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Partial Root-Zone Drying Technique: from Water Saving to the Improvement of a Fruit Quality

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Due to climate changes and increased demands of different water users (agriculture, industry, domestic) water becomes scarce resources worldwide. Since irrigated agriculture is the one of the largest consumer of these resources (so-called blue water footprint), irrigation management must be shifted from maximal production per crop area to maximal production per unit of water used by crops. Among the strategies for reducing water footprints, changing the full irrigation to the reduced crop's water supply (deficit irrigation techniques) is one of the options. In this mini-review, we present the latest advances of partial root-zone drying (PRD) applications in different agricultural plants, with the special emphases on the PRD effects on increasing WUE, yield and yield quality. We describe two PRD practical approaches (alternate and fixed), background of PRD induced increase in yield and water use efficiency and improved understanding about nutrient use efficiency. The evidence of PRD effect on the increase in nutritional and health attributes of yield in different species is also presented. Because of limited available data, further research is needed to understand complex biosynthetic pathway and synthesis of nutritive- and health-related metabolites and antioxidants in PRD-treated plants. Practical application and promotion of this knowledge will allow farmers in water scarce areas to adapt PRD not only as a strategy for saving water, improving nutrient use and increase/sustain yield, but also for producing food with enhanced nutritive and health characteristics.

Keywords: health-related attributes, nutrient use efficiency, partial root-zone drying technique, quality-related attributes, water use efficiency, yield

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INTRODUCTION

In different countries, water become limited resource due to the climate change (especially severe and frequent drought), environmental pollution and increased demands of different water users (agriculture, industry, and domestic). Water is necessary for plant growth and development and consequently for a high and stable yield of agricultural plants. Because of the high proportion of water used for agricultural purposes and the projections that water scarcity due to unpredicted climate change will increase in the future (Mancosu et al., 2015), there is a constant need to focus on efficient use of available water resources in order to increase crop productivity per unit of used water.

In accordance with this goal in many countries, concept of water footprint (WFP) is used to provide accurate and useful assessment of water demands (Schmitz et al., 2013). For food crops (Costa et al., 2016), WFP concept includes all the fresh water consumed per unit of product (e.g., per liter of wine), namely to grow the crop, water used in post-harvest processing and also polluted water produced (volume of fresh water required to assimilate the pollutant load). In such WFP calculations, irrigated agriculture (so-called blue water footprint) is a major consumer of water (Hoekstra and Mekonnen, 2012).

One of the strategy for reducing water footprints, and saving available water resources for agricultural production is to reduce the amount of irrigation water compared to the amount used for crop's full irrigation (deficit irrigation techniques). Deficit irrigation techniques in the use are: regulated deficit irrigation (RDI) and partial root-zone drying (PRD) and they are based on the knowledge of crop's reactions to drought (FAO, 2002). RDI is irrigation technique when the amount of applied water is less than current crop's water needs during a specific period of their growth and development. PRD is irrigation technique when the one side of the plant's roots is exposed to drought and in the same time other side is irrigated. To avoid drying of the roots the wet/dry sides are rotated. Theoretical background of PRD is that irrigation of the part of root system keeps the upper part of crops in favorable water conditions, while the drought in other part of the roots induces formation of root chemical signals (mainly hormones). Root born chemical signals are transported to the upper part of the plants to induce reduction of stomatal conductance and shoot growth (Dodd et al., 2006). Partial reduction of stomatal conductance prevent serious water loss by transpiration and reduction of CO_2 assimilation, that could happen in dry conditions (Chaves et al., 2007).

The result of successful application of both deficit irrigation techniques (RDI or PRD) and comparison of their effects in terms of increase WUE and sustained/improved yield depends on several factors, especially on soil characteristics, the degree and duration of applied water deficit as well as crop species and its phenological phases. This leads to a discrepancy in the published research results. In his meta-analysis, Sadras (2009) concluded that from the aspects of water productivity both PRD and RDI do not differ significantly. Very recently, in another meta-analysis Adu et al. (2018) did not report differences in relative crop yield between PRD- and RDI-treated crops, but they pointed out that the effect on yield depends on crop species and soil structure. However, Dodd (2009) comparative study of the effects of PRD and RDI on the yield of different crop species have shown that unlike PRD, RDI plants were more exposed to the potential reduction of yield. This risk could be diminished by close monitoring plant water status in order to avoid development of severe drought stress that could significantly reduce yield. Advantages of the PRD in comparison to RDI is also based on the enhancement root growth and development and better control of vegetative vigor and assimilate partitioning (Mingo et al., 2004; Costa et al., 2007). Disadvantages of PRD system compared to RDI, are additional, more costly adapted irrigation systems which allowed interchangeable wetting and drying of the root-zone part and the time of switching required in operating PRD irrigation.

The aim of this review is to provide the latest advances of PRD applications in different agricultural and horticultural plants, with the special emphases on the PRD effects on water use efficiency, yield and yield/fruit quality. For explaining the physiological and biochemical background of deficit irrigation methods, including PRD technique, several review papers could be recommended (Costa et al., 2007; Fereres and Soriano, 2007; Ruiz-Sanchez et al., 2010; Sepaskhah and Ahmadi, 2010; Stikić et al., 2010; Du et al., 2015; Chai et al., 2016; Galindo et al., 2017; Kang et al., 2017).

PRD PRACTICAL APPROACH

The PRD has been successfully applied to a large number of crops and in different production systems. A number of trials with the PRD demonstrated that the main benefit of PRD irrigation is the reduced use of water for irrigation (Sepaskhah and Ahmadi, 2010). Many results indicated that for the successful application of PRD several factors should be taken into consideration, including: crops and variety-rootstock interaction, type and characteristics of soil, agricultural practice, specific agro-climatic conditions etc. (De la Hera et al., 2007; Chaves et al., 2010; Yactayo et al., 2013).

Partial root-zone drying practical approaches are based on root-sourced signaling mechanism and included the following types: fixed and alternate partial root-zone drying. In fixed PRD, the one half of the root system is irrigated throughout the growing season, while the other half is exposed to soil drying during the whole growth period. In alternate PRD watering and drying parts of root zone are changed, which enables the wet side of the root to dry down and dry side to be fully irrigated.

During PRD treatment the irrigation must be rotated regularly from wet to dry side in order to avoid drying of the roots from dry side and at the same time to allow a continuous production and transport of root signals. The frequency of the switch of the irrigated and partially dried root-zone sides also depends on soil characteristics and other environmental factors (rainfall and temperature). Soil water potential is usually applied as indicator for changing the side for irrigation in PRD system. However, modeling approach could be also used for irrigation scheduling. Recently, the basic model used to predict time to switch sides for irrigation and based on xylem ABA accumulation in PRD-treated potato plants (Liu et al., 2008), was enhanced and integrated in an adapted version of agro-ecological model DAISY (Plauborg et al., 2010). The model is developed to simulate the mechanisms underlying the water saving effects of the PRD.

Partial root-zone drying strategy also includes a different approach, as "static" PRD irrigation where a reduced amount of water received by the plant was constant during the whole growth period. Another approach is "dynamic" when the amounts of irrigated water were changed according to specific crop's phenological phase (Jensen et al., 2010; Jovanovic and Stikic, 2012; Ahmadi et al., 2014). PRD may be applied by different field irrigation methods (drip lines, furrow, micro-sprinkler etc.) depending on the crop species or soil texture or climate variables (Kang and Zhang, 2004).

Climate change impact on decreasing precipitation and rising temperatures could be mitigated by application of PRD method as a water saving strategy, especially in the water scarcity areas. However, the future predictions in a climate change scenario included also the increase greenhouse gases, and therefore, elevated CO_2 concentrations together with water shortage will be an additional challenge for PRD. Recently, experimental studies with elevated CO_2 concentrations condition indicated that photosynthetic rate and grain yield as well as water productivity in maize plants were higher under deficit irrigation than in full irrigation (Li et al., 2018). These results open a new direction to test the efficiency of PRD strategy in specific agro-ecological conditions and under interaction of different environmental variables.

WUE AND YIELD

Usually, water use efficiency (WUE) is considered as a measure of plant's efficiency in using water. WUE is a ratio between two physiological processes (i.e., transpiration and photosynthesis, i.e., carbon assimilation) or between agronomic parameters (i.e., yield and crop water use). WUE is a complex multitraits character related to different physiological and biochemical processes (involved in carbon and water uptake and transpiration) and controlled by many genes and environmental influences. In many environmental conditions, the challenge is to balance crop loss of water during transpiration with the efficiency of carbon uptake during photosynthesis, and therefore the increase of WUE is not always connected with the increase in yield (Blum, 2009).

Water use efficiency (WUE) can be defined in different ways depending on plant organization levels (Medrano et al., 2015). At crop level WUE as a ratio of the crop yield (marketable or economic) to total available water used by crops is most important from agronomic aspect. Many data from literature showed that the deficit irrigation techniques, especially PRD, may increase WUE and in same time sustain or improve the yield of irrigated plants (**Table 1**). Such effects could be explained by a wide range of PRD-specific positive responses of plants. Changes in stomatal morphological characteristics observed in PRD plants (smaller guard cells, lower stomata density) and lower conductivity affected transpiration and contributed to increase of water use efficiency, as well as enhance the photosynthetic capacity have positive impact on net photosynthesis (Wang et al., 2012b; Yan et al., 2012). Also, reduction of vegetative vigor and canopy area allowed better exposure of grains/fruits to solar radiation (more light penetrate the canopy) and induced remobilization of assimilates from vegetative tissues to the fruits/grains that consequently could improve yield and its quality (dos Santos et al., 2007; Chaves et al., 2010; Yang and Zhang, 2010; Zhang et al., 2010; Price et al., 2013). In addition, promotion of root growth and development and greater root biomass under PRD conditions increase plant hydraulic conductivity and water uptake (Mingo et al., 2004; Ahmadi et al., 2011; Hu et al., 2011; Pérez-Pérez et al., 2012).

Several literature data also showed that PRD increase the activity of soil microorganisms and higher root nutrient uptake capacity (Li et al., 2010; Sun et al., 2013b; Wang et al., 2013). Recently, Dodd et al. (2015) explained the increase of nitrogen and phosphorus uptake from different PRD-treated crops (Shahnazari et al., 2008; Jovanovic et al., 2012; Liu et al., 2015; Sun et al., 2015; Wang et al., 2017) with so-called "Birch effect." The effect was named on the honors of Birch (1958) who discovered that re-wetting of previously dry soil induce an increase in N mineralization. According to Dodd et al. (2015), the cause of "Birch effect" are changes of physical processes (soil aggregate disruption and consequent release of reactive P form), and biological processes (stimulation of soil microbes biomass and activities in mineralization of soil organic compounds) and both processes are coupled. However, much research efforts with different soil types should be done to determine when the rate of nutrient uptake increases under PRD. Also, the challenge is also to investigate the competitions between soil microbes and plants for nutrient resources.

TABLE 1 | The effect of partial root-zone drying (PRD) on water use efficiency (WUE) increase and sustained or improved yield in different agricultural crops (selected references).

Crops	Species	Reference
Perennials	Grape	dos Santos et al., 2003, 2007; Chaves et al., 2007; De la Hera et al., 2007; Du et al., 2008; Intrigliolo and Castel, 2009; Romero et al., 2016
	Apple	Talluto et al., 2008; Zegbe and Serna-Perez, 2012; Francaviglia et al., 2013; Du et al., 2017
	Pear	Kang et al., 2002
	Olive	Wahbi et al., 2005
	Lemon	Coelho et al., 2012; Pérez-Pérez et al., 2012
	Orange	Hutton and Loveys, 2011; Consoli et al., 2017
	Mandarin	Kirda et al., 2007a; Panigrahi et al., 2013
	Grapefruit	Kusakabe et al., 2016
	Pomengranate	Parvizi et al., 2014
	Mango	Spreer et al., 2009; dos Santos et al., 2015
	Papaya	de Lima et al., 2015
	Strawberry	Dodds et al., 2007
	Raspberry	Grant et al., 2004
Grain crops	Maize	Sepaskhah and Parand, 2006; Du et al., 2010; Yang et al., 2010
	Wheat	Sepaskhah and Hosseini, 2008; Du et al., 2010; Yang et al., 2010
	Rice	Yang and Zhang, 2010
	Sunflower	Sezen et al., 2011
	Cotton	Du et al., 2006; Kirda et al., 2007b; Tang et al., 2010
Vegetables	Tomato	Kirda et al., 2004; Zegbe et al., 2004; Campos et al., 2009; Affi et al., 2012
	Potato	Liu et al., 2006; Shahnazari et al., 2007; Ahmadi et al., 2010; Jensen et al., 2010; Jovanovic et al., 2010; Yactayo et al., 2013
	Sugar beet	Abyaneh et al., 2017
	Pepper	Dorji et al., 2005; Shao et al., 2008; Foday et al., 2012; Sezen et al., 2014
	Bean	Wakrim et al., 2005; Gencoglan et al., 2006
	Eggplant	Zhang et al., 2014

Although there is not enough results about connection between phytohormonal signaling and nutrient use, Kudoyarova et al. (2015) showed that availability in water supply and mineral nutrients modified phytohormonal status (ABA and cytokinins). Beis and Patakas (2015) results also confirmed that ABA/CKs ratio modulated physiological and biochemical responses in PRD and RDI plants. In PRD plants, cytokinins controlled stomatal reaction and shoot growth, while ABA concentration play a dominate role in stomatal responses to drought in RDI grapevines. Recent comparative study indicated that alternate PRD crops have a higher yield compared to fixed PRD (Dodd et al., 2015). Alternating wet and dry zones modifies phytohormonal signaling (ABA and CK) and induces changes in physical and biological processes in the soil environment with feedback on soil nutrient availability and as a result consequently improves crop nutrition.

CROP AND FRUIT QUALITY

Results from diverse agricultural species also demonstrated a beneficial effect of PRD on quality of yield and its nutritional or health values (**Table 2**). This is of particular importance for fruit and vegetables, which are important sources of bioactive components that have increased nutritional and health values.

Chemical components responsible for fruit nutritional values are mainly primary metabolites as sugars, proteins, lipids or minerals, although for the health-promoting fruit value, different secondary metabolites and antioxidant (carotenoids, flavonoids, phenolic compounds, etc.) are of special importance. However, despite the fact that PRD induces different crop/fruit quality parameters (both nutritional and health promoted), the number of published results is smaller compared to the effects of PRD on WUE and yield (**Tables 1** and **2**). Also, there is a very limited number of papers that explain the metabolic and molecular background of the impact of PRD on the quality of fruits/grains/tubers.

Because the plants under PRD are exposed to a certain degree of water stress, their reaction toward the accumulation of the metabolites responsible for the nutritional and the health-promoting value of their fruits/grains/tubers could be related to the effects of drought. Plants respond to drought with the activation of several signaling pathways resulting in a change of gene expression and enhancement of the biosynthesis of primary and secondary metabolites relevant for crop quality (Wang and Frei, 2011; Stagnari et al., 2016). According to Fanciullino et al. (2014) water stress may influence the secondary metabolism through two interactive mechanisms: the changes of primary metabolite transport (major source in the biosynthesis of carotenoids and ascorbic acid) or oxidative stress which could affect the biosynthetic pathways of antioxidant compounds. However, the understanding the secondary metabolic pathway in drought or deficit irrigation conditions is challenging because its components are more qualitative than quantitative comparing to primary metabolism. Current transcript and metabolite analysis showed that grape berries respond to drought by stimulating production of secondary metabolites (phenylpropanoids, zeaxanthin, monoterpenes), which have significant potential to affect both, grape and wine antioxidants and flavor characteristics (Savoi et al., 2016).

Concerning PRD, results of Francaviglia et al. (2013) demonstrated that the improved peel color of apple fruit under PRD was the result of changes in canopy structure and increased WUE and NUE, while total soluble solids accumulation (TSS) in the fruits may be due to translocation

TABLE 2 | The effect of partial root-zone drying (PRD) on improved yield quality- and health-related properties in different agricultural crops (selected references).

Crops	Species	Quality-related properties	Health-related metabolites	Reference
Perennials	Grape	TSS		dos Santos et al., 2003; Antolín et al., 2008
		TSS/TA	Vitamin C	Du et al., 2008
			Anthocyanins, phenols	Antolín et al., 2006; Chaves et al., 2007; dos Santos et al., 2007; Bindon et al., 2008; Conesa et al., 2016; Romero et al., 2016
			Resveratrol, Antioxidant capacity	Conesa et al., 2016
			Aminoacids	Romero et al., 2015, 2016
			Polyamines	Antolín et al., 2008
	Apple	Color, TSS		Fallahi et al., 2010; Francaviglia et al., 2013
		Firmness		Talluto et al., 2008
	Pear	TSS		O'Connell and Goodwin, 2007
	Olive	Oils	Polyphenols, antioxidants	Aganchich et al., 2007, 2008
	Orange	TSS, TA		Hutton and Loveys, 2011; Consoli et al., 2017
		Color	Flavonoids	Grilo et al., 2016
	Pomengranate	TSS		Parvizi and Sepaskhah, 2015
	Strawberry		Vitamin C, ellagic acid	Dodds et al., 2007
Grain crops	Cotton	Fibers		Tang et al., 2005
Vegetables	Tomato	Color, TSS		Davies et al., 2000; Zegbe et al., 2004; Casa and Rouphael, 2014
		Sugars, organic acids		Yang et al., 2012; Sun et al., 2014
		TA		Campos et al., 2009; Casa and Rouphael, 2014
		Ca, Mg, P, K		Sun et al., 2014
			Vitamin C	Xu et al., 2009; Yang et al., 2012; Bogale et al., 2016
			Lycopene, β-carotene	Bogale et al., 2016
			Phenols, antioxidant activity	Tahi et al., 2008; Jensen et al., 2010; Marjanovic et al., 2012; Bogale et al., 2016
	Potato	N		Shahnazari et al., 2008; Wang et al., 2009; Jovanovic et al., 2010
		Starch	Antioxidant activity	Jovanovic et al., 2010
	Sugar beet	Sugars		Topak et al., 2016; Abyaneh et al., 2017
	Pepper	TSS		Shao et al., 2008

TSS, total soluble solids; TA, titrable acidity.

of assimilate from the leaves to fruits or metabolic changes. Metabolic changes, regulated by PRD induced phytohormones (ABA and cytokinins), could be the result of higher conversion of starch to sugar, enhanced activities of enzymes involved in carbohydrate metabolism (starch-breaking, invertase, etc.) or *ex novo* synthesis of sucrose in the fruits (Ruan et al., 2010; Yang and Zhang, 2010). Results of Sun et al. (2013a) showed that the concentration of ABA was higher in xylem sap of PRD-treated tomato in relation to RDI plants. Higher accumulation of ABA in the fruits stimulates the activity of enzyme invertase and as a result the concentration of sugars hexose in the fruits is increased (Ruan et al., 2010).

Partial root-zone drying also has significant effects on secondary metabolites that are of special interest as phytochemicals responsible for quality- or health-related characteristics and antioxidants of fruits/grains. Results of Antolín et al. (2006, 2008) showed that under PRD changes in ABA content improved berry quality by increasing anthocyanin content and that increased mRNA induced accumulation of genes responsible for anthocyanin biosynthetic pathway (Jeong et al., 2004). According to Romero et al. (2016) reduced vegetative growth and increased light penetration into the canopy in PRD vines together with the increased ABA content and salicylic acid (in berries at harvest) might have an increasing effect on production of phenolic compounds which have a different roles (as antioxidants, stabilizators of anthocyanins, for wine color, etc). The same study reported that elevated amino acids concentration was also associated with their role as antioxidants and osmoprotectants as well as precursors for the synthesis of some aromatic substances important for the taste of wine.

Another challenge for PRD technique is that the exposure of plants to mild drought stress induced by PRD condition also increases accumulation of reactive oxygen species (ROS) with a harmful effect on cells. Increased activity of antioxidative enzymes such as superoxide dismutase, catalase, and guaiacol peroxidase in PRD plants (Aganchich et al., 2007; Lei et al., 2009) indirectly indicated that some degree of drought-induced oxidative stress could be generated under PRD conditions. Novel proteomic analyses of PRD tomato revealed that some of antioxidative enzymes were upregulated during fruit expansion phase and also indicated their potential role in protection of fruits against the mild drought stress induced by PRD (Marjanovic et al., 2012). Also, the results of Jensen et al. (2010) and Jovanovic et al. (2010) demonstrated that elevated antioxidant activity in PRD-treated potato and tomato plants had a beneficial effect on their nutrient contents.

CONCLUSION REMARKS

Practical implementation of the PRD provides the potential to increase water and nutrient use efficiencies and to improve the nutritional and health attributes of the different agricultural species, and in some cases sustain or even increase their yield. Although recent results explained that re-watering dry soil under PRD induce changes of different processes which affect soil N and P and their uptake by plants, more research is necessary for understanding the relationships between roots and soils microorganisms for these and other nutrients in different soil types and environmental conditions. The challenge is also to understand hormonal signaling under changes of nutrient and water resources and, particularly the role of cytokinins. Because of limited available data, further research is needed to understand complex biosynthetic pathway and synthesis of nutritive- and health-related metabolites and antioxidants in PRD-treated plants. Practical application and promotion of this knowledge will allow farmers in water scarce areas to adapt PRD not only as a strategy for saving water, improving nutrient use, and increase/sustain yield but also for producing food with enhanced nutritive and health characteristics.

AUTHOR CONTRIBUTIONS

ZJ conducted the literature survey, collected the relevant data and then wrote the first version of the manuscript. RS evaluated and improved the manuscript.

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