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REVIEW

Does water-saving irrigation improve the quality of fruits and vegetables? Evidence from meta-analysis

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Abstract
Water productivity has become a key requirement in sustainable crop production and environmental management. Deficit irrigation (DI) and partial root-zone drying irrigation (PRDI) are two strategies that have been exploited to maximize crop production per unit water, with attendant effect on the quality attributes of harvest index. We employed meta-analysis to synthesize evidence for the relative performance of full irrigation (FI), DI and PRDI for three quality attributes of fruits and vegetables, namely, total soluble solids (TSS), titratable acidity (TA) and pH. Overall, TSS, TA and pH of crops under DI and PRDI do not differ significantly. However, TSS in crops under DI and PRDI are significantly larger than that of crops under FI. DI and PRDI improve TSS by $4.1 \pm 1.8\%$ and $5.0 \pm 2.0\%$, respectively, relative to FI. Crops under the three irrigation techniques do not differ significantly in TA and pH. The differences in TSS of crops are contextual, depending on type of crop, soil texture and irrigation frequency. The effect of water-saving irrigation on the selected crop quality attributes may, therefore, have the add-on effects of crop, system and/or site characteristics. Therefore, in terms of quality attributes, water-saving irrigation techniques are superior to FI when considering improvement in TSS without significantly altering TA or pH of fruits and vegetables.

Introduction

Agricultural water productivity has become an important requirement for sustainable crop production due to dwindling water supplies, intensive competition for freshwater from multiple use sectors, changing climate, and rising food demand. Adequate supply of water in the root zone is indispensable for attaining high yields in crops (Morison et al. 2007; Yawson et al. 2016) as water is a major determinant of crop yields and a limiting factor in most agro-ecosystems (Yawson 2013). Crop production consumes about 70% of water abstracted worldwide (Yang et al. 2006; Yawson et al. 2014), with irrigation accounting for 60–80% of total consumptive water use (Huffaker and Hamilton 2007) and about 40% of total crop production (FAO 2016). Increasing water scarcity, in combination with the limits on breeding for water-efficient crops (Adu et al. 2018), has created an imperative for water-saving irrigation techniques in crop production. Water stress, however, can adversely affect both crop yields and quality (Carrijo et al. 2017).

Regulated reduction of water supply to crops is seen as one of the sustainable ways of managing water footprint and ensuring efficient use of water in crop production. To this end, water-saving irrigation approaches (including deficit and partial root-zone drying irrigation) which reduce irrigation water supply to below the full requirements of crops, or limit water applications to drought-sensitive growth stages, have become instrumental to maximizing water productivity and yields (Geerts and Raes 2009). Deficit irrigation (DI) techniques involve the supply of water below the full or optimum amount required by the crop for its physiological

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functions (Chai et al. 2016). Partial root-zone drying irrigation (PRDI) is a form of water-saving irrigation where there is an alternating irrigation and drying of each half of the crop's root system (Dodd et al. 2006; Loveys et al. 2004; Jovanovic and Stikic 2018). During PRDI, the plant root system is divided into two so that half of the roots are exposed to dry soil, while the other half remains under well-watered conditions (Loveys et al. 2004). Thus, in PRDI, water deficit is more manifested in the soil rather than in the plant (soil deficit), with the opposite (plant deficit) occurring under DI.

In addition to water productivity gains from these water-saving approaches (Sadras 2009), water-saving irrigation methods have also been exploited to control excessive vegetative vigor, whilst minimizing the impact on fruit growth (Nora et al. 2012). Water-saving irrigation might lead to yield penalties (Adu et al. 2018) but many plant species can tolerate some level of water stress (Nora et al. 2012). Depending on the severity and timing of the water stress, crop plants show different physiological, biochemical and molecular responses which directly or indirectly affect the quantity and quality of harvest index (Liu et al. 2005; Sepaskhah and Ahmadi 2010). For example, reductions in soil available water can either cause an upturn in the proportion of sugar in fruits, or induce a reduction in photosynthesis and thereby the sugar concentration in fruits (Jensen 2011). Hence, the application of water-saving irrigation techniques, especially in fruits and vegetables, should serve the twin purpose of increasing yields per unit water while, at least, maintaining the quality attributes of the produce to compensate for potential yield penalties (Adu et al. 2018; Costa et al. 2007; Nora et al. 2012; Stefanelli et al. 2010). In terms of quality traits, it is not yet clear which water-saving method (i.e., DI or PRDI) is superior and how well they compare with full irrigation (FI).

For some crops, premium is placed on certain quality attributes and therefore, trade-offs or yield reductions under reduced irrigation could be accommodated as long as it is compensated for by some improvement in desirable quality parameters. For water stress studies in vegetables, health-related metabolites (such as ascorbic acid, anthocyanins, phenols and flavonoids contents) are commonly used as quality parameters. Fruits are evaluated mostly in terms of sensorial attributes, including total soluble solids (TSS) or brix, sweetness, titratable acidity (TA), firmness and color (Nora et al. 2012). In apples, for example, there are reports that fruits from crops grown under DI or PRDI have higher TSS than those from fully irrigated plants (Leib et al. 2003; Mpelasoka et al. 2001). On the other hand, little or no differences in fruit quality parameters have been reported between conventional, deficit and PRDI in a commercial apple orchard (O'Connell and Goodwin 2007). In pear, deficit irrigated plants which were irrigated to 20% of ET_c, exhibited higher contents of TSS than fully irrigated plants, irrigated to 100% ET_c (Lopez et al. 2011). On the contrary, water stress did not influence soluble solids in Asian pear (Behboudian and Lawes 1994). Citrus fruits subjected to water stress had significantly higher-quality parameters such as increased TSS and TA, resulting in better organoleptic properties of the fruits (Treeby et al. 2007; Velez et al. 2007). However, citrus plants irrigated to 60% of a fully irrigated control practically did not record any effect on fruit quality (Castel and Buj 1989).

Further, in grapes, Du et al. (2008) reported that plants subjected to DI and PRDI recorded higher concentrations of both ascorbic acid and TSS, and lower TA, culminating in healthier and sweeter grapes. In Muscatel grapevines, DI and PRDI led to higher-quality grapes due to increased concentrations of phenols (dos santos et al. 2007). Conversely, in Cabernet Sauvignon berries, while there was significant rise in TA and drop in pH under PRDI, there was no significant difference in TSS between control plants and those subjected to PRDI (Dry 2005). In a follow-up study, total anthocyanin and phenolic concentration were also unaltered under PRDI (Dry 2005). Similarly, Miller et al. (1998) and Reid et al. (1996) reported of contradictory effect of reduced irrigation on fruit quality in Kiwi. The reports of Bordonaba and Terry (2010) and Terry et al. (2007) also did not agree on the effect of water stress on all quality parameters of strawberry. While varieties of tomatoes irrigated to 50% of field capacity had significant decreases in phenolic compounds (Sánchez-Rodríguez et al. 2011), DI improved TSS, TA and vitamin C of processing tomato under semi-arid Mediterranean climate (Patanè et al. 2011). Tomato fruit pH was not affected by applied water (Machado and Oliveira 2005) but in contrast, Sanders et al. (1989) reported that fruit pH of processing tomatoes decreased as irrigation rates increased. Between DI and PRDI, the results for many crops are also sparse.

Evidently, the effect of water stress or water-saving irrigation on the quality attributes in many crops has either been inconsistent, fragmented or anecdotal, suggesting the need for a pooled analysis or synthesis of the evidence. Undeniably, several studies or reviews have investigated the effect of water-saving irrigation techniques on quality attributes in different crops (Jovanovic and Stikic 2018; Ripoll et al. 2014; Nora et al. 2012; Ruiz Sánchez et al. 2010). Some reports have demonstrated that water-saving improved physical appearance and chemical attributes of fruit and vegetables (Cui et al. 2008; Liu et al. 2001; Verreynne et al. 2001). Nonetheless, previous reviews have been narrative and may be characterized by subjectivity, irreproducibility and limited capacity to handle large dataset. Again, these reviews have either focused on only one water-saving technique or on various water-saving irrigation strategies applied at particular locations or to particular crops. For example, Nora et al. (2012) narratively reviewed the effect of regulated deficit irrigation on postharvest quality of fruit and vegetables and reported some successful practices of regulated water stress in reducing water use with minimal losses in yield and quality. Recently, in another narrative review, Jovanovic and Stikic (2018) presented some evidence of the effect of PRDI on the nutritional and health attributes in different crop species but were quick to point out limited availability of data on the subject and the need for further research to elucidate the mechanisms underlying the synthesis of quality attributes in crops grown under PRDI. The present study provides insights into the comparative and cumulative effects of PRDI and DI on selected quality attributes of fruits and vegetables relative to FI. Following the procedure of Adu et al. (2018), the present study used meta-analysis to examine the performance of FI, DI and PRDI on three quality attributes, namely TSS, TA and pH.

Methods

Literature search and selection of relevant primary studies

We followed the approach reported in Adu et al. (2018) to retrieve and select relevant studies. Briefly, we searched for primary studies published between January 2003 and December 2017 that reported crop quality comparisons between FI, DI and PRDI. The search was done in Scopus and in Google Scholar. Abstract, title and keywords search was conducted with combinations of the following search terms in both databases: "full irrigation" OR "deficit irrigation" OR "partial root-zone" OR "partial rootzone" AND "fruit quality" OR brix OR TSS OR "total soluble solids". We only included studies (i) that reported primary data on TSS, TA or pH on individual crops in all the three irrigation practices; (ii) in which the scale of the observations of the quality attributes for the FI, DI and PRDI was comparable; (iii) that reported the mean (X), sample size (n) and a measure of dispersion (SE, SD, 95% CI; not necessarily mandatory) as numerical or graphical data, or if SD could be estimated from the reported data for all three irrigation regimes; and (iv) the data were not already included from another paper, to avoid multiple counting.

Standard deviations (SD) are required for meta-analysis but in several studies, the SDs on data for the quality attributes were not available. On such occasions, the SD values were computed from SE as previously described by Adu et al. (2018). Even so, there were cases where either SD or SE was not available and we were unsuccessful in retrieving same from corresponding authors. In such instances, the SD was reassigned as 10% of the mean for respective variables (Luo et al. 2006; Gattinger et al. 2012; Zhao et al. 2017), and subsequently, the effect of multiplying the mean by 1/10 on the results of the meta-analysis was assessed by sensitivity analyses (Adu et al. 2018). In several studies, we encountered non-independent observations, where there were (i) repeated measurements on the same crop over time and hence the same crops provide data for the different time-points or; (ii) data for additional variant treatments (sub groups) in the control or in each of the experimental groups. Such data types were combined into a single group for each crop or treatment. The sum of the sample size and the weighted average for each of the quality parameters for the various forms of DI or PRDI was calculated and used in the meta-analysis. The combined standard deviation was computed for each of the non-independent scenarios as previously described by Adu et al. (2018). Conversely, different crops were considered as independent subgroups and were included separately in the meta-analysis if the data reported were single time-point data for the different crops species or varieties.

Effect size

Effect size expresses the magnitude of an effect of interest. For this study, response ratio (R), the ratio of the means of the two groups being compared, was used. The R was used chiefly because the comparisons in the present study were based on pairs of means ($\bar{Y}_1$ and $\bar{Y}_2$), with attendant, sample sizes (n_1 and n_2) and standard deviations (s_1 and s_2). The R is useful in comparing the magnitudes of two means with the same sign and could be back-transformed (i.e., $R = e^{\ln R}$) for ease in interpretation. Moreover, when R is computed, the effect sizes are not affected by different variance in control and experimental groups and although needed to calculate variance, SDs or SEs are not needed for calculation of the effect size (Koricheva et al. 2013; Rosenberg et al. 2013). The R is generally transformed to a metric with more desirable properties using the natural log and so was computed using Eq. (1) (Rosenberg et al. 2013).

$$\ln R = \ln\left(\frac{\bar{Y}_1}{\bar{Y}_2}\right) = \ln \bar{Y}_1 - \ln \bar{Y}_2, \tag{1}$$

where $\bar{Y}_1$ and $\bar{Y}_2$ are the mean of the experimental group and mean of the control group, respectively. The variance of ln R is given by Eq. (2):

$$v_{\ln R} = \frac{s_1^2}{n_1 \bar{Y}_1^2} + \frac{s_2^2}{n_2 \bar{Y}_2^2}, \tag{2}$$

where n_1 and n_2 are the sample size of the experimental group and the control group, respectively, and s_1 and s_2 are the SDs of the experimental group and the control group, respectively (Rosenberg et al. 2013). Dependent on which irrigation strategy was defined as the control, three categories of meta-analysis were performed in this study for each of the three quality attributes. Thus, individually for TSS, TA or pH, we compared (i) DI and PRDI, (ii) FI and DI, and (iii) FI and PRDI. In (i) 'experimental treatments' were defined as plots with PRDI and 'controls' as plot with DI; in comparing FI with either DI or PRDI, 'experimental treatments' were defined as plots with (ii) DI and (iii) plots with PRDI, and 'controls' as plots with FI.

Overall effect size

A random-effects model of meta-analysis was used to determine the grand mean or the overall effect of irrigation on each crop quality attribute. Thus, a random-effect model was used to assess the impact on TSS, TA and pH under DI compared with PRDI or under FI compared with DI or PRDI. The studies included in this meta-analysis differed from each other and so variance must be partitioned into within- and between-studies variance. Hence, we considered random-effect model to be more plausible than fixed-effect model because the former assumes that the data being analyzed, in addition to having sampling error (e), has a true random component of variation in effect sizes between studies (ε). The restricted maximum likelihood method was used to estimate between-study variance. The mean effect size is considered significantly different from zero, if its confidence interval does not include zero (Koricheva et al. 2013).

Moderator variables and analyses

Several explanatory variables (moderators) may affect the magnitude of the response of the quality attributes to irrigation regime. The moderators considered in this meta-analysis correspond to some of the factors we believe are likely to influence the relationship between soil water availability and the quality attributes. Study characteristics such as crop species (several), agronomic purpose of crops (vegetables or fruits), location of the experiment (field or greenhouse) and the frequency of water supply to the crops (several), were gleaned from the primary studies (Supplementary Tables S1–S3). We also wanted to test the effect of study site characteristics on the quality attributes, so we collected information on soil texture (several) of the primary study site. Information on moderators was extracted from primary studies when available; otherwise, it was marked as 'not specified'.

The effects of moderators on the magnitude and direction of the response of the quality attributes to irrigation strategy were assessed for subsets of the database. Moderator analyses were performed only when there were at least two levels with enough sample size. The influence of subgroups (e.g., crop spp. or location of experiment—i.e., field vs greenhouse) on effect size was assessed through analyses of heterogeneity (Ebensperger et al. 2012). Here, the amount of variation was estimated by a Q statistic, a measure that partitions total heterogeneity into variance explained by the model (Q_{M}, often referred to as Q_{Between} or Q_{B}) and residual error not explained by the model (Q_{E}, often referred to as Q_{Within} or Q_{W}; i.e. $Q_{\mathrm{T}} = Q_{\mathrm{M}} + Q_{\mathrm{E}}$) (Koricheva et al. 2013; Rosenberg et al. 2000). Q_{B} and Q_{W} were tested against a X^2-distribution (significance level $p < 0.05$) (Koricheva et al. 2013; Rosenberg et al. 2000). We used mixed-effects models for the analysis of heterogeneity (Koricheva et al. 2013). Two moderator levels were significantly different if their 95% CI did not overlap (Ferreira et al. 2016). Respectively, statistically significant Q_{B} and Q_{E} imply that there are differences among cumulative effect sizes for the subgroups or there are differences among effect sizes not explained by the model (Rosenberg et al. 2000). Due to reported limitations of the Q statistic (Ebensperger et al. 2012; Koricheva et al. 2013), we complemented the Q estimates with the I^2 index. The I^2 can be interpreted as the percentage of total variability in a set of effect sizes because of differences between-study or between-comparisons (true heterogeneity) (Ebensperger et al. 2012).

Cumulative meta-analysis

It is plausible for the conclusions of meta-analyses on the same topic conducted in different years to differ. Analyzing the evolution of the effect size over time is, thus, important in interpreting the results of meta-analysis (Koricheva and Gurevitch 2014). We, therefore, conducted a cumulative meta-analysis in the present study. Here, the dataset was sorted in chronological order and the earliest study entered into the analysis first. A number of iterations of meta-analysis were conducted on the dataset but at each iteration, one more study was added to the analysis and the mean effect size and its attendant 95% CI recalculated (Leimu and Koricheva 2004; Rosenberg et al. 2000). The log response ratio of means, as described in Eq. 1, was used in calculating the effect sizes and CIs in the cumulative meta-analysis, except that the mean was not calculated for the whole dataset at once but rather, the mean and CI are recalculated each time a new study is added to the analysis (Leimu and Koricheva 2004).

Publication bias and sensitivity analysis

Publication bias was visually assessed by the funnel plot and subsequently, the 'trim and fill' method was used to assess potential impact of bias on the overall effect size if there was evidence of publication bias (Duval and Tweedie 2000; Ferreira et al. 2016; Jennions et al. 2013). In addition, the Rosenberg's fail-safe number (Nfs) was used to determine evidence of publication bias. The results were considered robust despite the possibility for publication bias if

Nfs > 5 × n + 10, where n = number of effect sizes (Adu et al. 2018; Jennions et al. 2013). In 78.5% of the total number of case studies for the TSS analysis, (Supplementary Table S1), SDs were estimated as 10% of the mean. A sensitivity analysis was, therefore, conducted to compare the robustness of results for primary studies that reported SDs and those that SDs were estimated as 10% of the mean. Data from both controlled environments (e.g., green or glasshouses, growth cabinets or in pots) and field were utilized in the present study. Using the TSS analysis, case studies from experiments conducted under field and controlled environments were 34 (81% of case studies) and 8 (19% of case studies), respectively (Supplementary Table S1). A second sensitivity analysis was conducted by comparing the effects for case studies where experiments had been conducted in controlled environments with that of case studies conducted under field conditions.

Data analyses

The data collection and classification were conducted with Excel 2016 (Microsoft Co. Redmond, USA). Some of the graphics were also produced using Excel 2016. OpenMEE, the open-source, cross-platform software for ecological and evolutionary meta-analysis (Wallace et al. 2016) was used for statistical analyses and in producing forest plots. Trim and Fill analysis was conducted using Metafor (Viechtbauer 2010), the package for meta-analysis in the R statistical software (R Core Team 2018).

Results

Overview of included studies

For the analysis of TSS, 46 studies met our inclusion criteria, representing 14 study countries, and reporting 58 DI-to-PRDI, FI-to-DI and FI-to-PRDI comparisons on 7 different crop species (Supplementary Table S1). The most commonly studied crop was grapes (39.1% of studies; 36.2% of comparisons) followed by apples (21.7% of studies; 20.7% of comparisons), tomatoes (17.4% of studies; 15.5% of comparisons), oranges (10.9% of studies; 8.6% of comparisons), peppers (8.7% of studies; 8.6% of comparisons), eggplant (4.3% of studies; 5.2% of comparisons) and pomegranates, (2.2% of studies; 5.2% of comparisons) (Supplementary Table S1). The studies included in this meta-analysis for TSS span 15 years with the earliest published in 2003 and the latest in 2017 (Supplementary Table S1). For the analysis of TA, 28 studies met our inclusion criteria, representing 12 study countries, and reporting 35 DI-to-PRDI, FI-to-DI and FI-to-PRDI comparisons on 5 different crop species (Supplementary Table S2). The analysis of pH included 17 studies conducted in 8 countries and reporting 21 DI-to-PRDI, FI-to-DI and FI-to-PRDI comparisons on 5 different crop species (Supplementary Table S3). In both the analyses of TA and pH, the crop mostly studied was grapes (Supplementary Tables S2 and S3).

TSS, TA and pH responses as a function of crop species to irrigation

Deficit irrigation and partial root-zone drying irrigation

Total soluble solids for all crops considered in the meta-analysis were not significantly different from zero (ln$R$ = 0.002; 95% CI = − 0.011 to 0.015; Q_T = 77.91, I^2 = 32.375, df = 57, p = 0.785) (Fig. 1a and Supplementary Fig. S1A). Similarly, effect sizes for TA did not significantly differ from zero for all of the crops considered, except for apples (ln$R$ = 0.082; 95% CI = 0.016–0.148; p = 0.016) and the overall mean effect was not significant (ln$R$ = − 0.027; 95% CI = − 0.086 to 0.033; p = 0.377) (Fig. 1b and Supplementary Fig. S1B). From a meta-regression analysis, the differences among cumulative effect sizes for the various crop species were insignificant (Q_B = 2.79; I^2 = 89.50%; df = 4; p = 0.594). The Cochran's Q and I^2 statistics computed for the TA analysis were large, exemplifying the fewer number of studies included in the analysis for TA and the inconsistency of studies' results, respectively (Q_T = 209.455, I^2 = 90.232, df = 34). When the pH analysis was disaggregated into crop species, data on three crops were reported by one study each and so were removed, leaving pH data on only two crops, grapes and pomegranate. Even so, data on pomegranate came from the same authors and the analysis showed that pH for none of the two crops included were significantly different from zero (ln$R$ = 0.008; 95% CI = − 0.013 to 0.029, p = 0.449) (Fig. 1c). The overall mean effect size for pH was not different between DI and PRDI (ln$R$ = 0.010; 95% CI = − 0.009 to 0.028; p = 0.298) (Supplementary Fig. S1C).

Full irrigation and deficit irrigation

The mean effect size for TSS was 0.040 (95% CI of 0.021–0.058; Q_T = 129.32; I^2 = 60.86%; p < 0.001), when the data were disaggregated into crop species (Fig. 2a). The overall effect size was unchanged for the non-disaggregated data (Supplementary Figure S2A). Back-transforming the ln$R$ suggested that deficit irrigation leads to approximately 4.1 ± 1.8% increase in TSS in crops under DI compared to crops under full irrigation. Significantly large TSS advantage of DI over FI was observed for tomatoes (ln$R$ = 0.094; 95% CI = 0.024–0.163; p = 0.008) and for peppers (ln$R$ = 0.072; 95% CI = 0.021–0.124; p = 0.006) (Fig. 2a). Although, the

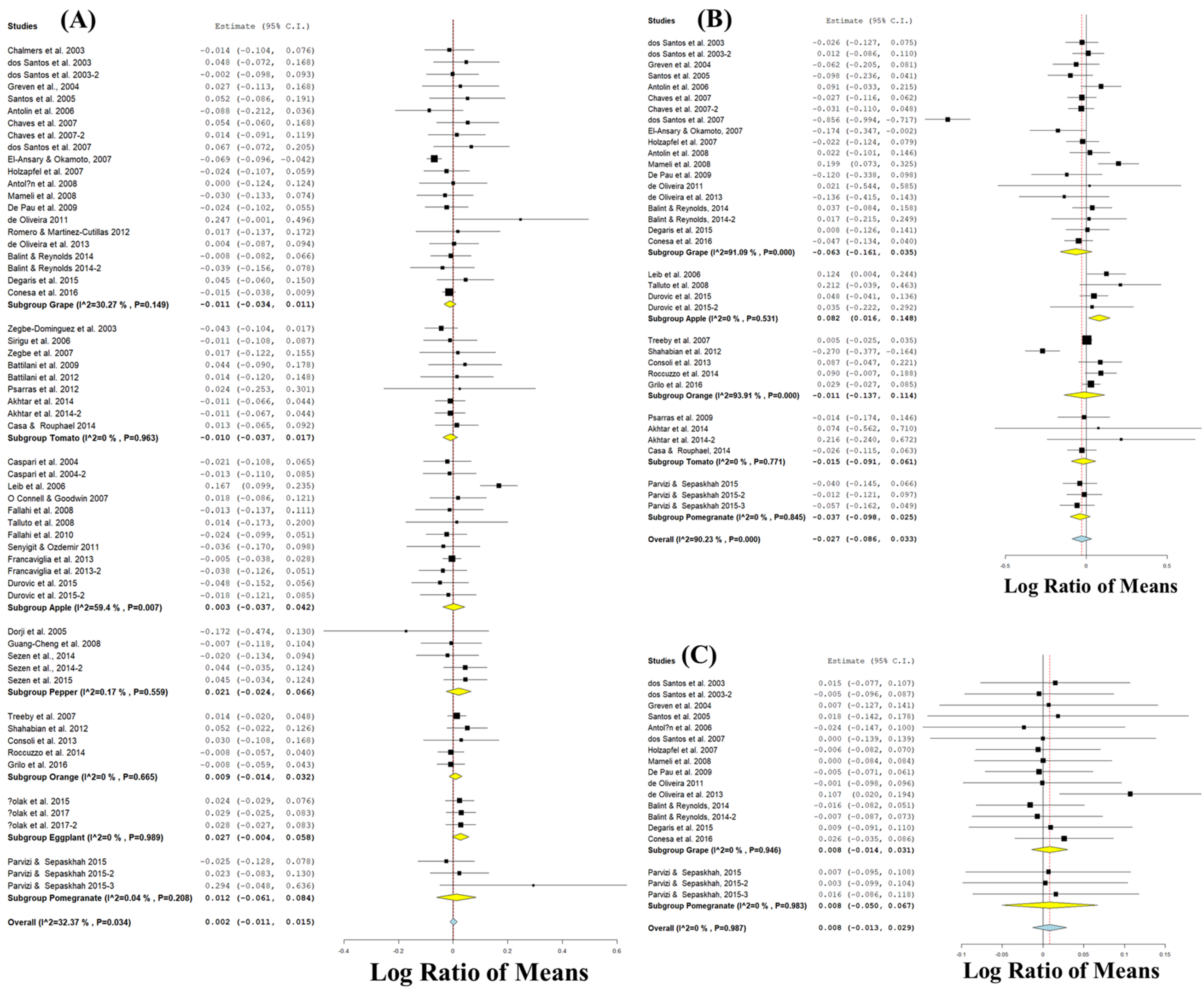

Fig. 1 Effect of deficit and partial root-zone drying irrigation on: **a** total soluble solids; **b** titratable acidity and **c** pH in fruits and vegetables. Overall effect size and effect size as a function of crop species are shown. Log ratio of means = 0 (continuous vertical line) indicates no effect; log ratio of means > 0 indicates TSS, TA or pH advantage of PRDI over DI and log ratio of means < 0 indicates TSS, TA or pH advantage of DI over PRDI. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The dotted line indicates the overall effect size across all crops

increase in TSS under DI was driven mainly by vegetables (Fig. 2a), meta-regression analysis suggested that the differences among cumulative effect sizes for the various crop species were insignificant ($Q_B = 9.93$; $I^2 = 54.25\%$; $df = 6$; $p = 0.128$).

The effect sizes for TA did not significantly differ from zero for all the crops considered, except for apples and the overall mean effect was not significant ($\ln R = 0.010$; 95% CI = −0.050 to 0.070; $p = 0.749$) (Fig. 2b and Supplementary Fig. S2B). There seemed to be superior titratable acids in apples under full irrigation ($\ln R = -0.171$; 95% CI = −0.268 to −0.075; $p < 0.001$) compared to those receiving deficit irrigation (Fig. 2b). Meta-regression analysis, however, indicated that there was no significant difference among cumulative effect sizes for the various crop species ($Q_B = 6.34$; $I^2 = 88.19\%$; $df = 4$; $p = 0.175$). The pH for the two crops included was not significantly different from zero ($\ln R = -0.016$; 95% CI = −0.038 to 0.006, $p = 0.151$) (Fig. 2c). The overall mean effect size for pH was, however, significantly different from zero ($\ln R = -0.019$; 95% CI = −0.037 to −0.002; $p = 0.030$) (Supplementary Fig. S2C).

Full irrigation and partial root-zone drying irrigation

The mean effect size for TSS was 0.047, with a 95% CI of 0.030–0.065, ($Q_T = 120.324$; $I^2 = 55.75\%$; $p < 0.001$), when

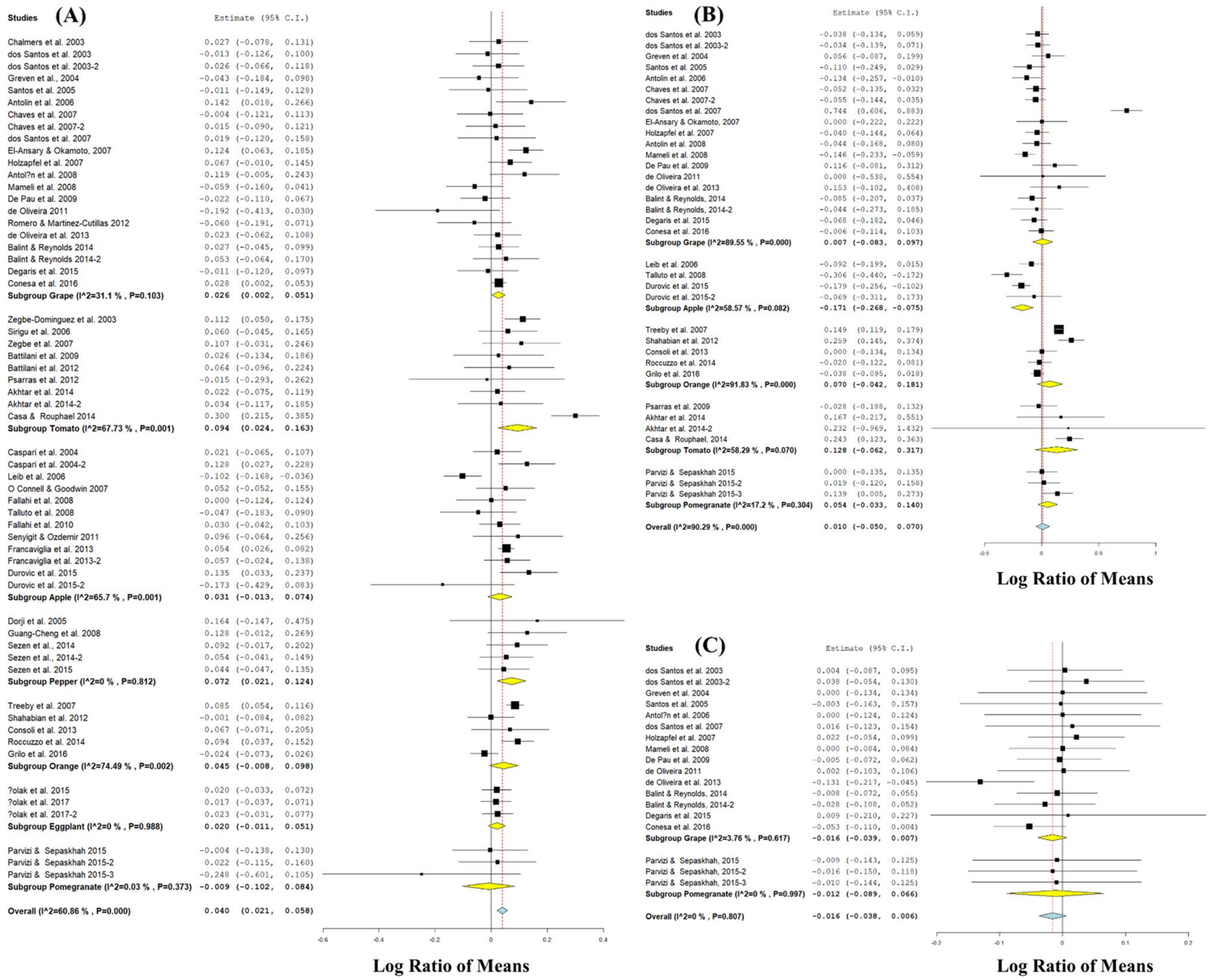

Fig. 2 Effect of full and deficit irrigation on: **a** total soluble solids; **b** titratable acidity and **c** pH in fruits and vegetables. Overall effect size and effect size as a function of crop species are shown. Log ratio of means = 0 (continuous vertical line) indicates no effect, log ratio of means > 0 indicates TSS, TA or pH advantage of DI over FI and log ratio of means < 0 indicates TSS, TA or pH advantage of FI over DI. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The dotted line indicates the overall effect size across all crops

the data were disaggregated into crop species (Fig. 3a). The overall effect size was unchanged for the non-disaggregated data (Supplementary Fig. S3A). Back-transforming the ln*R* suggested that PRDI leads to approximately 5.0 ± 2.0% increase in TSS in crops compared to crops receiving full irrigation. Significantly large TSS advantage of PRDI over FI was observed for six of the seven crop species included in the meta-analysis. The effect sizes for pomegranate were not significantly different from zero (Fig. 3a). Meta-regression analysis showed that the differences among cumulative effect sizes for the various crop species was not significant (Q_B = 11.5; I^2 = 46.58%; df = 6; p = 0.0731).

The effect sizes for TA did not significantly differ from zero for all the crops considered, except for grapes and the overall mean effect was not significant (ln*R* = − 0.016; 95% CI = − 0.049 to 0.017; p = 0.348) (Fig. 3b and Supplementary Fig. S3B). The subgroup analysis for TA based on crop species indicated that there are higher titratable acids in grapes receiving full irrigation (ln*R* = − 0.058; 95% CI = − 0.087 to − 0.030; p < 0.001) compared to those receiving PRDI (Fig. 3b). There was significant difference among cumulative effect sizes for the various crop species (Q_B = 17.9; I^2 = 48.22%; df = 4; p = 0.0013). Back-transforming the effect size for grapes suggested that titratable acids in grapevines under full irrigation increased by approximately 6.0 ± 3.0% compared to those under PRDI. For the analysis of pH, the effect size for the two crops included in the subgroup analysis was not significantly different from zero (ln*R* = − 0.007;

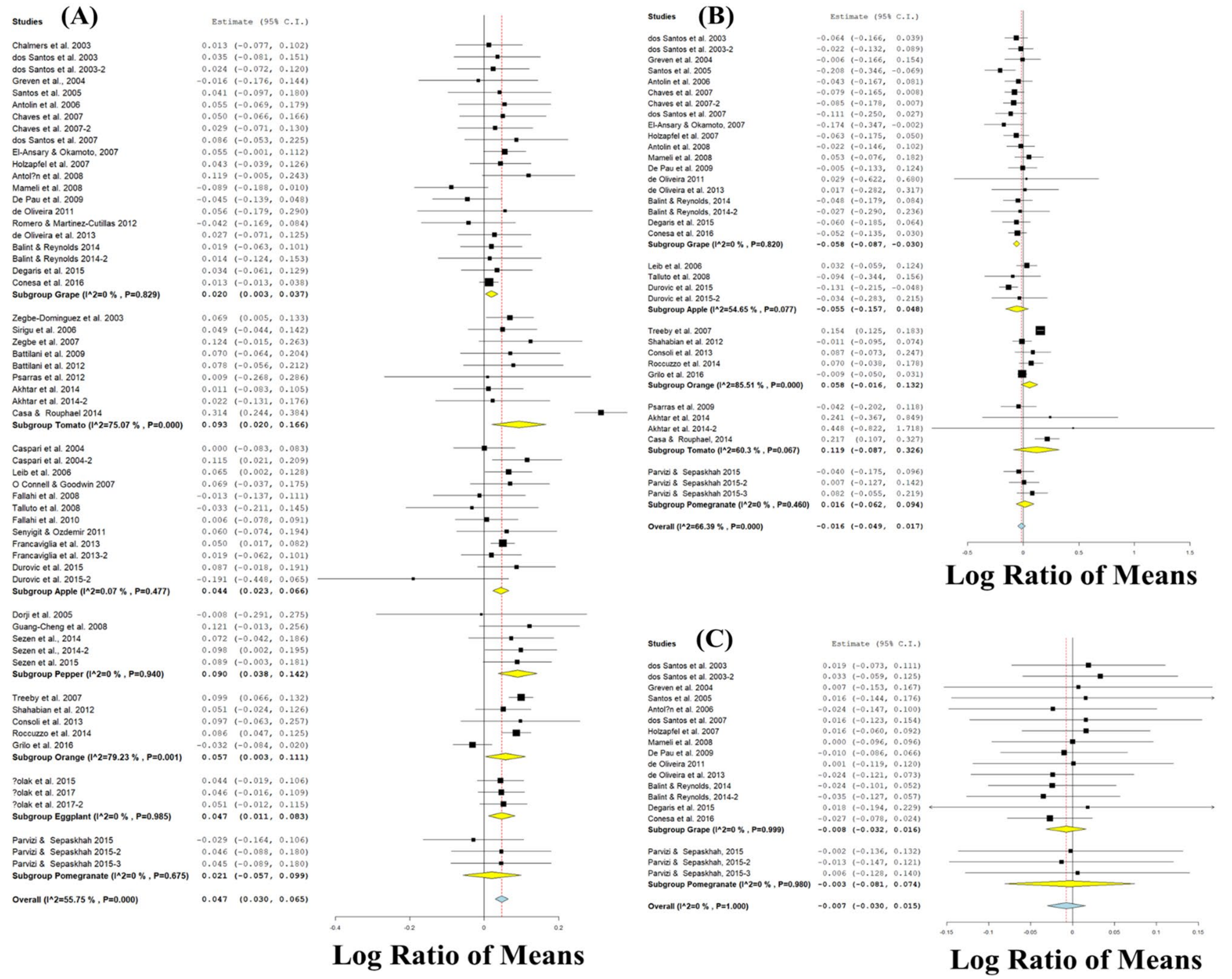

Fig. 3 Effect of full and partial root-zone drying irrigation on: **a** total soluble solids; **b** titratable acidity and **c** pH in fruits and vegetables. Overall effect size and effect size as a function of crop species are shown. Log ratio of means = 0 (continuous vertical line) indicates no effect, log ratio of means > 0 indicates TSS, TA or pH advantage of PRDI over FI and log ratio of means < 0 indicates TSS, TA or pH advantage of FI over PRDI. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The dotted line indicates the overall effect size across all crops

95% CI = − 0.030 to 0.015, $p = 0.527$) (Fig. 3c). The overall mean effect size for pH was not different between FI and DI (ln$R$ = − 0.006; 95% CI = − 0.026 to 0.014; p = 0. 0.549) (Supplementary Fig. S3C).

Analyses of other moderators on total soluble solids

Crop group effects

Deficit irrigation versus partial root-zone drying irrigation

Crops included in this meta-analysis were categorized into three agronomic groups, namely vegetables, perennial vine fruits and perennial tree fruits. Effect size for the different crop groups was either positive or negative. The effect sizes for vine fruits (ln$R$ = − 0.011; 95% CI = − 0.034 to 0.011; $p = 0.320$) were negative but those of tree fruits (ln$R$ = 0.008; 95% CI = − 0.016 to 0.032; $p = 0.527$) and vegetables (ln$R$ = 0.008; 95% CI = − 0.010 to 0.027; $p = 0.374$) were positive. None of the effect sizes were, however, statistically significant from zero, suggesting that there is no difference in TSS of categories of crops grown under DI and those grown under PRDI (Fig. 4a).

Full irrigation versus deficit irrigation

Effect sizes linked to comparisons from studies involving different crop groups were positive. The effect size of

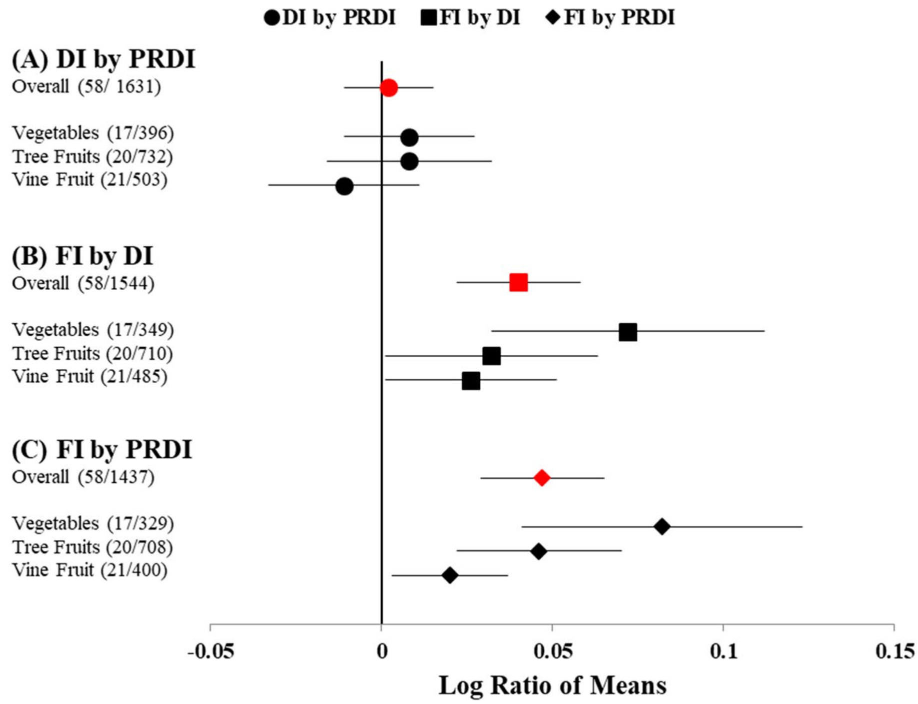

Fig. 4 Influence of different agronomic crop grouping on effect sizes of total soluble solids content of crops: **a** TSS response to partial root-zone irrigation (PRDI) compared with deficit irrigation in different agronomic crop groups; **b** TSS response to deficit irrigation compared with full irrigation (FI) in different agronomic crop groups; **c** TSS response to partial root-zone irrigation (PRDI) compared with full irrigation in different agronomic crop groups. The overall effect size for the three meta-analyses performed in this study is highlighted in red. The error bar indicates the 95% confidence interval (CI) and the continuous vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The number of comparisons and total sample size included in each crop category are displayed in parentheses (color figure online)

vegetables was significantly different from zero (ln$R$ = 0.072; 95% CI = 0.032–0.112; $p < 0.001$), indicating that there is highly significant difference between TSS of vegetables under FI and DI (Fig. 4b). The effect sizes of vine fruit (ln$R$ = 0.026, 95% CI = 0.002–0.051, $p = 0.036$) and tree fruits (ln$R$ = 0.032, 95% CI = 0.001–0.063, $p = 0.040$) were only marginally significantly different from zero (Fig. 4b). Back-transforming the log ratios showed that there were 7.5 ± 4.0%, 2.6 ± 2.4%, 3.3 ± 3.2% increase in TSS of vegetables, vine and tree fruits, respectively, under DI. Mixed-effects meta-regression analysis revealed that there was no significant difference among cumulative effect sizes for the various crop groups ($Q_B = 4.61$; $df = 2$; $p = 0.100$; $I^2 = 58.43\%$; Fig. 4b). Although the magnitude of TSS of vegetables under DI seems larger, the results suggest that TSS of vegetables grown under water-saving irrigation is not significantly different from that of tree and vine fruits.

Full irrigation versus partial root-zone drying irrigation

Effect sizes linked to comparisons from studies involving the three crop groups were all positive, and were all statistically significant from zero (Fig. 4c). There was difference in TSS between FI and PRDI for vegetables (ln$R$ = 0.082; 95% CI = 0.041–0.123; $p < 0.001$), tree fruit (ln$R$ = 0.046; 95% CI = 0.022–0.070; $p < 0.001$) and for vine fruit (ln$R$ = 0.020; 95% CI = 0.003–0.037; $p = 0.023$; Fig. 4c). The results suggested that there was 8.5 ± 4.2% increase in TSS of vegetables grown under PRDI compared to crops receiving full irrigation. Respectively, there was approximately 5.0 ± 2.4% and 2.0 ± 1.8% increase in TSS of tree and vine fruits grown under PRDI compared to crops receiving full irrigation. Mixed-effects meta-regression analysis revealed that differences among cumulative effect sizes for the three crop groups were marginally significant ($Q_B = 8.34$; $df = 2$; $p = 0.015$; $I^2 = 48.51\%$).

Soil texture effects

Deficit irrigation (control) versus partial root-zone drying irrigation

The effect size of TSS was either positive or negative across all the included soil textures but only that of sandy soil (ln$R$ = −0.060; 95% CI = −0.089 to −0.031; $p < 0.001$) was significantly different from zero. Thus, there is no difference between DI and PRDI in TSS for all soil textures with the exception of sandy soil (Fig. 5a). There is approximately 6.0 ± 3.0% decline in TSS of plants subjected to DI on sandy soils, compared to plants grown under PRDI on same soil texture. Meta-regression analysis revealed that differences among cumulative effect sizes for the various soil textures were significant ($Q_B = 45.3$; $df = 12$; $p < 0.001$; Fig. 5a).

Full irrigation (control) versus deficit irrigation

The effect size related to comparisons from experiments conducted using bark pumice peat (ln$R$ = 0.114; 95% CI = 0.063–0.165; $p < 0.001$), clay loam (ln$R$ = 0.066; 95% CI = 0.034–0.099; $p < 0.001$) and sandy loam soils (ln$R$ = 0.069; 95% CI = 0.043–0.094; $p < 0.001$) was positive and significant, suggesting difference between FI and DI in TSS for these soil textures (Fig. 5b). There were approximately 12 ± 5.0%, 7.0 ± 3.4% and 7.0 ± 2.6% increase in TSS of crops grown on bark pumice peat, clay loam and sandy loam soils, respectively, under deficit irrigation compared to crops grown on these soil types but receiving full irrigation. In contrast, the effect size calculated from experiments conducted using sandy clay, silt loam, sandy clay loam, clay silt loam, sand silt clay, sandy, clayey, loamy soils, clay silt and for all experiments, for which the soil texture was not specified, did not differ from zero, suggesting that for these soil

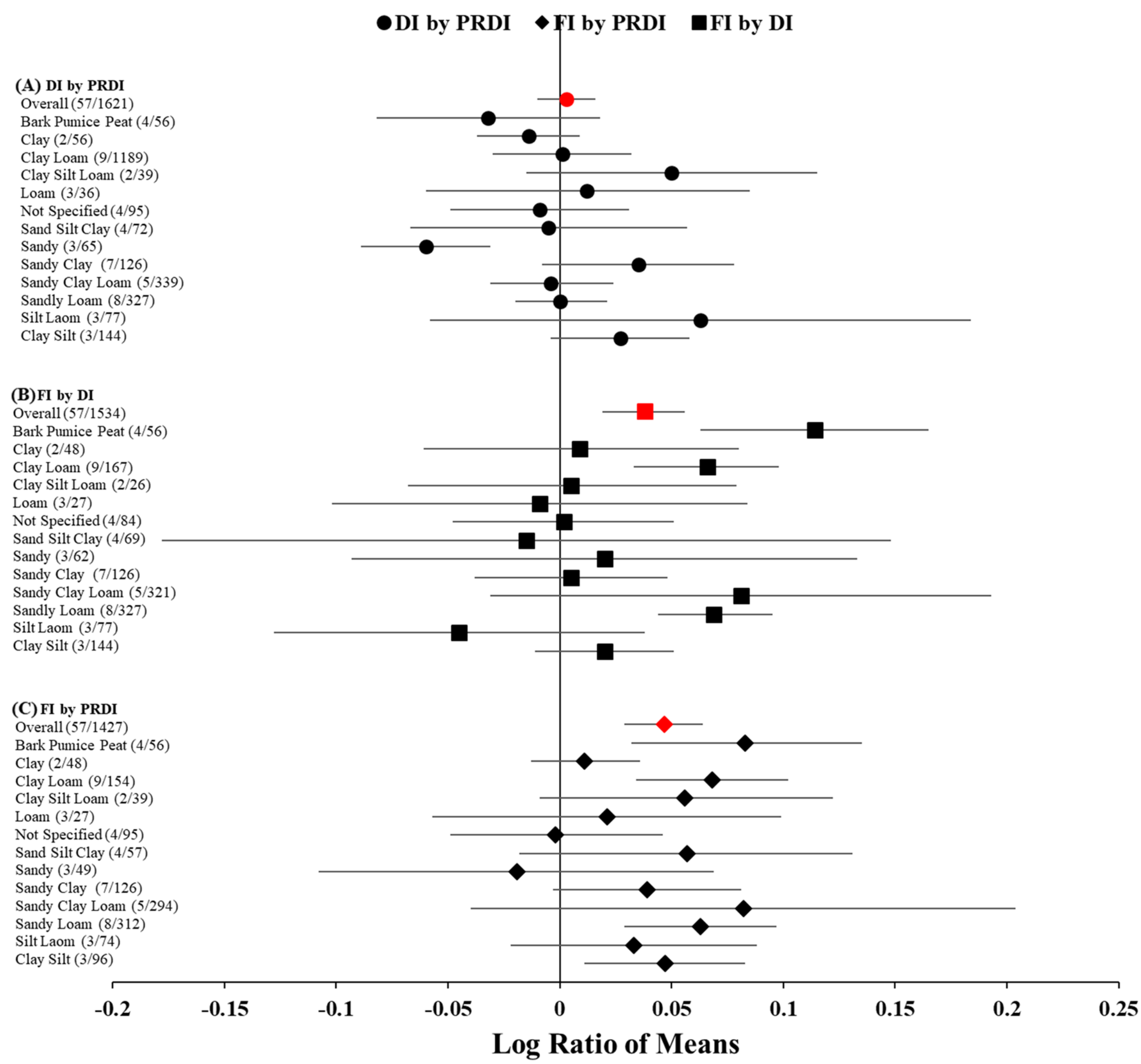

Fig. 5 Influence of different soil textures on effect sizes of total soluble solids (TSS): **a** TSS response to partial root-zone irrigation (PRDI) compared with deficit irrigation in different soil textures; **b** TSS response to deficit irrigation compared with full irrigation (FI) in different soil textures; **c** TSS response to partial root-zone irrigation (PRDI) compared with full irrigation in different soil textures. The overall effect size for the three meta-analyses performed in this study is highlighted in red. The error bar indicates the 95% confidence interval (CI) and the continuous vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The number of study comparisons and total sample size included in each soil texture category are displayed in parentheses (color figure online)

textures, there is no difference in TSS between crops grown under FI and DI. Meta-regression suggested that the cumulative effect size of TSS did not differ across the different soil textures $Q_B = 20.3$; $df = 12$; $p = 0.062$; $I^2 = 45.80\%$; Fig. 5b).

Full irrigation (control) versus partial root-zone drying irrigation

The effect size of TSS did not differ across different soil textures ($Q_B = 12.0$; $df = 12$; $p = 0.448$; $I^2 = 48.85\%$; Fig. 5c). The effect size related to comparisons from experiments conducted using bark pumice peat, clay loam and sandy loam soils was positive and significant, suggesting difference between FI and PRDI in TSS for these soil textures (Fig. 5c). There were 8.7 ± 5.2%, 7.0 ± 3.4% and 6.5 ± 3.4% increase in TSS of crops grown on bark pumice peat, clay loam and sandy loam soils, respectively, under partial root-zone drying irrigation compared to crops grown on these soil types but receiving full irrigation. In contrast, the effect size calculated from experiments conducted using all other soil types gleaned from the included studies and for all experiments, for which the soil texture was not specified, did not differ from zero, indicating that for these soil textures, there is no difference in TSS between crops grown under FI and PRDI (Fig. 5c).

Irrigation frequency effects

The subgroup analysis for DI (control) versus PRDI showed that the effect size of TSS does not differ across the different irrigation frequencies ($Q_B = 6.33$; $df = 8$; $p = 0.611$; $I^2 = 29.27\%$). Thus, content of TSS in fruits and vegetables does not significantly vary between DI and PRDI and across crops irrigated at various irrigation frequencies (Fig. 6a). For the comparisons involving FI (control) and DI, the effect size recorded for experiments that re-supplied soil water daily was positive and significantly different from zero ($\ln R = 0.082$; 95% CI = 0.030–0.134; $p = 0.002$; Fig. 6b). Thus, for crops irrigated daily, there is a significant difference between TSS recorded under FI and that recorded under DI. Similarly, effect sizes recorded for experiments that re-supplied soil water thrice a week or every 2 days ($\ln R = 0.228$; 95% CI = 0.074–0.382; $p = 0.004$; Fig. 6b), or based on water depletion from the soil ($\ln R = 0.051$; 95% CI = 0.018–0.084; $p = 0.002$; Fig. 6b) and for all experiments for which the frequency of water supply was not provided in the papers ($\ln R = 0.027$; 95% CI = 0.002–0.053; $p = 0.038$; Fig. 6b) were positive and significantly different from zero (Fig. 6b). Meta-regression of the irrigation frequency covariate showed that there is a difference in the cumulative effect sizes for TSS ($Q_B = 24.1$; $df = 8$; $p = 0.0022$; $I^2 = 45.89\%$ Fig. 6b). There were 8.5 ± 5.4%, 25.6 ± 16.7%, 5.2 ± 3.4%, and 2.7 ± 2.6% increase in TSS of crops irrigated daily, thrice a week or every 2 days, those for which water was re-supplied based on water depletion threshold, and experiments with non-specified irrigation frequencies, respectively, under DI compared to crops irrigated at these frequencies under FI.

For comparisons involving FI (control) and PRDI, the effect size of TSS differed across different irrigation frequencies ($Q_B = 34.5$; $df = 8$; $p < 0.001$; $I^2 = 24.46\%$; Fig. 6c). The effect size related to comparisons from experiments irrigated daily, twice a week, weekly and those for which water was re-supplied based on water depletion threshold in the soil, were positive and significant, suggesting difference between FI and PRDI in TSS for these irrigation frequencies (Fig. 6c). There were 5.7 ± 5.1%, 6.3 ± 5.2%, 6.1 ± 3.2% and 5.0 ± 2.6% increase in TSS of crops irrigated daily, twice a week, weekly and those for which water was re-supplied based on water depletion threshold, respectively, under PRDI compared to crops irrigated at these frequencies under FI. In contrast, the effect size calculated from experiments conducted using all other irrigation frequencies extracted from the included studies and for all experiments, for which the irrigation frequency was not specified, did not differ from zero, suggesting that for these irrigation frequencies, there is no difference in TSS between crops grown under FI and PRDI (Fig. 6c).

Cumulative meta-analysis

Cumulative meta-analysis was performed only on the dataset for TSS. The cumulative meta-analysis revealed temporal changes in the magnitude and stability of reported effects for all three comparisons (Fig. 7a–c). For the comparison between DI and PRDI, a few early studies (those conducted in 2003–2004) reported negative effect sizes, signaling superior TSS under DI, albeit insignificant. However, as the number of studies and possibly the diversity of crops included in the meta-analysis increased, the effect size stabilized and from 2005 it became positive until 2011, suggesting superior TSS under PRDI but still non-significant (Fig. 7a). Subsequently, the effect size has been near zero (Fig. 7a). For the comparison between FI and DI, about four evolutions are evident from the temporal trends of the mean effect size in the 14 years' published data included in the cumulative meta-analysis (Fig. 7b). Firstly, the magnitude of the effect was larger in the early years (between 2003 and 2004), but largely insignificant (Fig. 7b). The magnitude of the mean effect size insignificantly decreased between 2004 and 2007, then increased and became significant between 2007 and 2011, while the variance around the mean effect fell. From 2014 to 2017, the mean effect size has been stabilized and the variance around the mean effect has fallen markedly, showing superior TSS in crops grown under

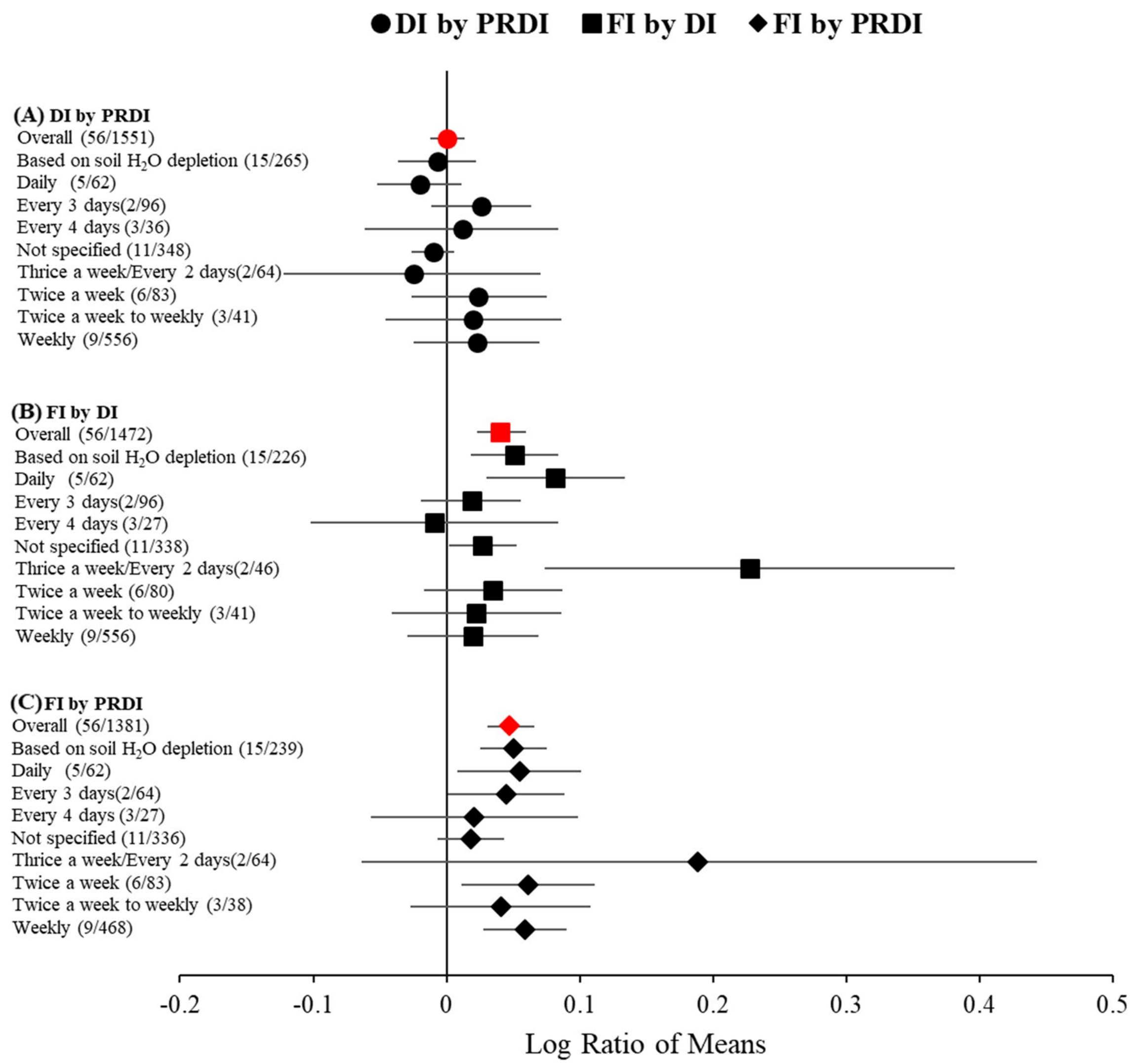

Fig. 6 Influence of frequency of irrigation on effect sizes of total soluble solids (TSS) content of fruits and vegetables: **a** TSS response to partial root-zone irrigation (PRDI) compared with deficit irrigation (DI) as a function frequency of irrigation; **b** TSS response to DI compared with full irrigation (FI) as a function frequency of irrigation; **c** TSS response to partial root-zone irrigation (PRDI) compared with FI as a function frequency of irrigation. The overall effect size for the three meta-analyses performed in this study is highlighted in red. The error bar indicates the 95% confidence interval (CI) and the continuous vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). The number of study comparisons and total sample size included in each category of irrigation frequency are displayed in parentheses (color figure online)

DI (Fig. 7b). The results for the comparison between FI and PRDI revealed similar temporal changes in the mean effect size (Fig. 7c). Early studies conducted in 2003 recorded insignificant mean effect size but this quickly became significant when studies of the following year were added. Subsequently, the mean effect sizes have been significant and stable (Fig. 7c).

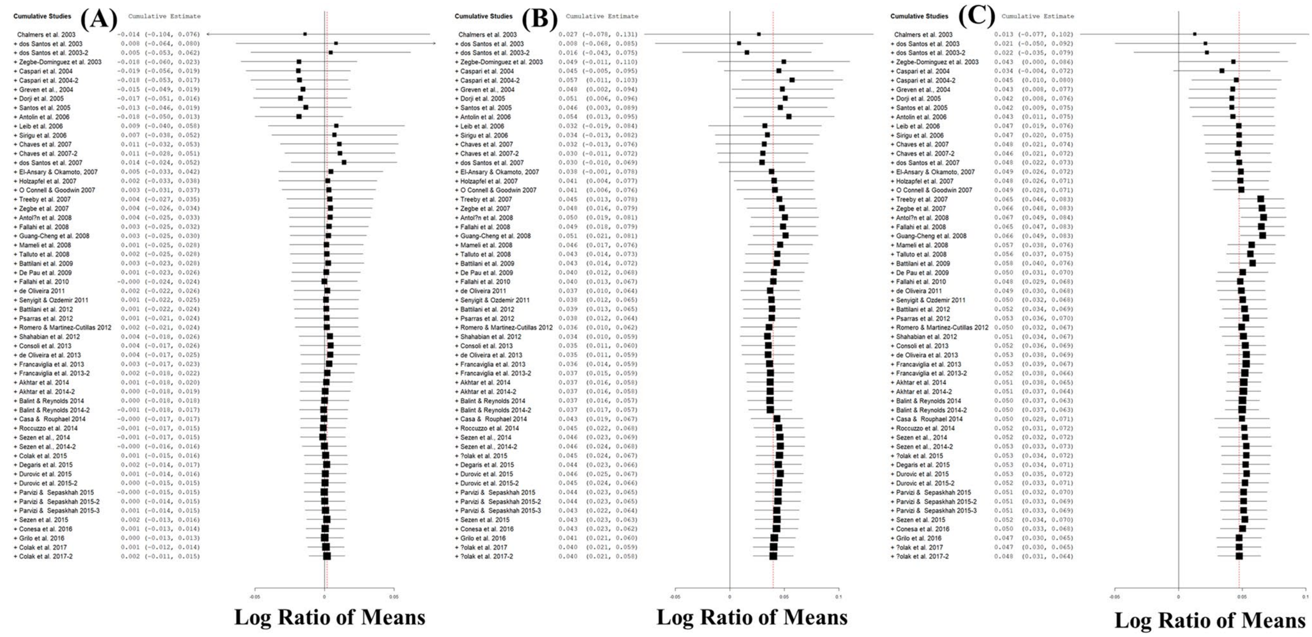

Fig. 7 Effect sizes and 95% CI of 42 comparisons from 35 individual studies published in 2003–2016, on total soluble solids (TSS) in fruits and vegetables, in chronological order. The temporal changes in reported magnitude of mean effect sizes show the content of TSS in fruits and vegetables in response to: **a** partial root-zone irrigation (PRDI) compared with deficit irrigation (DI); **b** deficit irrigation (DI) compared with full irrigation (FI); **c** partial root-zone irrigation (PRDI) compared with full irrigation (FI). Error bars represent 95% CI. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by vertical lines). Analysis begins with the chronologically oldest study (at the top of each graph) and the analysis is iterated. At each step, the effect size from the next study in chronological order is added to the analysis, and mean effect sizes and 95% CI are recalculated

Sensitivity analysis for the meta-analysis of total soluble solids

Data with available SDs by data with estimated SDs

Here, we provide sensitivity analysis for the dataset on TSS. When DI was compared with PRDI and the TSS dataset grouped into studies that had originally reported measures of dispersion (i.e., SEs, SDs or CIs; $n = 13$) and studies for which these measures had to be estimated ($n = 45$). Similar to the overall effect size, the effect size for studies with estimated measures of dispersion was positive and insignificant (ln$R = 0.014$; 95% CI $= -0.000$ to 0.029; $p = 0.057$), but that effect size for studies which originally reported measures of dispersion was negative and marginally significantly different from zero (ln$R = -0.019$; 95% CI $= -0.038$ to -0.001; $p = 0.038$; Fig. 8a). When we compared FI with DI, similar to the overall effect size (ln$R = 0.040$; 95% CI = 0.021–0.058; $p < 0.001$), the log ratios of means were positive and significantly different from zero, both for studies with available (ln$R = 0.058$; 95% CI = 0.009–0.107; $p = 0.021$; Fig. 8b) and estimated SDs (ln$R = 0.032$; 95% CI = 0.014–0.050; $p < 0.001$; Fig. 8a). Similar trends were observed when FI was compared with PRDI (Fig. 8a).

Field by greenhouse experiments

When the dataset was grouped into experiments conducted under field conditions ($n = 49$) and those conducted under controlled environments ($n = 9$), no qualitative changes were observed in the trends compared to those found when considering the entire database. For example, when DI was compared with PRDI, and the analysis was done considering experiments conducted under field conditions, the effect size (ln$R = 0.006$; 95% CI $= -0.008$ to 0.021; $p = 0.400$) was positive but not significant. When the analysis was done considering experiments conducted under controlled environments, the effect size (ln$R = -0.021$, 95% CI $= -0.049$ to 0.007; $p = 0.135$) was negative but still not significant (Fig. 8b). There was no TSS difference between field and greenhouse experiments when DI was compared with PRDI ($Q_B = 2.12$; $df = 1$; $p = 0.145$; $I^2 = 32.63\%$, Fig. 8b). When we compared FI with DI, the log ratio of means observed was significantly positive for experiments conducted under both controlled environments and for those conducted under field conditions. The effect sizes were 0.032 (CI = 0.012–0.052; $p = 0.002$) and 0.093 (CI = 0.056–0.130; $p < 0.001$), respectively, for field and greenhouse experiments (Fig. 8b). There was difference in TSS between crops grown under field and greenhouse experiments when FI was compared with DI

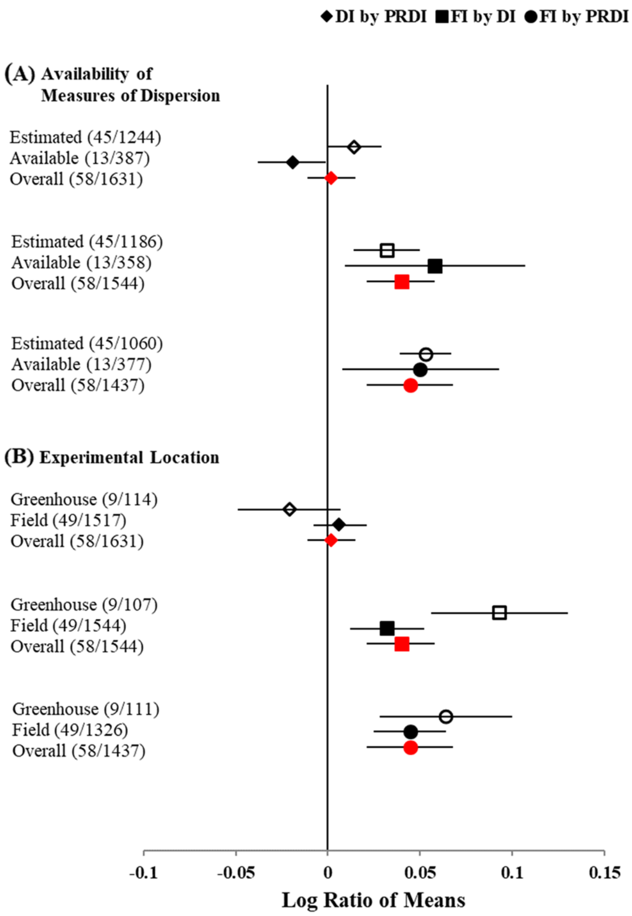

Fig. 8 Sensitivity study of deficit-to-partial root-zone drying irrigation; Full-to-deficit irrigation and Full-to-partial root-zone drying irrigation effect sizes. **a** Availability of measures of dispersion—primary studies that originally reported SDs, SEs or CIs (filled symbols) and primary studies for which SDs were estimated as 10% of the mean (unfilled symbols). **b** Siting of experiment either under field conditions (filled symbols) or in a controlled environment (unfilled symbols). The overall effect sizes for the three meta-analyses performed in this study are highlighted in red. The error bar indicates the 95% confidence interval (CI) and the continuous vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if its 95% CI does not overlap zero (marked by continuous vertical line). Numbers in parentheses indicate the number of studies and the total sample size for each category (color figure online)

(Q_B = 4.57; df = 1; p = 0.0326; I^2 = 59.08%, Fig. 8b). The results suggested that when crops are irrigated with DI, there were 3.3 ± 2.0%, and 9.7 ± 3.8% increase in TSS in field-grown and greenhouse-grown crops, respectively, compared to crops irrigated with FI. This also indicates that that there is approximately, 194% or threefold difference between TSS of crops grown under field and greenhouse conditions, even when both are irrigation with PRDI. When we compared FI with PRDI, the log ratio of means observed was significantly positive, as it was for the entire database, for both experiments conducted under field conditions and those conducted under controlled environments. The effect sizes were 0.045 (CI = 0.025–0.064; $p < 0.001$) and 0.064 (CI = 0.028–0.100; $p < 0.001$), respectively, for field and greenhouse experiments (Fig. 8b). There was no TSS difference between field and greenhouse experiments when FI was compared with PRDI (Q_B = 0.587; df = 1; p = 0.444; I^2 = 56.26%, Fig. 8b).

Analysis of publication bias

Funnel plots produced for the analysis of TSS indicated a weak tendency for smaller sample sizes to be associated with stronger negative effects (Fig. 9). For the comparison of DI by PRDI, funnel plot obtained was near symmetrical (Fig. 9a) and for this, trim and fill analysis indicated that there were no studies missing to the side of the grand mean. For the analyses of FI by DI, there were 11 estimated missing studies on the right side of the grand mean (s.e. = 5.0272; Fig. 9b), and correcting for these with trim and fill method, although changed the magnitude of the effect size, did not affect the significance (ln$R$ = 0.0570; 95% CI = 0.0376–0.0764; $p < 0.0001$). The results suggested that when the effect size is corrected for by trim and fill, there is 6.0 ± 2.0% increase in TSS in plants grown under DI compared those grown under FI. For the analyses of FI by PRDI, there were 19 estimated missing studies on the right side of the grand mean (s.e. = 4.8326; Fig. 9c), and correcting for these with trim and fill method, although changed the magnitude of the effect size, did not affect the significance (ln$R$ = 0.0726; 95% CI = 0.0554–0.0897; $p < 0.0001$). The results suggested that when the effect size is corrected for by trim and fill, there is 7.5 ± 1.7% increase in TSS in plants grown under PRDI compared to those grown under FI. Rosenberg's fail-safe numbers were computed for the two comparisons which produced significant effects sizes. Respectively, the fail-safe numbers for the analysis of FI by DI and FI by PRDI were 1041 and 1333, which are approximately 247% and 344% greater than the threshold of 300 ($5 \times n + 10$) needed to consider the mean effect size robust.

Discussion

Given that agriculture is the most water-intensive human activity and water scarcity is becoming widespread, effort to save water in agriculture remains a topical and priority issue globally. Irrigation techniques that help conserve water have, therefore, both socio-economic and ecological appeal. The current study used meta-analysis to assess the effect of three irrigation techniques (DI, PRDI, and FI) on three commonly studied quality attributes of crops (namely TSS, TA and pH). We used a relatively larger dataset encompassing data from both field and controlled environments and diverse horticultural crops. Seven crops were included based on the

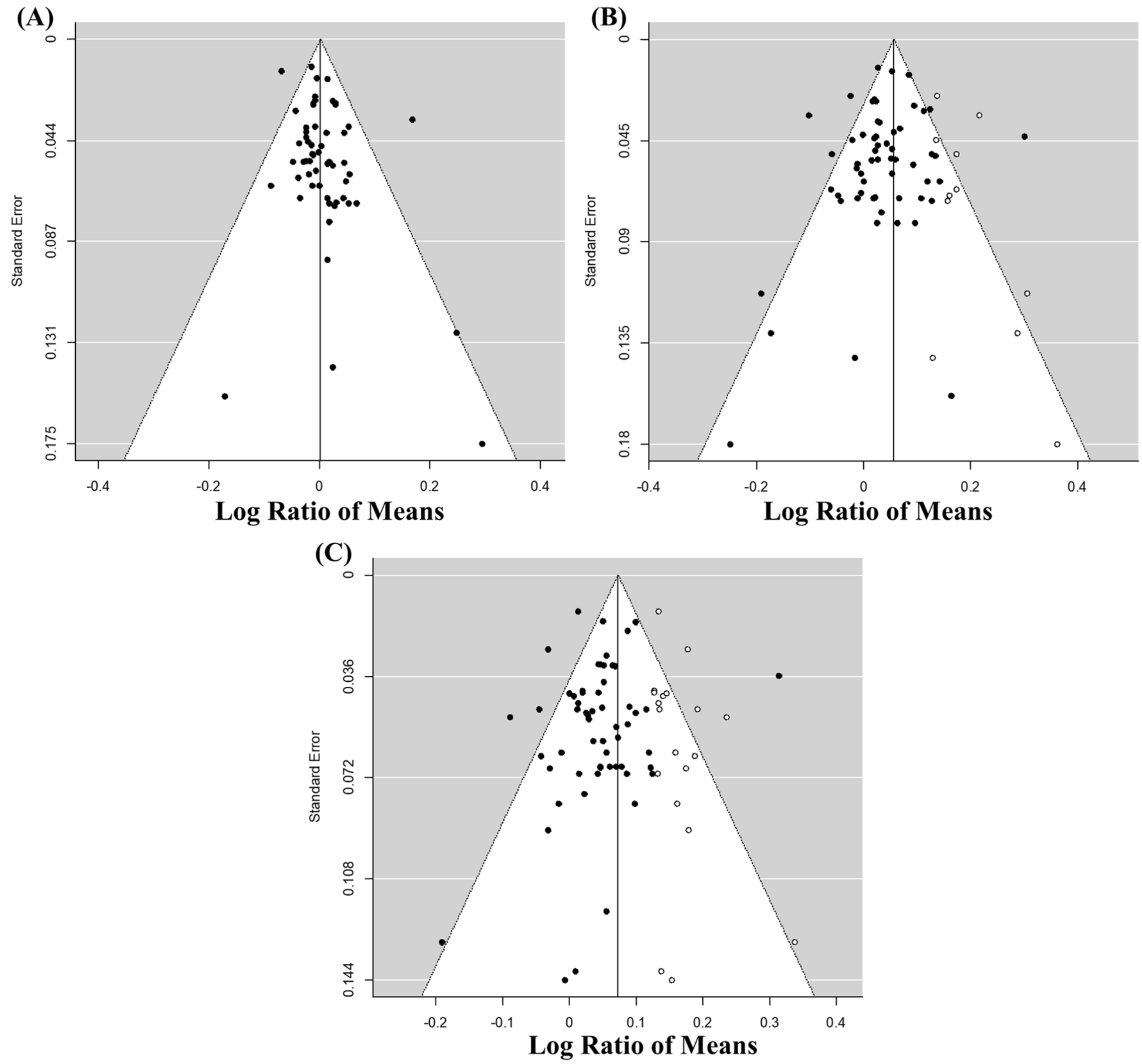

Fig. 9 Funnel plots of average effect sizes (log ratio of means) for: **a** studies which compared TSS between deficit irrigation and partial root-zone drying irrigation; **b** studies which compared TSS between full irrigation and deficit irrigation. One effect size was estimated missing on the right side of the grand mean and was corrected for with trim and fill method and **c** studies which compared TSS between full irrigation and partial root-zone drying irrigation. Fifteen effect sizes were detected missing on the right side of the grand mean and were corrected for with trim and fill method

studies that met the inclusion criteria. Use of the inclusion criteria (as a requirement of systematic review and meta-analysis) implies not all crops or studies would finally be included. For example, deficit irrigation has been reported to be very effective for many fruit trees or woody crops such as apricot, peach, plum, and persimmon (Tejero and Zuazo 2018), which would have been excluded from the current meta-analysis.

Total soluble solids (TSS) are greater under water-saving irrigation

The results showed that TSS in crops grown under both water-saving irrigation strategies (DI and PRDI) were higher than that of crops cultivated under full irrigation (Figs. 2a and 3a). Indeed, several studies have reported increased TSS in crop plants under water-saving irrigation, including Mpelasoka et al. (2001) for apple, Perez-Pastor et al. (2007) for apricot, García-Tejero et al. (2010) for citrus, Lopez et al. (2011) for pear and dos Santos et al. (2003) for grapes. The underlying mechanisms for the rise in TSS under water deficit are still an active and evolving area of research. Nora et al. (2012) observed that increased TSS in fruits correlates with smaller fruit sizes due to dehydration during water restriction. Similarly, Etienne et al. (2013) and Guichard et al. (2001) reported that accumulation of soluble sugars in fruits in response to water deficit may be due to dehydration effect. Active solute accumulation (Lo Bianco et al. 2000) and starch breakdown (Ripoll et al. 2014) have also been cited to be responsible for increased sugars in fruits of plants under water stress.

Under water stress, vegetative vigor and above-ground canopy of crop plants are reduced (Jovanovic and Stikic 2018; Loveys et al. 2000). This facilitates increased penetration of radiation into crop canopies, inducing remobilization of assimilates from vegetative tissues to fruits with possible improvements in the crop's quality (dos Santos et al. 2007; Chaves et al. 2010; Jovanovic and Stikic 2018; Yang and Zhang 2010; Francaviglia et al. 2013) Assimilate remobilization under water stress may be directly or indirectly related to plants' responses to drought, including stomatal responses, ion transport, activation of stress signaling pathways, and responses to protect photosynthesis from injury (Osakabe et al. 2014a, b). Abscisic acid (ABA), a critical plant hormone associated with water stress on fruit development and physiology, could stimulate sugar accumulation in fruits by increasing the activity of sorbitol oxidase (Kobashi et al. 2001; Ripoll et al. 2014) just as sucrose-metabolizing enzymes (Beckles et al. 2012). In general, there is a progressive trend in TSS under water-saving irrigation (Tejero and Zuazo 2018). Inconsistent reports or differences in the magnitude of TSS reported in the literature might be attributable to a number of factors, including amount of irrigation water applied or severity of drought stress, varied drought sensitivities of the phenological stages of fruit growth and hence, the timing or growth stage of water stress, as well as the duration of the water stress employed in various studies (Pérez-Pérez et al. 2014; Domingo et al. 2011; Dichio et al. 2007; Besset et al. 2001; Johnson et al. 1992). An expedient water-saving irrigation strategy, which warrants consideration in irrigation trials, might be the type in which water stress is applied at the right phenological stage of fruit growth to enhance fruit quality with negligible yield penalties.

When independently compared with FI, there is greater TSS in crops grown under PRDI than under DI

Generally, there were no significant differences between crops cultivated under DI and PRDI in the crop quality attributes evaluated when these two water-saving practices were compared. Nonetheless, the results seem to suggest that there is greater improvement in TSS under PRDI than under DI, when each of these water-saving practices was independently compared with FI (Figs. 2a and 3a). There was approximately 5% rise in TSS (or even up to 7.5% if missing studies are corrected for by trim and fill) in fruits of crops grown under PRDI, compared to a 4% rise in fruits of crops grown under DI. The 50% of root system momentarily exposed (say for 10–15 days) to dry soil in PRDI generate a chemical signal that move to shoots to limit shoot growth and functioning, while the fully watered roots supply the plant's water requirements (Dodd et al. 2006; Morison et al. 2007; Stikic et al. 2003). The signaling induced under PRDI leads to increased concentration of xylem sap ABA and pH, reduced stomatal conductance and cytokinin content in roots (Davies et al. 2000; Dodd et al. 2006; Stoll et al. 2000; SunY and Liu 2013). Plant roots do not have the natural capacity to maintain ABA production for longer duration (Loveys et al. 2000). Unlike under DI, the alternating wetting and drying of roots achieved in PRDI becomes advantageous as it triggers continuous root-to-shoot signaling, leading to sustained ABA production with attendant rise in sugar content in fruits (Stikic et al. 2003). It is also probable that water stress is initiated in the soil under both DI and PRDI but the difference could be that under PRDI water stress manifests more consistently, but DI crops are exposed to episodic water stress, resulting in cyclical stress signaling. The viability of PRDI in increasing fruit quality in comparison with DI seemed to be confirmed by De la Hera et al. (2007) and dos Santos et al. (2007). Apparently, 'soil deficit' as a consequence of PRDI induces greater accumulation of TSS in fruits, due to consistent or sustained root-to-shoot signaling, compared with 'plant deficit' as a consequence of DI, where signaling could be episodic.

Overall, there is no difference in TA and pH between the three irrigation strategies

The TA and pH did not vary between any of the three irrigation strategies (Figs. 1, 2, 3). However, subgroup analysis and meta-regression showed that TA in grapevines under full irrigation (FI) increased by approximately $6.0 \pm 3.0\%$ compared to those established under the PRDI. Our result here is consistent with that of several other studies, including dos Santos et al. (2007), Esteban et al. (1999), Santesteban et al. (2011), Song et al. (2012) and Valdés et al. (2009) who have reported elevated TA under FI. Full irrigation leads to the production of larger leaf surface area and usually more compact canopies, thereby generating cooler and more shaded microclimate (Escalona et al. 2012). Meanwhile, malic acid increases under FI (Gamero et al. 2014), but the microclimate generated under FI causes lesser combustion of this acid during maturation of grapes (Escalona et al. 2012). It is possible that rise in malic acid is responsible for the rise in TA in grapes under FI.

The question that remains is: why were overall increases observed here in only TSS under reduced water application and not in TA or pH? Could it be that the remobilization of assimilates is selective for certain metabolites or there are possibly other underlying factors? Perhaps, it is unsurprising that both TA and pH behaved similarly in this meta-analysis. Although TA and pH are analytically assayed separately and each provides its own particular insights on food quality, the two are interrelated concepts, both dealing with acidity (Tyl and Sadler 2017). Ripoll et al. (2014) noted that the effects of water deficit on fruit acidity are more conflicting. There have been both negative and positive correlations of water supply with acid content in fruits, depending on the crop species (Ripoll et al. 2014; Etienne et al. 2013; Bertin et al. 2000). Perhaps, this is because, acid accumulation in fruits is often reported either on fresh weight or dry weight basis. These inconsistencies in reporting could lead to variations in response to water deficit (Ripoll et al. 2014), with the potential of canceling out results from different studies. For example, in strawberries, water deficit does not affect acid content relative to fresh weight; however, it reduces acid content relative to dry weight (Terry et al. 2007), suggesting that presence of good amount of water might contribute to a certain process which might result in the production of hydrogen ions under FI. Such a process or reaction is perhaps reduced under water deficit. The reduction in acidity relative to dry weight might suggest that some hydrogen ions remain in the water within the crop.

Moderator analysis

Effect of type of crop, soil texture and irrigation frequency on TSS

Total sugars of vegetables grown under deficit irrigation were higher but not significantly different from that of tree and vine fruits (Fig. 4b) but TSS of vegetables grown under PRDI were higher and significantly different from that of tree and vine fruits (Fig. 4c). These suggest that, to some extent, different groups of crops responded differently to water-saving irrigation. Thus, although sugar accumulation is improved under DI and PRDI, the magnitude of this improvement might not be the same for all crop species and types. Even among crop cultivars or varieties, differences in sugar content under water deficit have been reported. Bertin et al. (2000) and Veit-Köhler et al. (1999) reported that under water deficit, magnitude of sugar accumulation in tomato fruits depends on the cultivar and timing of stress. This might be because sensitivity to water stress varies between different crop species and types (Adu et al. 2018). Compared to vegetables, perennial tree and vine were less sensitive to water restrictions. The relatively stronger and larger root system of perennial crops may be providing an adaptive mechanism for foraging for water under deficit irrigation. Unless the stress is very severe and prolonged, signal induction leading to sugar accumulation may be moderated in these perennial crops.

Sugar content significantly varied across soil textures between only DI and PRDI (Fig. 5). Although the result indicated a significant decline in TSS (of about $6.0 \pm 3.0\%$) of plants subjected to DI on sandy soils, compared to plants grown under PRDI on same soil texture, this must be considered cautiously. This is because the sample size for studies conducted on sandy soil was relatively smaller ($n = 3$) and only one study, which incidentally had a higher weighting, was significant (Fig. 5a). Regression analysis indicated that cumulative effect size of TSS did not significantly differ across the different soil textures when FI was compared with DI. However, TSS on some soil texture types appear to be enhanced when FI was analyzed with DI. There seemed to be superior sugar accumulation when crops are cultivated on bark pumice peat, clay loam and sandy loam soils compared with that of crops grown on sandy clay, silt loam, sandy clay loam, and clay silt loam, as well as sand silt clay, sandy, clayey and loamy soils (Fig. 5). Compared to the other soil types, peat, clay and sandy loam soils are deep and fine textured soils. These soil types usually have sufficient time to adjust to low soil water matric pressure, and may not be easily and rapidly affected by low soil moisture content (Adu et al. 2018; Kirda 2002). Given that plants may undergo water stress rapidly under deficit irrigation when grown in soils such as sandy soils (Kirda 2002), the present results suggest that there is possibly an increased sugar accumulation in plants grown on deep and fine textured soils that are not easily and rapidly affected by low soil moisture content. These soils are able to hold water for a considerable period of time to support photosynthesis; while stomata closure could be larger under the other soils due to rapid drainage that elevates water stress.

Different crop species and growth stages require different irrigation schedules. For some crops, including cucumber, watermelon and melon, excessive irrigation immediately after transplanting adversely affect growth and flowering (Sensoy et al. 2007). In the present study, TSS did not vary across various irrigation frequencies for comparisons between DI and PRDI, (Fig. 6a). For comparisons involving FI and DI, crops watered daily, thrice a week or every 2 days, and those for which water was re-supplied based on water depletion threshold, under DI were significantly superior in TSS (Fig. 6b). For FI and PRDI, TSS of crops watered daily, weekly and those for which water was re-supplied based on water depletion threshold in the soil, were significantly superior in TSS under PRDI (Fig. 6c). Previous research regarding performance of crop quality attributes and irrigation frequency has produced inconsistent results (Ucar et al. 2016). Studies that have linked improved quality with more frequent irrigations include Ucar et al. (2016) for apples and Sensoy et al. (2007) for melon. In contrast, others including García-Tejero et al. (2011) have noted the advantages for low-frequency irrigation in citrus. Sensoy et al. (2007) noted that there were trade-offs between yield of melon and some quality attributes. The highest yield was obtained from more frequent irrigation (6-day intervals) but the lesser the irrigation frequency, the sweeter and less acidic the melon fruit became (Sensoy et al. 2007). Our results largely support the theory that TSS between FI and water-saving irrigation strategies vary significantly if crops are frequently irrigated or if irrigation is based on measurements of soil water depletion. This conclusion, however, has to be indexed with the potential influences of other factors such as climate, physicochemical properties of soil, and irrigation water quality, on crop quality attributes. The results here also emphasize the need for water productivity estimations to consider not only the amount of water applied, but also the irrigation strategy applied.

Effect of other potential moderators on TSS

The quality of the irrigation water affects the osmotic potential of soil water, the soil physical conditions, and ultimately may affect both crop yields and quality (Tejero and Zuazo 2018). We, therefore, sought to extract other soil parameters as moderators thought to be influenced by irrigation water, including soil electrical conductivity (EC), soil pH and bulk density measurements from the included studies. Unfortunately, only about 21% (12 of 58), 36% (21 of 58) and 41% (24 of 58) of the included studies for TSS reported on soil EC, bulk density and soil pH measurements in the original papers, respectively (data not shown). Salinity, for example, was of particular interest due to potential osmotic effects that could result from increased ion concentrations in the soil water and the fact that sizeable proportion (about 11% ≈ 34 Mha) of irrigated lands in the world are said to be saline (FAO 2011). It has been suggested that one of the major problems related to irrigation water quality is the increased salinity of the water, which has been reported to be accompanied by both yield and quality reductions of most crops (Grattan 2002). Soil electrical conductivity (EC) is often used as a measure of soil salinity. Meta-regression analysis, in the present study, for the difference between FI and DI for TSS revealed that differences among cumulative effect sizes for the various EC measurements was insignificant ($Q_B = 4.87$; $df = 11$; $p = 0.937$). Similarly, regression analysis for the difference between FI and PRDI for TSS showed that differences among cumulative effect sizes for the EC was insignificant ($Q_B = 5.127$; $df = 11$; $p = 0.925$) and that for the difference between DI and PRDI for TSS was also insignificant ($Q_B = 4.82$; $df = 11$; $p = 0.940$; data not shown). Indeed, osmotic and ionic effects of the EC could affect crop quality but the rate of yield and quality decline varies with interactions between crop cultivars, crop phenology, timing and/or duration of water stress, environmental factors, and crop management, among others (Dorai et al. 2001; Tejero and Zuazo 2018). Many of these potential moderators are, however, rarely or appropriately reported in published papers. The lack of effect of EC or salinity on TSS, in the present study, could possibly be due to the relatively fewer studies which did not offer sufficient variation in the EC measurements. Irrigation water quality must be an important moderator in subsequent analysis but this is an issue which also borders on quality of reporting practices in the publications and the need for certain critical information to be provided in published papers related to irrigation and crop quality parameters.

Publication bias, cumulative and sensitivity analysis

Our results are robust to publication bias as indicated by the Rosenberg fail-safe number and visually, by funnel plots (Fig. 9) generated for the analysis. Relatively large number of unpublished relationships would be required to change statistically significant effects observed in the present meta-analysis. However, for comparison of TSS between FI and the two water-saving strategies, the effect sizes obtained in the original analysis might be quite conservative as the 'trim and fill' method suggested an even bigger effect sizes of TSS advantage for water-saving irrigation (i.e., DI or PRDI) over FI. Cumulative analysis was employed here to display evolution of irrigation effects over time, display temporal changes in the magnitude of the effect size over the 14 years' data included in this analysis and reveal irregular changes in the effect sizes. The cumulative meta-analysis revealed clear temporal changes in the magnitude of reported effects sizes. Although insignificant, early studies (2003–2004) for the comparison between DI and PRDI, seem to largely suggest that there is superior TSS in plants grown under DI but this changed to favor PRDI in studies published from 2005 to 2010 (Fig. 7a). For the comparisons between FI and DI, and FI and PRDI, the results largely supported the hypothesis that there is superior TSS accumulation under water-saving irrigation, but the magnitude of the effect were in the early years inconsistent but seem to have stabilized since 2011 (Fig. 7b and c). Thus, after a series of undulating evolutions in the magnitude of the effect size, in the latest studies, a trend towards an increasing and stabilized effect sizes were observed (Fig. 7b and c). Possibly, as the diversity of plant species studied increased, the effect size increased and stabilized, and perhaps more recent studies may have been designed to account for trade-offs under conditions where they are most likely to occur (Leimu and Koricheva 2004).

Even though water-saving irrigation technologies have been noted to induce different fruit quality attributes, it appears that the number of published results is smaller compared to the effects of these technologies on water-use-efficiency and yield. In the present study, 58, 35 and 21 effect sizes derived from 47, 28 and 17 studies met our inclusion criteria for TSS, TA and pH, respectively (Supplementary Tables S1–S3). Notwithstanding the seemingly fewer number of effect sizes and/or studies used in the present meta-analysis, the non-independence of multiple effect sizes per study, as indicated by sensitivity analysis, at least for TSS, did not affect the present results. Even so, when DI was compared with PRDI, there were some inconsistency in the significance of the effects size for studies which originally reported measures of dispersion and studies for which SDs had to be estimated. Unlike the overall effect size and that for studies for which SDs were estimated, the effect size for studies which originally reported measures of dispersion was negative and marginally significantly different from zero (Fig. 8a). Approximately, only 22% of the included papers in the TSS meta-analysis have originally reported some form of measures of dispersion. It is, thus, possible that the effect size of studies with reported SDs was significantly different from zero because of the fewer studies in this category. This, yet again, highlights one of the critical shortcomings of reporting practices in the reviewed studies and the need for some form of improvement in the quality of reporting in published papers. A suggestion here is that journal editors and article reviewers strongly enforce that articles tended in for publication fulfill certain standardized reporting criteria.

Implications for irrigation and crop quality management

Irrigation provides higher and stable yields compared to rain-fed crop production. For some agro-environments and crops, irrigation is inevitable. However, globally, water scarcity is becoming widespread and climate change threatens to amplify it. There is an urgent need for widespread adoption of water-saving irrigation techniques if food systems are to be sustained. Adu et al. (2018) showed that, cumulatively, yields under the water-saving irrigation techniques considered in the current study did not differ significantly but were lower compared to those under full irrigation. A major concern (especially to farmers and processors), in addition to the reported yield penalty, is whether deficit irrigation techniques have a positive or negative cumulative effect on crop quality compared to FI. There is paucity of information on the relationship between water-saving irrigation techniques and quality parameters of crops (Jovanovic and Stikic 2018) and such insights are required for the promotion and wider adoption of water-saving irrigation techniques. The TSS is one of the key primary metabolites that represent the nutritional quality of crops. The results in the current study indicate that there is a positive cumulative effect of the water-saving irrigation techniques on TSS in crops. In addition, TA and pH were not significantly different between the water-saving irrigation techniques and FI. Hence, it can be said that water-saving irrigation techniques can be applied to simultaneously increase crop water use efficiency and nutritional quality. This cumulative evidence from a meta-analysis is very important in addressing the concerns over reductions in crop quality under water-saving irrigation techniques. While water saving irrigation techniques can be easily rationalized on socio-economic and ecological grounds, the yield and quality penalties cannot. Based on the cumulative result in the current study, farmers have to only worry about tolerable yield penalties when considering adopting water-saving irrigation techniques, while bearing in mind the gains in crop quality. In addition, because yields and quality parameters do not differ significantly between DI and PRDI, cost becomes the main basis of choice between the two. It is known that PRDI is expensive to install and more difficult to operate compared to DI. Hence, on a balance, DI might be preferable than PRDI but this choice would also need to consider other contextual factors.

Conclusion

In the context of global change, efficient use of water in crop production has become one of the main agendas of environmental sustainability. In regions where irrigation is inevitable, there is an urgent need to improve both crop yield and quality per unit of water supplied. While there are studies on the effects of water-saving irrigation on crop quality attributes, the cumulative evidence has not been synthesized into a holistic product. Here, we provide meta-analysis of current knowledge of the effects of full irrigation (FI), deficit irrigation (DI), and partial root-zone drying (PRDI) on three quality attributes (total soluble solids—TSS, titratable acidity—TA, and pH) of fruits and vegetables. It was observed that TSS of crops under FI was significantly lower than that of crops under DI and PRDI but TSS did not differ significantly between DI and PRDI. Thus, when targeting TSS as a quality parameter, the water-saving irrigation techniques would be a better choice but the choice between DI and PRDI should probably be determined by the scale of water savings vis-à-vis yield penalties, cost, installation and operational complexities, and other contextual factors. However, pH and TA did not differ significantly between the three irrigation regimes, suggesting that either DI or PRDI can be chosen over FI to save water and improve crop quality simultaneously. The TSS response to DI or PRDI is crop- or system specific and the variations are dictated by crop type, soil texture and irrigation frequency. For example, vegetables contributed largely to the observed higher TSS under PRDI compared to perennial trees and vine crops. This suggests a need to take into account differences in crop responses to TSS accumulation to exploit opportunities for further water savings under PRDI for perennial tree crops. Further, TSS accumulation appears to be enhanced under water-saving irrigation techniques when crops are cultivated on deep and finely textured soils as these have the ability to hold water to support physiological processes. As this meta-analysis has shown, many factors underlie the effect of reduced water application on quality attributes of crops. This may include the type of crop, the frequency of irrigation, physical and chemical properties of soil, among others. This means that a multidisciplinary approach is required for further research to understand the mechanisms underlying the combined effect of water-saving irrigation techniques on yield and quality of fruits and vegetables.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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