 2010). Table 1 shows a summary of the effect of different PRD experiments on water use, water use efficiency, fruit quality, fruit size, fruit number, total biomass and yields. Table 2 indicates the corresponding soil and climatic characteristics of different PRD experiments.

Table 1. Effect of different PRD experiments on water use, WUE, fruit quality, fruit size, fruit number, total biomass, and yield

Crop	Applied Water (PRD/CI)	IWUE as % of full Irrigation	Total Biomass	Fruit Quality	Yield (%)	Reference
Grapes	1	+40	+	NM	+43 (+27 to +38 FS)	(De la Hera et al., 2007)
Potato	0.5	+38 to 61	NS	I	NS	(Jovanovic et al., 2010)
Potato	0.5	+61	NS		+20 MY	(Shahnazari et al., 2007)
Hot pepper	0.5	+52.1	-7.3 to -44.1		-23.98	(Shao et al., 2008)
Canola	0.5	+	+	NM	+	(Mousavi et al., 2010)
Mango	0.5	+	NS	I	+FS and +MY	(Spreer et al., 2007)
Green bean	0.5	+	NS		NS	(Gençoğlan et al., 2006)
Hot pepper	0.5	+166	-19	I	-20FN	(Dorji et al., 2005)
Apple	0.5	+	NS	I	+FQ	(Zegbe and Serna-Pérez, 2011)
Apple	0.5	+	NS		NS	(Leib et al., 2006)
Grapes	0.5	+54.5	NS	NM	NS	(Poni et al., 2009)
Pears	0.48 to 0.77	+12 to +28	NS	I	NS	(Kang et al., 2002)
Maize	0.5	+13.6 to +41.8	-	NM	NS	(Li et al., 2010)
Maize	0.5	+	NS		NS	(Hu et al., 2010)
Maize	0.5	+	-6 to -11		NS	(Kang et al., 1998)
Cotton	0.7	+	NS		-4.44 NS	(Tang et al., 2010)
Cotton	0.5	+88 to +95	NM		-3 to -6.4NS	(Kaman et al., 2006)
Tomato	0.5	+88 to 95	NM		NM	(Kaman et al., 2006)
Tomato	0.5	+64	NS	I	NS	(Zegbe et al., 2004)
Tomato	0.3 and 0.5	+56	-17 to -28	I	+10 to +27 MY	(Kirda et al., 2004)
Tomato	0.5	NM	NS	I	NS	(Zegbe-Domınguez et al., 2003)
Tomato	0.5	+	-22 to -26	I	-30	(Stikic et al., 2003)

(+): PRD practice increased the indicated factor
(-): PRD practice decreased the indicated factor
(NS): No significant differences
(NM): Not measured
(MY): Marketable yield
(FQ): Fruit quality
(FS): Fruit size
(FN): Fruit number
(I): Improvement of quality
(Blank): Information not indicated

Table 2. Soil and climatic Characteristics of selected PRD Experiments

Crop	Soil Type	pH	Bulk Density (g/cm^3)	Field Capacity (%)	Temperature (°C)	Humidity (%)	Rainfall (mm)	Reference
Grapes	Deep Clay Loam		NI	NI	15.5-30		290	(De la Hera et al., 2007)
Potato	Silty Clay		1.53		10-35	NM	187-237	(Jovanovic et al., 2010)
Potato	Coarse textured meltwater sand		1.46	43.9	10- 34		800	(Shahnazari et al., 2007)
Hot pepper	Clay Loam	6.4	1.35	25.8	20- 42	30- 80		(Shao et al., 2008)
Mango	High Stone Content (Regosol)							(Spreer et al., 2007)
Green bean	Sandy Clay	7.63	1.43	26.34	14.7- 38	48.1- 55.9	3.06- 55.9	(Gençoğlan et al., 2006)
Hot pepper	Bark: Pumice: Peat				15- 25			(Dorji et al., 2005)
Apple	Sandy Loam	7.5			14.6		416	(Zegbe and Serna-Pérez, 2011)
Canola	Sandy Loam	7.68	1.43	25	19.2		106	(Mousavi et al., 2010)
Grapes								(Poni et al., 2009)
Pear	Lemnos Loam		1.5					(Kang et al., 2002)
Maize	Loess Loam	4.5		24				(Li et al., 2010)
Maize	Loam	7.87	1.3	24	29/20	30- 60		(Hu et al., 2010)
Maize	Sandy Loam		1.1	24.3	30/15	70	110	(Kang et al., 1998)
Cotton	Saline Clay Loam		1.45	31			160	(Tang et al., 2010)
Cotton	Heavy Clay	7.7- 8	1.16- 1.25	40	28.1/9.9	66		(Kaman et al., 2006)
Tomato	Heavy Clay	7.7- 8	1.16- 1.25	40	28.1/9.9	66		(Kaman et al., 2006)
Tomato	Bark: Pumice: Peat (60:30:10)				25/15			(Zegbe et al., 2004)
Tomato	Heavy Clay				25/15	80/40		(Kirda et al., 2004)
Tomato	Bark: Pumice: Peat (60:30:10)							(Zegbe-Domınguez et al., 2003)
Tomato	Commercial Compost				28/20	70		(Stikic et al., 2003)

(NM): Not measured
(Blank): Information not indicated

Crop quality in partial root zone drying irrigation

Previous research showed that PRD can improve quality of several crops such as tomato, hot pepper, grapes, and pears (Table 1). In tomato, PRD did not only save water but it also improved the fruit quality by increasing water soluble dry matter (WSDM) in tomato fruits; WSDM consists of sugars mainly glucose and fructose, and organic acids, mostly citric and malic acids which have large influence on complete flavour of tomato fruits. The tomatoes marketable yield increased by 10- 27% for PRD compared to DI (Kirda et al. (2004) and Stikic et al. (2003). In hot pepper, fruit quality in terms of the total soluble solids concentration (sugars mainly glucose and fructose, and organic acids, mostly citric and malic acids) and colour development produced in a glasshouse improved under PRD (Dorji et al. (2005). PRD increased marketable yield in potatoes significantly by 15% due to improved tuber size distribution (Table 1) (Jensen et al. (2010). Dos Santos et al. (2003) reported an increase in grapes sugar content (sucrose). They showed that this was mainly attributed to better control of vegetative growth of the grapevine. The increase in sugar content had a direct influence on wine quality from PRD irrigated wine yards. In Golden Delicious apples production PRD increased the total soluble solids concentration (glucose and fructose) by 8.7% compared to CI (Table 1). The mean fruit weight loss was insignificantly different between PRD and CI treatments (Zegbe and Serna-Pérez, 2011).

Nutrient uptake in partial root zone drying irrigation

Dos Santos et al. (2003) and Kang et al. (2001) reported that due to PRD drying and rewetting episodes, new roots (secondary) were formed which extract nutrients from the soil and make them more available to the plants for efficient growth and physiological processes. Nutrient uptake was reported to be higher in PRD than in FI treatments (Kirda et al., 2004, Li et al., 2007, Shahnazari et al., 2008, Wang et al., 2009). (Kirda et al., 2004) applied nutrients continuously with irrigation water. Nutrient concentrations of 100, 30 and 200mgl^{-1} of N, P and K, respectively were maintained in irrigation water for FI treatment. The nutrient concentrations were attuned for other treatments in proportion to percentage decrease of applied irrigation water to ensure that all irrigation treatments received similar amount of nutrients. Fertilizers were applied continuously with irrigation water. The flow meter was installed in the delivery unit of the irrigation system to measure the amount of water applied for each independent irrigation treatment. The fruit quality was determined using brix method. Brix reading measures the actual sugar content within the plant after nutrients are applied. The higher the level of sugar within the plant tissue the stronger the plant and the better the yields which may indicate the nutrient uptake in relation to nutrient supply. (Li et al., 2007) studied the effect of (2 levels of soil moisture, 2 fertilization regimes (Nitrogen and no Nitrogen treatment) and 3 levels of irrigation water) and their combination on how growth and dry mass accumulation could vary with soil moisture and nutrition conditions. No fertilization and fertilization (with 0.10 g N/kg soil, 0.07 g P_2O_5/kg soil and 0.10 g K_2O/kg soil added) was used. Total N uptake is the sum of shoot and root uptakes. Nitrogen apparent recovery fraction (Nr, %) was defined as

$$Nr(\%) = \frac{\text{Total N uptake (N treatment)} - \text{Total N uptake (zero N treatment)}}{\text{Nitrogen applied}} X100$$

Irrigation method and water level had distinctly significant effect on apparent recovery fraction of applied N by the plant root system (Nr, defined as the ratio of the increased N uptake to N applied). They established that PRD increased Nr by 16.4% when compared to CI. (Shahnazari et al., 2008) investigated how PRD, DI, and FI irrigation strategies affected nitrogen content in the soil-plant system during the growing season. Fertilizers concentrations of 150 N, 30 P, 220 K, 30 Mg, and 200 S (kg ha^{-1}) after the initial N content in the root zone was determined in the laboratory as 12.3 kg ha^{-1} were used. Total nitrogen (N) content in plant dry material was determined at each harvest by complete combustion of the sample in oxygen and measurement in thermal conductivity cell. Drainage water was collected at the bottom of the lysimeter to measure the leached N during the growing season. Physiological N-use efficiency (PNUE, kg tuber yield per kg N uptake), and agronomic N-use efficiency (ANUE, kg tuber yield per kg N applied) were calculated for various treatments. The residual N content determined in layers 10–20 and 20–30cm for PRD was significantly lower than for FI. They deduced that the leaf N concentration for PRD was significantly higher than that of FI. This shows that N uptake was higher in PRD than FI. Wang et al. (2009) investigated the effects of PRD and DI on N uptake in potatoes. A peat substrate at concentrations of 1.78, 1.90 and 3.60 g mineral N, P and K, respectively was used for each pot (Table 2). After four weeks from plant emergence, 0.6 g N per pot (in form of urea) containing 5% ^{15}N-atoms was applied with irrigation water from the top of the pots. After the plants were subjected to 4 weeks of irrigation water treatment, leaf biomass, stems and tubers were harvested, oven dried and ground into fine powder to determine ^{15}N and total-N content analysis using the Dumas dry combustion method. PRD plants had significantly higher N contents in the leaves, stems and tubers; whereas, the ^{15}N content in the plant organs was similar for the FI, PRD, and DI plants. Kang and Zhang (2004) reported that the newly formed roots had higher nutrient recovery from the soil as a result of more available soil moisture after an irrigation event. The also noted that dewatering the soil-dried roots caused a flush of secondary roots to grow out which were responsible for efficient in nutrient uptake.

Crop biomass and yield in partial root zone drying irrigation

In maize, Wang et al. (2008) found out that there was 50% reduction in biomass accumulation in a severe water deficit treatment under PRD irrigation while maximum accumulation of biomass was reported under Conventional Irrigation (CI) (Table 1). In their experiments, three irrigation methods were used: conventional irrigation, alternate irrigation and fixed partial root zone drying irrigation with three different watering levels; severe water stressed plants; mild water stressed plants and well-watered plants. In almond fruits production, Egea et al. (2009) reported that PRD had a negative impact on the final kernel dry weight for the water stressed treatments (Table 1). Stikic et al. (2003) reported that as a consequence of PRD, the growth of the whole tomato plant was reduced. According to Zegbe et al. (2004), PRD maintained the fresh and dry mass of tomato fruits for processing when compared to fully irrigated plants. Fruit maturity was more pronounced in PRD in terms of the red colour exhibited by the tomato fruit (Table 1). The PRD tomatoes had a high total soluble solids concentration (sugars mainly glucose and fructose) and fruit dry mass than the control. In potato, Shahnazari et al. (2007) reported insignificant difference between the Conventional Irrigation (CI) and PRD in the leaf area index, dry mass and tuber yield. However, at the final harvest the high quality potatoes were higher by 20% in PRD than in full irrigation. In a hot pepper experiment, Shao et al. (2008) reported a 24% reduction in yield in PRD compared to CI. Dasgan and Kirda (2007) observed that PRD resulted in 25% and 17% decreases in shoot fresh weight and leaf area of plant, respectively, yet therefore was a 39% increase in fruit production for soilless grown eggplant in the greenhouse (Table 1).

Conclusion

There is no or limited information available on African indigenous vegetables (ALVs) water use in Kenya. African Leaf vegetables are known to grow under limited moisture levels due to their origin either in the tropics or subtropics areas where water is either scarce or it's of low quality. These vegetables are hardy and can withstand high daytime temperatures, intense sunlight and are rarely irrigated. Despite the numerous benefits and few limitations associated with PRD (Partial Rootzone Drying), its adoption has been low particularly in vegetable production. Research has shown that plants respond to PRD by production of Abscisic acid (ABA). ABA is produced by roots which restricts leaf area expansion and stomatal conductance causing a reduction in water loss thus increasing water use efficiency. The reduction in water use under PRD occurs without substantial effect on economic yield. ALVs are grown for their leaves in contrast to other vegetables such as tomatoes, potatoes, beans, canola and hot pepper that are grown for their fruits and where a lot of previous research on PRD has been carried out. There are a few scientific reports on the effect of PRD on herbaceous plants and vegetables in general. There is a need to further research on PRD as a water saving strategy not only on exotic vegetables but also on ALVs. To answer the question, if PRD is a feasible water saving strategy in ALVS production in Kenya? A research program on two model ALVs vegetables namely: Spider Plant and Ethiopian Kales will be carried out using drip and PRD irrigation methods at three different water levels of 40%, 60% and 80% field capacity (FC) at Jomo Kenyatta University of Agriculture and Technology (JKUAT) demonstration farm Juja, Kenya and later on in a farmer's field in Matuu area of Machakos County. These two areas were preferred because they are located in semi-arid areas of the country receiving annual rainfall of less than 800 mm. It's worth noting, these two areas produce both exotic and ALVs to meet the market demands for both urban and peri-urban areas of Machakos, Kiambu and Nairobi Counties. It's envisaged that we will determine the optimal amount of water required for Spider Plant and Ethiopian Kale production under drip and PRD irrigations and ultimately determine the response of drip and PRD irrigations on Spider plant and Ethiopian Kales production. The research will be carried out during the dry spell which occurs between December and March and again during the dry seasons which is estimated to occur in between November and January months. Overall, the results from the research are expected to be applied production at farm level conditions and guide approach on maximizing ALVs production under limited water conditions.

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