Agricultural Water Management 333 (2026) 110555

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Yield and water productivity responses to deficit irrigation: A meta-analysis from Ethiopia

Abdu Yimer Yimam [a,b,*], Desale Kidane Asmamaw [d], Margaret Chen [c], Seifu A. Tilahun [b,g], Tewodros T. Assefa [b], Abebech Abera Beyene [b], Mekete Dessie [b], Kristine Walraevens [e], Enyew Adgo Tsegaye [d], Amaury Frankl [f], Wim Cornelis [a]

[a] Department of Environment, Ghent University, Gent 9000, Belgium
[b] Faculty of Civil and Water Resource Engineering, Bahir Dar University, P.O.Box 26, Ethiopia
[c] Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussels 1050, Belgium
[d] Department of Natural Resource Management, Bahir Dar University, P.O.Box 79, Ethiopia
[e] Laboratory for Applied Geology and Hydrogeology, Department of Geology, Ghent University, Ghent 9000, Belgium
[f] Department of Geography, Ghent University, Ghent 9000, Belgium
[g] International Water Management Institute (IWMI), Cantonments, Accra PMB CT 112, Ghana

ARTICLE INFO

Keywords:
Climate-smart irrigation
Ethiopia
Metafor
Random-effects model
Response ratio

ABSTRACT

To meet global food demand, strategies promoting efficient water use are essential for sustainable agricultural practices. Deficit irrigation (DI) is increasingly promoted as a water-saving strategy, though reports on its effect on yield and water productivity (WP) remain inconsistent. To address this inconsistency, we conducted a meta-analysis on eight crops from 62 studies: maize (*Zea mays*), wheat (*Triticum aestivum*), sesame (*Sesamum indicum L.*), bean (*Phaseolus vulgaris L.*), onion (*Allium cepa*), potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), and pepper (*Capsicum annuum*) for their high socio-economic importance for Ethiopia. We used PRISMA 2020 reporting guidelines. Effect size was computed using response ratio of means as effect size measure. Our results indicated that sesame, tomato, and wheat are resilient crops to water stress. Applying DI at 50–70% ETc in wheat increased WP by 48% (95% CI:1.34–1.64) with only 16% yield loss (95% CI: 0.77–0.91). Similarly, in tomato, WP improved by 51% (95% CI:1.35–1.69) with a 21% yield reduction (95% CI: 0.71–0.87). Across all moderators, DI at 80% ETc produced yield comparable to full irrigation ($p > 0.05$). Applying DI under drip irrigation below 80% ETc appeared suboptimal, causing substantial yield loss (up to 45%) with marginal WP gains. Alternate and fixed furrow irrigation performed effectively at 100% ETc with a 50% increase in water productivity (95% CI:1.32–1.71) with only 18% yield reduction (95% CI:0.74–0.92). These findings provide evidence to optimize irrigation strategies and inform sustainable agricultural water management in Ethiopia and for regions with similar agro-climatic conditions.

1. Introduction

Climate change, population growth, and increasing competition for water resources are exerting pressure on global water-resource availability (du Plessis, 2023). Water scarcity has become one of the major constraints to food production worldwide (Cheeseman, 2016), while global food demand is projected to double by 2050 (Hall et al., 2017). The challenge is particularly acute in developing regions where agricultural productivity remains highly dependent on water availability. In Africa, the population is expected to reach 2.4 billion by 2050 (Hall et al., 2017), raising concerns about food security (Sasson, 2012) under changing climatic conditions, limited technological adoption, and inadequate agricultural infrastructure (Arslan et al., 2022). Sustainable agricultural production depends fundamentally on reliable water availability, particularly in arid and semi-arid regions where water scarcity increasingly limits productivity (Golla, 2021; McKenzie and Williams, 2015). In Sub-Saharan Africa, this challenge is amplified by climate change, dependence on rainfed agriculture, low irrigation coverage, and growing competition for water from urban and industrial sectors (Avazdahandeh and Khalilian, 2021; Burney et al., 2013; Jiang

* Corresponding author at: Department of Environment, Ghent University, Gent 9000, Belgium.
E-mail address: abduyimer.yimam@ugent.be (A.Y. Yimam).

https://doi.org/10.1016/j.agwat.2026.110555
Received 1 April 2026; Received in revised form 15 June 2026; Accepted 16 June 2026
Available online 19 June 2026

et al., 2014; Wudil et al., 2022). Despite the region's high vulnerability, existing evidence remains fragmented across locations and production systems, limiting the development of context-specific strategies for sustainable water and agricultural management.

Ethiopia exemplifies these challenges, with agriculture dominated by smallholder farmers (Zerssa et al., 2021) contributing about 60% of the country's gross domestic product (Temesgen et al., 2009) and more than 80% of export earnings (Worqlul et al., 2019). More than 95% of the cropland depends on rainfall, exposing farmers to rainfall variability (Kassaye et al., 2021), land degradation (Solomon et al., 2024), poor soil fertility (Aleminew and Alemayehu, 2020), and weed and pest challenges (Eshetu and Yimer, 2024). Only 5–10% of the cropland is irrigated (Gebul, 2021). Moreover, existing irrigation systems are highly inefficient due to failure of operating gates, canal siltation, leakage through the main canals (Belay et al., 2023), as well as poor infrastructure, limited technology, poor water management, lack of market access, and weak institutional arrangements (Berhe et al., 2022; Eshete et al., 2020). Improving irrigation efficiency through innovative methods is therefore critical for enhancing yield and water productivity (Lakhiar et al., 2024; Sabir et al., 2024; Yadav et al., 2024). Climate-smart agriculture has been promoted globally, encouraging the adoption of irrigation technologies beyond traditional furrow irrigation, including sprinkler, drip, and center-pivot systems(Neupane and Guo, 2019). Alongside these technologies, deficit irrigation (DI), which is the application of water below full crop water requirement (ETc) (Rai et al., 2022), has emerged as a key water saving strategy. DI approaches include partial root zone drying (PRDI), sustained deficit irrigation (SDI), and regulated deficit irrigation (RDI) (Champaneri et al., 2024), with their suitability depending on climate, soil type, crop type, and soil management conditions, and irrigation method (Singh et al., 2021). Accordingly, evaluating the effects of soil pH and irrigation method on the effectiveness of DI is essential. For this study DI refers to the percentage of ETc supplied throughout the entire growing season.

Experimental studies show diverse crop responses to deficit irrigation (DI), particularly in terms of yield and water productivity (WP). Wang et al. (2024) reported regulated deficit irrigation (RDI) improved wheat root growth and delayed senescence, while increasing WP by 26% when applied across all growth stages except booting to grain filling (Zhang et al., 2005). In wheat, combining soil amendments with DI at 50–80% ETc. produced yields comparable to full irrigation without soil amendments (Asmamaw et al., 2023). Likewise, maize achieved maximum production potential with improved WP at 80% ETc (Suna et al., 2023), and PRDI saved up to 50% of irrigation water while maintaining productivity in crops such as maize and tomato (Johnson et al., 2024). Despite these benefits, crop responses remain inconsistent. For example, some studies reported only minimal wheat yield reduction at 70% ETc (Bayisa et al., 2024; Meskelu et al., 2017), whereas others observed substantial yield losses at the same irrigation level across different crops (Narayanan and Seid, 2015; Temesgen et al., 2018; Yenesew and Tilahun, 2009).

To address such inconsistencies, meta-analysis has been increasingly applied to synthesize findings and improve statistical power (Borenstein et al., 2021). Meta-analysis evidence showed that DI reduced yield by an average of 7.1% in wheat and 18.7% in maize (Li et al., 2022), while Yu et al. (2020) reported a comparable 6.6% reduction for wheat. Vegetable yield losses ranged from 7% to 51% depending on DI intensity (Singh et al., 2021). At the same time, DI improved fruit and vegetable quality attributes, including soluble solids and vitamin C (Adu et al., 2019; Lu et al., 2021). Water productivity also increased under DI, with gains of 9% in maize grown on heavy soils (clay, clay loam, silt, silt clay, silt clay loam) (Allakonon et al., 2022), average increases of 9.3% for wheat and 6.4% for maize in China (Li et al., 2022), and improvements of 8–30% in vegetables (Singh et al., 2021)

Despite providing evidence on the effects of DI on crop yield and WP, these meta-analyses exhibit the following limitations. i) Most focused on a single crop response to water stress. ii) Little was done to see the effect of DI level on yield and WP of crops and vegetables. iii) Few studies considered the impact of DI level implemented with PRDI on yield and WP. iv) Most studies overlooked the impact of soil pH levels, soil texture, climate, and irrigation method as explanatory variables (moderators). v) Most global meta-analyses include limited data from Ethiopia. Ethiopia provides a particularly important context for evaluating DI due to increasing water scarcity, high climate variability, and ongoing efforts to expand irrigation as a means of improving agricultural productivity. Moreover, the country encompasses diverse agro-ecological zones and climatic conditions over relatively short distances, which can influence crop responses to water stress and irrigation management. These characteristics necessitate a context-specific assessment of DI strategies. However, most global meta-analyses include limited data from Ethiopia and often fail to capture this environmental heterogeneity, potentially limiting the applicability of their conclusions to Ethiopian conditions. To address this gap, we hypothesize that the impacts of DI on crop yield and water productivity in Ethiopia vary significantly across agro-ecological zones. Accordingly, the objective of this study was to conduct a comprehensive meta-analysis focused on Ethiopia that quantifies the impacts of DI on crop yield and water productivity, considering explanatory variables of crop type, irrigation method, deficit irrigation amount, climate, soil pH level, and soil type.

2. Materials and methods

2.1. Data collection

Data were collected from peer-reviewed articles and conference papers. A literature search covered studies from 1986 to July 2024. The study followed PRISMA 2020 guidelines (Fig. 1), which provide a standard reporting format for a systematic review and meta-analysis (Park et al., 2022). A comprehensive literature review was conducted using three databases: Scopus, Web of Science, and Google Scholar. All records identified through these databases were exported and imported back into EndNote reference management software for duplication check and were further assessed manually to ensure accuracy. Studies that reported crop yield and water productivity differences due to deficit irrigation or moisture stress were searched to develop the databases. The search query was made using the following search key words: ("Water*") AND ("partial root zone*" OR "deficit*" OR "irrigation*" OR "water saving*" OR "drip*" OR "furrow irrigation" OR "every furrow*" OR "alternate furrow*" OR "stage wise deficit*" OR "regulated deficit*" OR "overhead irrigation") AND ("yield") AND ("Ethiopia*")) for years until July 2024.

Articles not fully accessed and review articles were not considered in the database. However, efforts were made to obtain the full access article through author contact or ResearchGate. Data mining and extraction were conducted using Microsoft Excel by compiling relevant information from tables and text. The compiled dataset included author name, publication year, article title, crop type, soil pH, soil texture, irrigation method, irrigation amount (% ETc), yield (t ha^{-1}), water productivity (kg m^{-3}), number of replications, annual rainfall (mm), altitude (m), latitude and longitude (decimal degree), and journal name and publisher. Additional statistical parameters, including coefficient of variation (%), standard error (units), sample size, and standard deviation, were also recorded. Units were standardized to ensure consistency across studies. Missing information on annual rainfall and soil pH was collected from other studies conducted at the same experimental site (same location) and to minimize potential bias, only studies with comparable site conditions and time periods were used.

Articles were screened based on the following criteria: (i) Experiments conducted in the field with side-by-side comparison of full irrigation with deficit irrigation. (ii). Yield and water productivity data reported. For studies not reporting water productivity, the ratio of yield to crop evapotranspiration was used (Appendix A). (iii). Studies

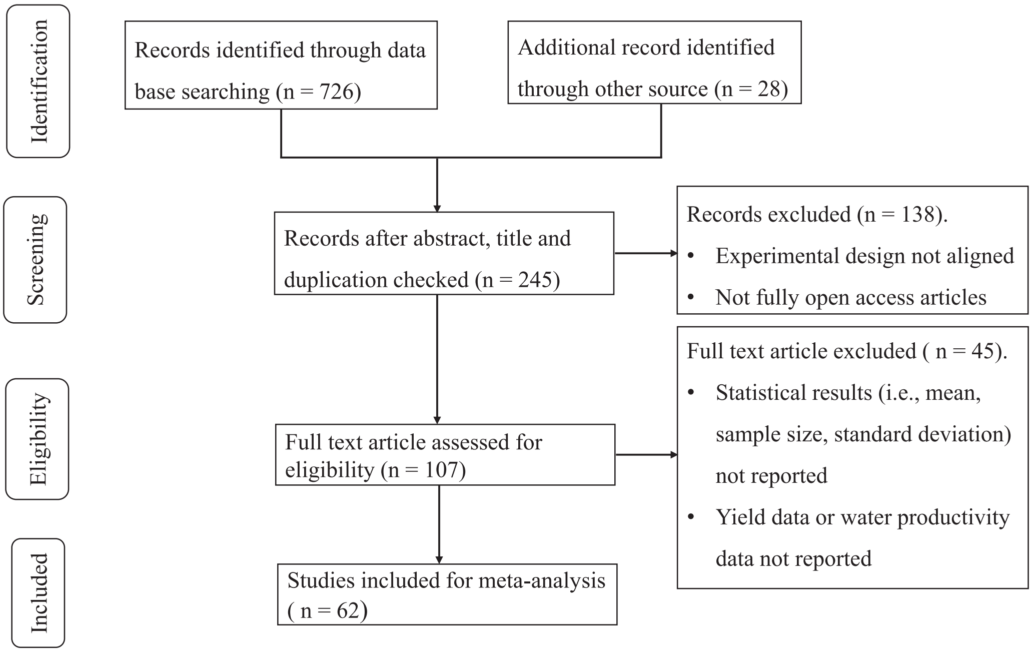

Fig. 1. Flow chart showing the publication selection process following PRISMA protocol.

reported measures of central tendency (mean, sample size, and standard deviation or coefficient of variation, or standard error). (iv). Studies documented in English. (v). Experiments conducted in Ethiopia. Based on these criteria, a total of 62 studies were included in the meta-analysis (Fig. 1, Fig. 2, and Table A9). From these studies, 217 effect sizes for yield and 158 for water productivity were extracted. The analysis focused on eight major crops: maize, bean, sesame, wheat, potato, tomato, pepper, and onion. Additional crops such as barley, cabbage, groundnut, teff, and watermelon were initially identified during database development, but were excluded from further analysis due to insufficient data availability. The number of studies varied across crops due to differences in publication volume. Consequently, crops represented by more studies yielded more precise pooled estimates with greater statistical power, whereas crops with fewer studies produced less precise estimates and wider confidence intervals, reflecting increased uncertainty in the effect size estimates. In this meta-analysis, each pair of data was treated as an independent observation (Wang et al., 2024).

Subgroup analysis was conducted considering crop type, soil texture, irrigation method, climatic region, soil pH level, and DI amount (% ETc) as potential moderators influencing yield and WP variations across the selected studies. Because of lack of data availability in the published literature, the potential influence of electrical conductivity, bulk

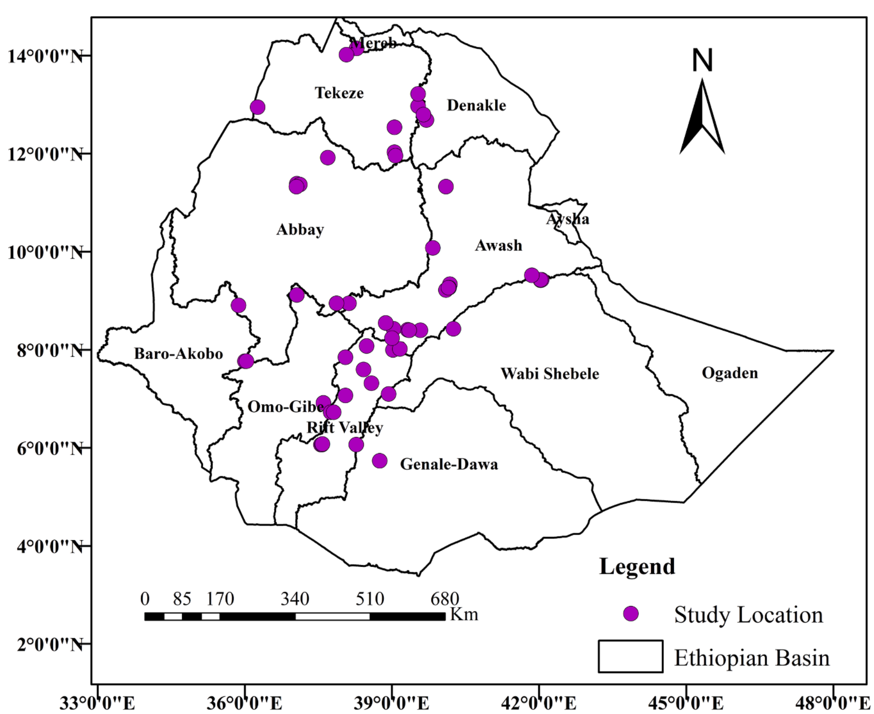

Fig. 2. Geographical location of studies used in the meta-analysis. Details of agro-ecological zones for each sub-basin can be referred (Fenta et al., 2024).

density, and organic matter content on yield and WP was not considered as a potential moderator. Crop type was categorized as bean, maize, wheat, sesame, onion, pepper, potato, and tomato. Soil texture classes were grouped according to the classifications reported in the included studies: clay, clay loam, loam, sandy clay loam, sandy loam, silty clay, and silty clay loam. Climatic regions were classified into humid, sub-humid, and semi-arid based on annual rainfall (Wubaye et al., 2023). Although aridity index, which is the ratio of annual rainfall to potential evapotranspiration (Gebremedhin et al., 2018), is a good index to classify climate regions, it was not applied due to a lack of potential evapotranspiration data in the selected studies. As such, the classification was based on annual rainfall (Haftom et al., 2019). Irrigation methods considered were furrow irrigation methods (alternate furrow, fixed furrow, and every furrow irrigation) and drip irrigation. Partial root zone drying (alternate and fixed furrow) were separately considered during evaluation. DI amounts were classified into four groups: less than 50% ETc, 50 – 70% ETc, 70 – 80% ETc, and more than 80% ETc. PRDI under 100% ETc was treated separately. Similarly, soil pH was classified as acidic (< 5.5), optimal ($5.5 \leq pH \leq 7$), slightly basic ($7 < pH < 8$), and basic (≥ 8) (Sadovski, 2019). These categories are agronomically relevant because soil pH strongly influences nutrient availability, microbial activity, and overall soil fertility, which in turn affect crop growth and yield responses under deficit irrigation. In particular, nutrient availability is generally optimal within the neutral range, while acidic or highly alkaline conditions may limit nutrient uptake and constrain crop performance. To avoid bias, DI amounts that were not common within each subgroup analysis were not considered. Additionally, across all analyses, the influence of rainfall was negligible, as irrigation was applied exclusively during dry spells, and no rainfall occurred during the irrigation periods.

2.1.1. Effect Size Computation and Hypothesis Testing

A random-effects model was used for this study (Hedges and Vevea, 1998) as it is appropriate for analyzing data gathered from published literature (Borenstein et al., 2021). The model assumes that effect size estimates vary among studies (Borenstein et al., 2021; Bracken, 2019). This study used the response ratio of means as an effect size measure (Hedges et al., 1999; Sánchez-Tójar et al., 2020; Wang et al., 2020). Effect size and the corresponding confidence interval were computed (Eq.1 – Eq.3). Details of the statistical analysis followed for response ration of means can be referred from Borenstein et al. (2021).

$$\ln R_i = \ln\left(\frac{x_1}{x_2}\right) \tag{1}$$

where $\ln R_i$ is the log response ratio of individual studies, x_1 is the treatment group mean in each study, and x_2 is the mean of the control group in each study. The average effect size of all studies was computed as:

$$\ln RR = \frac{\sum_{i=1}^{n} w_i \ln R_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where $\ln RR$ is the average effect size of all studies in log scale, w_i is the weight assigned to each study effect size estimate, and $\ln R_i$ is the log response ratio of each study effect size estimated from Eq. 1. The term "n" is the number of studies included. The corresponding confidence interval was computed as:

$$\ln CI \quad (95\%) = \ln RR \pm 1.96 * Se_{\ln RR} \tag{3}$$

where *lnCI (95%)* is the 95% confidence interval, $\ln RR$ is the average log response ratio of the effect size estimate from Eq. 2, and $Se_{\ln RR}$ is the corresponding standard error. The confidence interval is used to determine the range within which the true effect size is likely to fall and also to indicate the precision of the estimate and the statistical significance as well (Nakagawa and Cuthill, 2007). The term ± determines the lower and upper confidence intervals.

The probability of either accepting or rejecting the null hypothesis (effect size estimate between the treatment group and the control group is the same) was estimated as:

$$p = 1 - \Phi(\pm Z) \tag{4}$$

where $\Phi(\pm Z)$ is the standard normal cumulative distribution function, in which the value of "Z" can be determined as:

$$Z = \frac{\ln RR}{Se_{\ln RR}} \tag{5}$$

In this study, the statistical significance was reported using either the limit of confidence interval (Tong et al., 2022) or the p-value of the "Z" statistics, with $p < 0.05$ indicating statistical significance (Hedges and Pigott, 2001), as both convey the same message. Finally, the effect of DI on yield and WP was reported as a percentage change for ease of understanding by the readers (Wang et al., 2020), with negative values indicating a reduction and vice versa relative to the control:

$$\% \quad change = \left(\exp^{\ln RR} - 1\right) * 100 \tag{6}$$

2.1.2. Test of Heterogeneity in Effect Size

Heterogeneity in effect size was assessed using Cochran's Q-statistics (Cohen et al., 2015), where the null hypothesis assumes a common effect size across studies and was tested at 5% significance level for this study.

Additionally, τ^2 and I^2 were used to quantify the degree of heterogeneity (Borenstein et al., 2021), with τ^2 estimating the amount of heterogeneity and I^2 estimating the proportion of heterogeneity. Restricted maximum likelihood (REML) estimator was employed as τ^2 estimator. Random-effects model, incorporates both within-study and between-study variances (τ^2) to account for heterogeneity whereas fixed-effect model weights studies by the inverse of within-study variance assuming a common effect size.

According to Higgins et al. (2003), I^2 ranges from 0 to 100% with a value higher than 75% indicating a true variation in effect size between studies which can be explained by subgroup analysis. A simplistic categorization of I^2 values is not appropriate across all contexts; however, as a provisional guide, values of 25%, 50%, and 75% may be described as low, moderate, and high heterogeneity, respectively (Higgins et al., 2003).

2.1.3. The three core parameters in meta-analysis

For continuous data, effect size estimation requires sample size, mean, and standard deviation for both treatment and control groups in each study and these data were gathered from reported studies. In this study, missing data for standard deviation was estimated from standard error (Lee et al., 2015) or coefficient of variation (Jalilibal et al., 2021).

$$Se = \frac{SD}{\sqrt{n}} \tag{7}$$

where SD is the standard deviation, n is the sample size, and Se is the standard error.

$$CV = \left(\frac{SD}{Xmean}\right) * 100 \tag{8}$$

where CV is the coefficient of variation in percentage, and x_{mean} is the mean of the treatment.

2.2. Publication Bias

Publication bias was assessed using Egger's regression test, which detects funnel plot asymmetry (Lin et al., 2018). If the probability of the Egger's test is significant, it shows publication bias (asymmetry in the funnel plot). Trim and fill method was applied to examine the potential impact of publication bias on the robustness of the overall effect size estimate.

2.3. Statistical Analysis Methods

All analyses were performed in R 4.2. The Metafor (version 4.6.0) package in R was used to assess the effect size estimates (Viechtbauer, 2010). The individual effect size and the associated variance were computed in R using the 'ROM' measure in the escalc function (Sánchez-Tójar et al., 2020). The random effect model was fitted with 'rma' as a code for the model (Jackson and Turner, 2017).

3. Results

In this study, the term crop refers broadly to cereals (maize, wheat), legumes (bean), oilseed (sesame), and vegetables (potato, onion, pepper, and tomato). To avoid repetition when reporting moderator specific statistical results, the following principles apply: (i) Confidence intervals that encompass one indicate a non-significant effect; (ii) high heterogeneity ($I^2 > 75\%$) (Borenstein et al., 2017) suggests true variability in effect size; (iii) a Cochrane Q test p-value < 0.05 indicates significant heterogeneity; (iv) all statistical analyses used 5% significance level.

Egger's test indicated no publication bias for either yield or WP, with p-values of 0.68 and 0.14, respectively. The overall effect size for DI on yield was 0.76, indicating a 24% yield reduction relative to the control (Table 1). In contrast, the overall effect size for WP was 1.22, reflecting a 22% increase under DI (Table 1). For both outcomes, the confidence interval did not encompass one, indicating statistically significant effects. Heterogeneity statistics (τ^2, I^2, Q) further showed substantial between-study variations in effect size estimates for yield and WP indicating the average pooled effect is highly-context dependent, which can be explained by subgroup analysis in the following sections.

3.1. Effect of Crop Type

The effect of DI on yield and WP was evaluated using crop type as a moderator (Figs. 3a – 3b). Overall, DI significantly reduced crop yield, although the magnitude of reduction varied by crop type. Yield reductions were highest for pepper (37%) and maize (27%), followed by bean (24%), onion (25%), potato (18%), tomato (17%), and wheat (13%) (Table A1). Sesame showed the lowest yield reduction (9%), and its effect was statistically insignificant as the confidence interval encompasses one (Fig. 3a). Significant heterogeneity was observed among studies for all crops with an I^2 value exceeding 80%, indicating considerable variation in effect size across studies (Table A1). On the other hand, DI improved WP across crops except sesame (Fig. 3b). The highest increase in WP was observed in tomato (40%), followed by bean and potato (37%) (Table A2). Among cereals, wheat showed a higher improvement in WP (32%) than maize (13%). Onion and pepper also exhibited significant WP gains of 19% and 22%, respectively. Similar to yield, WP exhibited significant heterogeneity across all crops ($p < 0.0001$) with an I^2 value exceeding 80%, indicating considerable variation in effect size across studies (Table A2).

Table 1
Average effect size of deficit irrigation on crop yield and water productivity (WP) based on 62 studies with corresponding summary statistics.

Outcome	Yield (t ha^{-1})	WP (kg m^{-3})
Effect Size	0.76	1.22
Se	0.0195	0.0206
Z-val	−13.78	9.67
p-val	< 0.0001	< 0.0001
LCI	0.736	1.17
UCI	0.795	1.27
τ^2	0.0078	0.0582
se	0.0078	0.0075
I^2	98.84	99.68
H^2	86.5	317.41
Q(df)	17974.1(216)	12200.1(157)
p	< 0.0001	< 0.0001

Note: LCI and UCI are lower and upper bounds of confidence interval, respectively. Se is standard error, Z-val is z statistics, Q(df) represent Cochrane Q test (degree of freedom). τ^2, I^2, H^2 are statistical parameters used to assess the heterogeneity in effect size estimates.

3.2. Effect of soil texture

The effect of DI on yield varied with soil texture (Fig. 4a). Across soil texture, yield reduction ranged from 18 to 35% (Table A1, Fig. 4a). The lowest yield reduction occurred in clay soil (18%), while the largest was observed in sandy clay loam (35%). Yield reductions of 22% were recorded in silty loam, whereas silty clay loam, loam, and clay loam soils exhibited reductions of 21%, 25%, and 27% respectively. Effect size estimates showed significant heterogeneity among soil textural classes ($p < 0.0001$) and an I^2 value exceeding 96% (Table A1). In contrast, DI significantly improved WP across soil types, except in sandy clay loam (Fig. 4b) in the range from 17 to 39% (Table A2, Fig. 4b). The highest improvement was observed in loam soils (39%), while the lowest occurred in clay loam soils (17%). WP increased by 26% in silt and silty clay loam soils, whereas clay and silty loam soils exhibited improvements of 21% and 22%, respectively. Effect sizes for WP showed high heterogeneity ($I^2 > 96\%$) among studies (Table A2).

3.3. Effect of irrigation application method

Crop yield was significantly influenced by the method of irrigation application (Fig. 5a, Table A1). The yield under alternate furrow irrigation was 82% of the control, corresponding to 18% yield reduction. Every furrow irrigation reduced yield by 23%, while fixed furrow irrigation resulted in a 21% reduction. All effect size estimates were statistically significant ($p < 0.0001$), and the heterogeneity was high with an I^2 value exceeding 97% (Table A1). Despite the observed yield reductions, all irrigation methods significantly improved WP under DI (Fig. 5b, Table A2). WP improvement was highest for every furrow irrigation (24%), followed by fixed furrow irrigation (18%), alternate furrow irrigation (13%), and drip irrigation (14%). Heterogeneity in effect size was significant for all irrigation methods ($p < 0.0001$), with I^2 exceeding 97% (Table A2).

3.4. Effect of climate

Crop yield was significantly reduced across all climatic regions (Fig. 6a, Table A1). Yield declined by 20% in humid regions (80% of the control), 26% in sub-humid regions (74% of the control), and 18% in semi-arid regions (82% of the control). In contrast, WP showed significant improvement under DI across all climatic regions (Fig. 6b, Table A2). The highest gain in WP occurred in semi-arid regions (33%), followed by sub-humid (21%) and humid (18%) regions. The corresponding effect size estimates were highly heterogeneous across studies ($p < 0.0001$), with I^2 value exceeding 97% (Table A2).

3.5. Effect of Soil pH Level

Yield response to DI showed clear reductions across soils of varying pH (Fig. 7a, Table A1). The highest reduction occurred in soils with pH 5.5 – 7 and 7 – 8 by 24% and 26%, respectively, followed by acidic soils (15%) and alkaline soils (12%). The corresponding improvement in WP ranged from 3 to 38% across soil pH levels (Fig. 7b, Table A2). In soils with optimal pH, WP increased by 29%. Similarly, WP improved in slightly basic soils by 19%, and by 38% in alkaline soils. In contrast, statistically, there was no gain in WP in acidic soils (Fig. 7b).

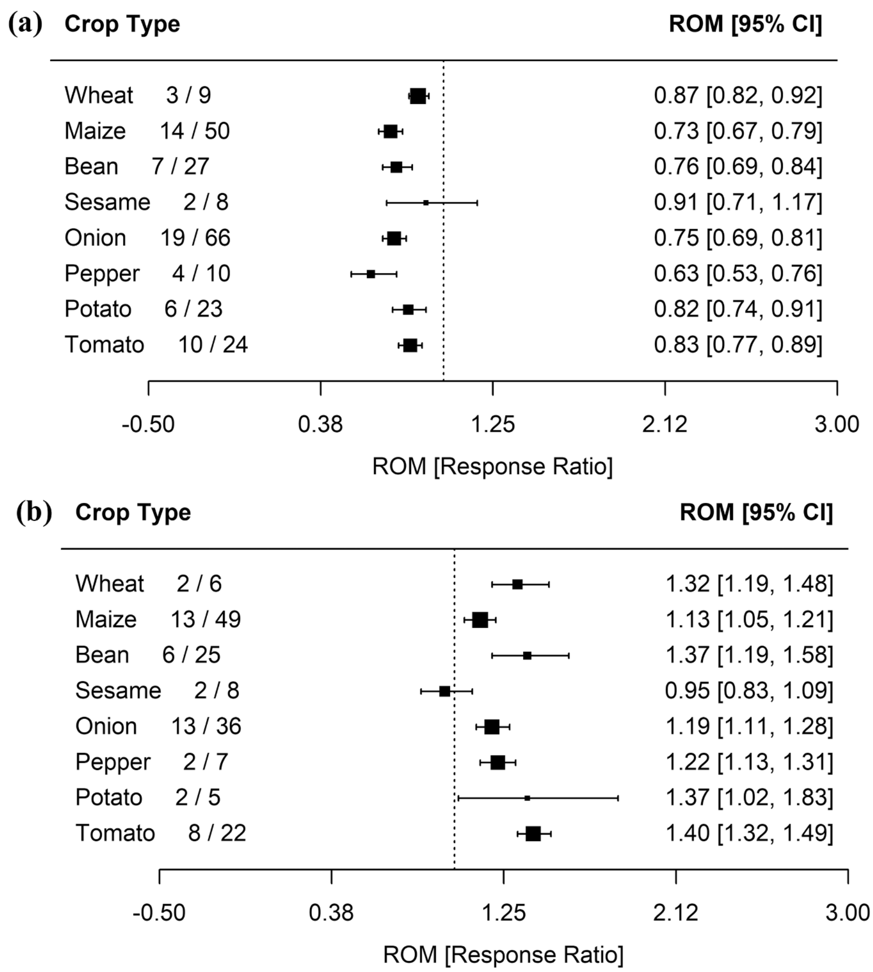

Fig. 3. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across crop type. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

3.6. Effect of deficit irrigation level

The amount of DI was identified as the main moderating factor influencing crop yield. Across DI, significant yield reduction ($p < 0.0001$) was observed compared to the control (Fig. 8a, Table A1). The highest yield loss occurred under severe deficit (< 50% ETc) with a 57% yield reduction. Yield reduction decreased with decreasing water stress, resulting in 34%, 16%, and 8% under DI levels of 50 – 70% ETc, 70 – 80% ETc, and 80 – 100% ETc, respectively. Similarly, full irrigation under partial root zone drying (Fim, Fig. 8a) reduced yield by 18%. At the same time, WP improved across DI levels in the range from 15% – 50% relative to the control (Fig. 8b, Table A2). The highest WP improvement was achieved under partial root zone drying irrigation managed at full irrigation. Similarly, WP increased by 23%, 17%, and 15% under DI levels of 50 – 70% ETc, 70 – 80% ETc, and 80 – 100% ETc, respectively.

The combined effects of DI levels with crop type, soil texture, climate, soil pH, and irrigation method on yield and WP are presented in the order of increasing DI level: 50 – 70% ETc, 70 – 80% ETc, and 80 – 100% ETc.

3.6.1. Crop Type and DI Level

Across all crops except sesame, DI at 50% – 70% ETc caused significant yield loss ranging from 16 to 53% (Table A3). Pepper experienced the highest yield loss (53%), while wheat showed the lowest reduction (16%). Yield reductions for maize, bean, onion, potato, and tomato were 41%, 37%, 42%, 29% and 21% respectively (Table A3). Despite yield losses, WP increased significantly ($p < 0.05$) by 9% – 51% for all crops except sesame and maize (Table A6). Tomato exhibited the largest WP increase (51%), followed by wheat (48%) and bean (38%), while onion and pepper showed moderate improvement of 26% and 27% respectively.

When irrigation water supply increased to 70 – 80% ETc, yield reductions were relatively improved compared to 50 – 70% ETc for all crops (Table A4). Yield declined by 10% for wheat, 23% for maize and pepper, 14% for beans, 15% for onion, and 13% for potato. Correspondingly, WP increased significantly ($p < 0.01$) for wheat (21%), bean (35%), onion (18%), and tomato (25%) (Table A7). WP gains were not significant for maize, sesame, and pepper. Yield reduction for all crops was found statistically insignificant ($p \geq 0.05$) except for pepper at DI level between 80% and 100% ETc (Table A5), with significant improvement in WP (9% – 47%) except for beans (Table A8). Irrigating at 80–100% ETc could yield statistically comparable yield to full irrigation while improving water productivity for the studied crops. Pepper remained the only crop consistently sensitive to DI across all deficit levels, indicating low resilience to water stress.

3.6.2. Soil Texture and DI Level

Yield reduction was found to be significant ($p < 0.05$) for DI between 50% and 70% ETc across soil textural classes (Table A3). The highest

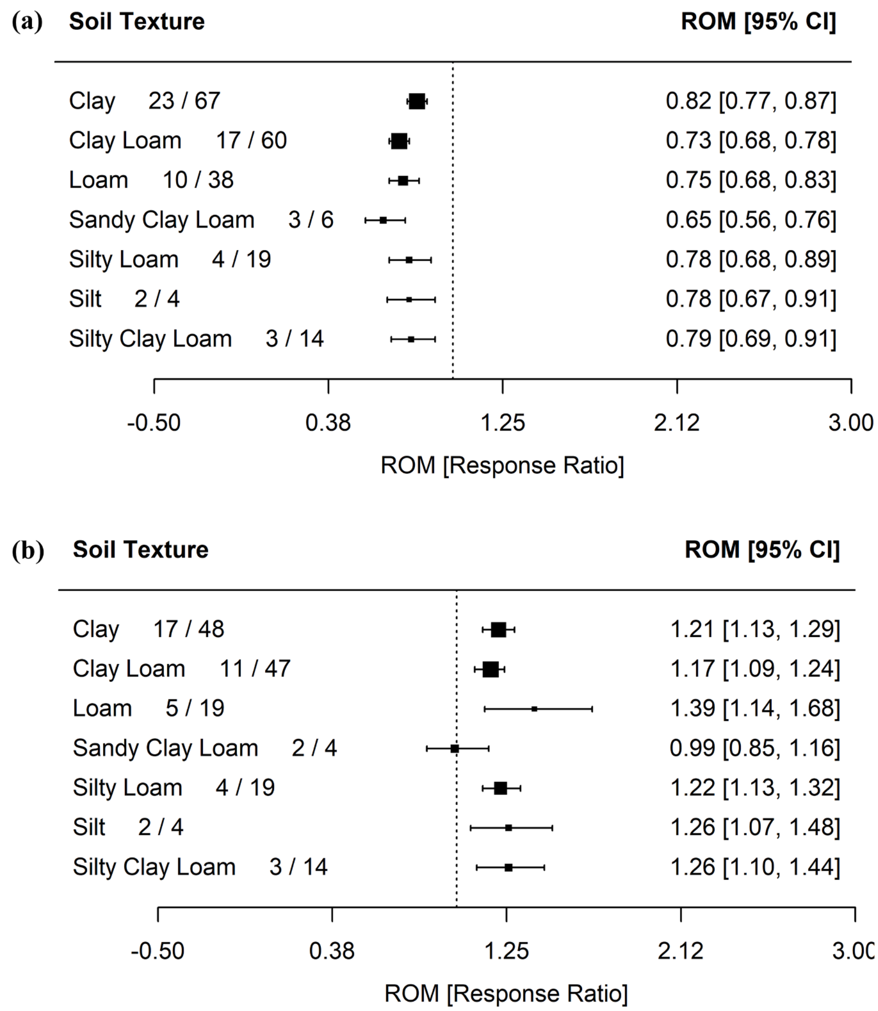

Fig. 4. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across soil type. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

yield loss occurred in loam soil (36%), followed by silty loam (31%), silty clay loam (30%), and sandy clay loam (23%). Clay and clay loam soil showed similar yield reduction (28%) while silty soil experienced a 27% loss. At the same time, WP increased significantly ($p < 0.05$) across soil texture except silty loam (Table A6). WP increased in loam (41%), silt (40%), and silty clay loam (39%), whereas clay and clay loam soils showed less improvement of 16% and 15% respectively.

When DI increased to 70 – 80% ETc, yield loss became relatively smaller compared to lower irrigation levels. Yield loss was significant ($p < 0.05$) across soil textural classes with reductions of 11% for clay, 21% for clay loam, 12% for loam, 15% for silt, 16% for sandy clay loam, and 13% for silty clay loam (Table A4). Correspondingly, WP increased across all soil texture (Table A7) with the largest improvement observed in loam soil (40%), followed by silt (30%) and silty clay loam (17%). At DI levels between 80% and 100% ETc, yield reductions were statistically insignificant ($p > 0.05$) for most soil texture except clay and clay loam soils (Table A5). Correspondingly, a significant WP increment of 9% for clay, 12% for clay loam, and 16% for silty loam soil was found (Table A8), proving that irrigating at 80–100% ETc can maintain yields comparable to full irrigation while improving water productivity across most soil types.

3.6.3. Soil pH and DI Level

DI application at 50% – 70% ETc significantly ($p < 0.05$) reduced yield in acidic, optimal, slightly basic, and basic soils by 21%, 35%, 40%, and 16%, respectively (Table A3). Correspondingly, WP increased significantly by 31%, 17%, and 57% in the optimal, slightly basic, and alkaline soils, respectively (Table A6), while there was statistically no improvement for acidic soils (Table A6). At DI levels of 70% – 80% ETc, WP significantly improved by 19%, 18%, and 20% in optimal pH, slightly basic, and basic soils, respectively (Table A7). The corresponding yield reductions were 14%, 20%, and 9%, respectively (Table A4). In both cases, the difference in acidic soils was statistically insignificant. WP improvement for acidic soil remained insignificant for DI between 80% and 100% ETc, whereas in optimal and slightly basic soils, a 10% and 17% improvement was observed (Table A8). Correspondingly, yields at 80–100% ETc were found statistically comparable to full irrigation across soil pH levels except slightly basic soil (Table A5).

3.6.4. Climate and DI Level

In both humid and semi-arid regions, yield was significantly reduced by 26% and by 41% in sub-humid regions under 50 – 70% ETc (Table A3). Despite yield loss, WP increased by 19%, 22% and 40% in humid, sub-humid, and semi-arid regions, respectively (Table A6). Similarly, at DI levels of 70 – 80% ETc, yield declined significantly by 10.5%, 17%, and 21% in humid, sub-humid, and semi-arid regions, respectively (Table A4), while WP improved by 12%, 19%, and 17% (Table A7). Across climatic regions, irrigating crops at 80–100% ETc was

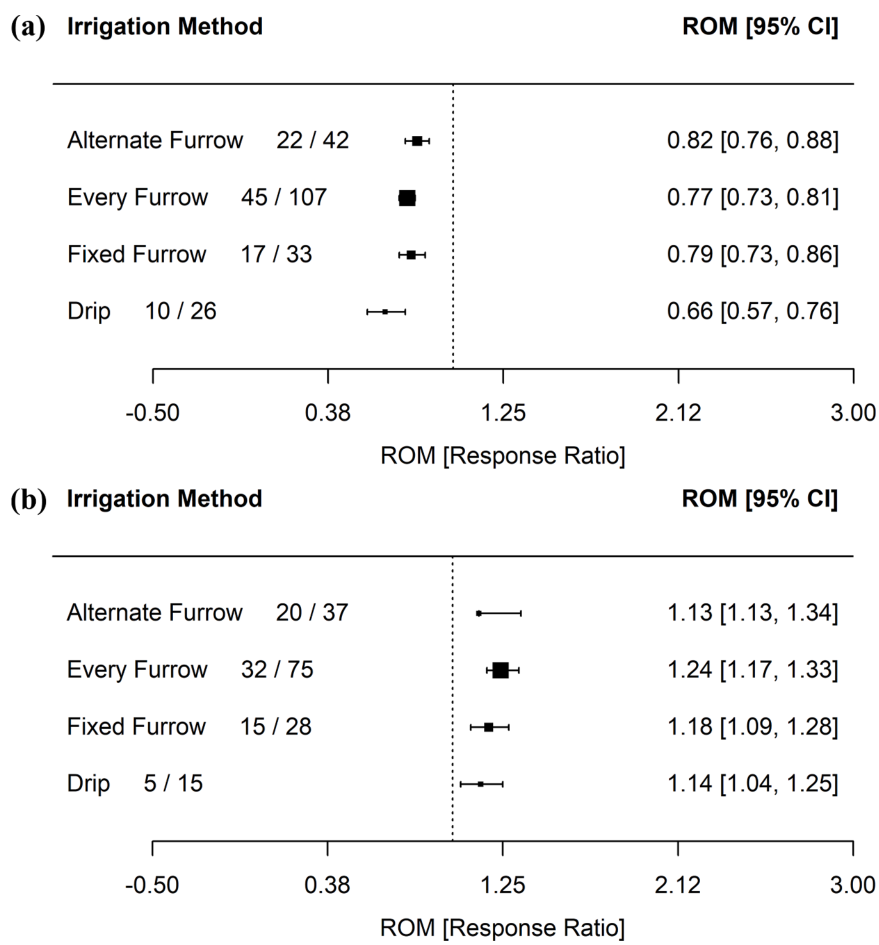

Fig. 5. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across irrigation methods. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

found statistically comparable as full irrigation, with improvement in WP in the range from 12 to 16% (Table A5, Table A8)

3.6.5. *Irrigation application method and DI Level*

Under drip irrigation, yield dropped by 45% at DI between 50% and 70% ETc ($p < 0.05$; Table A3), based on the subset of studies included in our analysis. For the same irrigation level, practicing alternate furrow and fixed furrow irrigation significantly reduced yield by 26%. The corresponding WP improvement was only significant ($p < 0.05$) for fixed furrow (22%) and every furrow irrigation (30%) (Table A6). When DI increased to 70% – 80% ETc, yield significantly reduced in the range of 13% – 34% across irrigation methods (Table A4), with 7% – 23% improvement in WP (Table A7) except for drip irrigation. At 80% ETc, yield reductions fall in the range of 5% – 16% with improvement in WP up to 21% across irrigation methods (Table A5, Table A8).

4. Discussion

4.1. *Yield response to DI*

Deficit irrigation (DI) consistently reduced crop yield in our meta-analysis. The magnitude of yield loss is context-dependent and moderated by crop type, soil texture, climate, irrigation method, and the severity of water stress. Among crops, cereals showed contrasting responses to water deficit. Wheat showed higher resilience to DI than maize. Li et al. (2022) also reported lower average yield reduction (7.1%) for wheat compared to maize (18.7%) under DI. Vegetables except tomato displayed higher sensitivity to DI. Pepper was the most sensitive crop across all deficit levels, which is aligned with experimental and genotype-based studies showing up to 58% yield loss under water stress (Araz et al., 2025; Singh et al., 2021). While our analysis did not measure physiological mechanisms directly, water stress in pepper reduces leaf area and stem diameter while sharply increasing oxidative stress markers such as malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), which impair photosynthesis, leading to yield loss. In contrast, tomato exhibited notable tolerance to water stress consistent with Khalid et al. (2023). Oilseed crops, particularly sesame, showed statistically insignificant yield loss even under severe water deficits, consistent with their reported physiological and phenological adaptations to drought (Jahan and Nassiri-Mahallati, 2022; Pabuayon et al., 2019). Sesame, tomato, and wheat resilience to water stress is linked to their physiological mechanisms. Sesame relies on deep rooting and osmotic adjustment via proline and sugars, supported by protective proteins that stabilize cells and enable rapid recovery (Baghery et al., 2023). Tomato combines osmotic regulation with strong antioxidant resistance, maintaining metabolic activity and fruit development under limited moisture (Haghpanah et al., 2024). Wheat employs early stomatal closure, osmotic balance, and antioxidant enzyme activity, alongside deeper roots and high water-use efficiency to sustain yield (Fan et al., 2022; Haghpanah et al., 2024).

As expected, the dominant driver of yield loss was found to be the amount of deficit level. Under severe DI, yield losses across most crops were pronounced, whereas irrigating at 80% ETc produced yields statistically comparable to full irrigation in many cases (Abdelkhalik et al.,

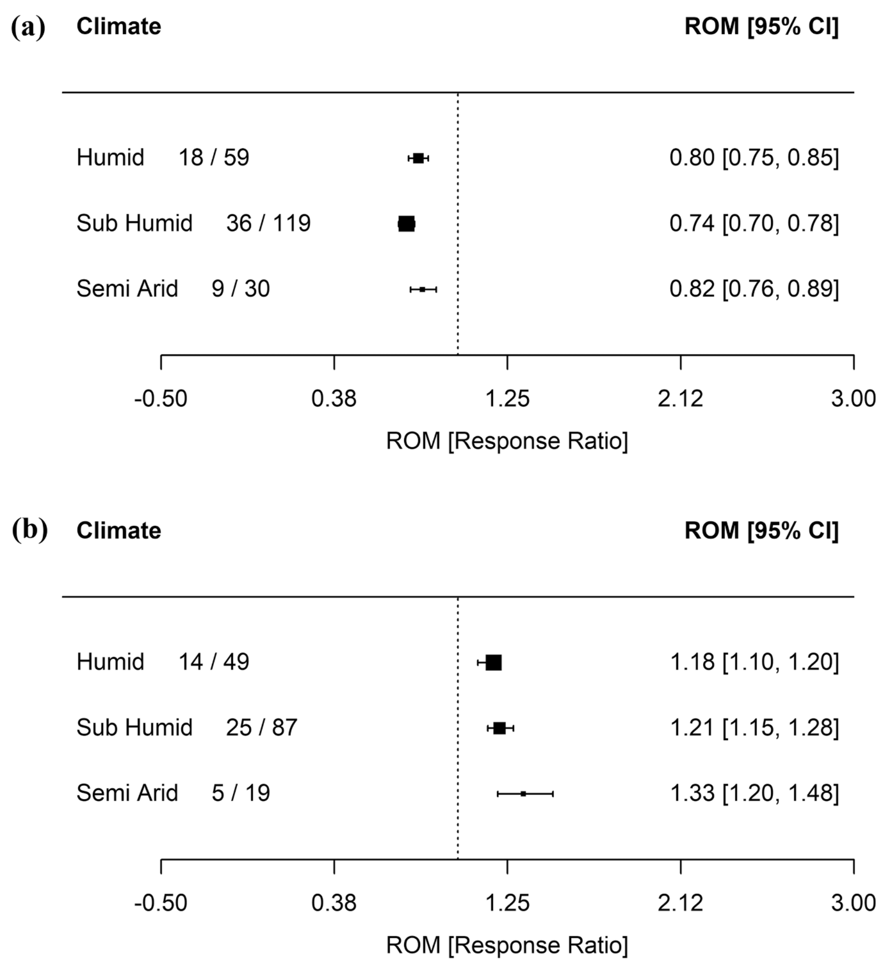

Fig. 6. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across climate. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

2020; Champaneri et al., 2024). This finding is supported by root-zone relative water deficit threshold optimization studies in the North China Plain, showing that moderate water deficits can maintain near-optimal yield and water productivity (Zhang et al., 2023). Soil texture also strongly represented yield responses to DI. Clay soils showed lower yield reductions than other textures. Clay soils, due to their fine texture and high water holding capacity (Song et al., 2025), can buffer crops against transient water stress by maintaining sufficient aeration and infiltration, thereby reducing yield losses compared to coarser-textured soils.

Climatic conditions further influenced yield loss. The lowest yield reductions observed in semi-arid regions (18%) may reflect greater crop drought tolerance or due to crop selection that are well adapted to local growing conditions. Moreover, the level of soil pH also determines crop productivity. Under optimal soil pH, the highest (24%) observed yield loss might be due to the limited interaction between water and nutrients, which happens because of water stress (El-Hendawy et al., 2024; Ramaswwamyreddy et al., 2021). However, crops grown in acidic and basic soils showed smaller yield loss, which might be due to the adaptations of plants and soil microbial communities in these environments (Hemkemeyer et al., 2024). Additionally, in acidic soils, the availability of essential nutrients such as phosphorus, calcium, and magnesium is limited, which limits crop growth (Prakash et al., 2024; Yadav et al., 2020). Irrigation strategies also play a role for crop production. For example, drip irrigation below 80% ETc resulted in pronounced yield loss up to 45% across crops and agro-climate in our study.

The yield reduction observed in this study agrees with the findings of Al-Ghobari and Dewidar (2018) who reported significant tomato yield losses under drip irrigation when water application was reduced below 80% ETc. The likely reasons might be due to restricted root development, reduced wetted soil volume, and uneven nutrient distribution under low irrigation rates (Amare, 2020; Hashem et al., 2023; Yang et al., 2023). Moreover, during fertigation practice under reduced irrigation volumes, nutrient mobility becomes limited, exacerbating yield loss as yield is influenced by farmers' improved farm input usage (Zewdie et al., 2020). Among furrow irrigation methods, partial root zone drying performed better under 70 – 80% ETc, offering a balance between yield maintenance and water productivity (Asres, 2023). Alternate furrow irrigation (AFI) improves water-use efficiency by applying water to only every other furrow during each irrigation event (Golzardi et al., 2017). This practice reduces the amount of irrigation water required, thereby lowering pumping costs, labor requirements, and water losses through runoff and deep percolation and creates a favorable condition for effective root water uptake and improves crop water-use efficiency (Kifle et al., 2017). Under such conditions, reliable modelling tools provide accurate quantification of crop root water uptake for efficient water resource management (Zhang et al., 2025). Recent advances in root water uptake modeling show that accounting for water-salinity stress hysteresis improves prediction of root water uptake under deficit conditions, offering a better mechanistic interpretation of crop responses to water stress (Xu et al., 2026). Moreover, in areas where groundwater contributes to plant root water uptake,

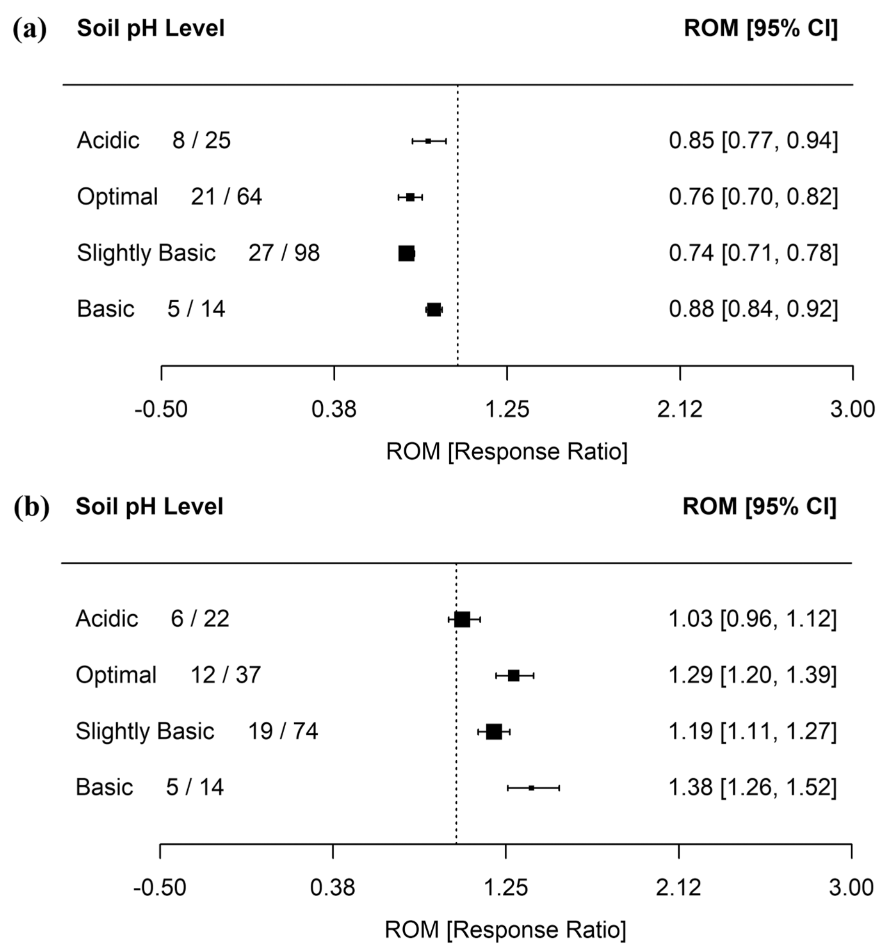

Fig. 7. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across soil pH. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

accurate quantification of groundwater depth is essential for developing effective irrigation water management strategies (Yanqi et al., 2025).

4.2. Water Productivity Response to DI and Implications

DI consistently increased water productivity (WP) across most crops and agro-environmental settings, emphasizing a fundamental trade-off between yield maximization and irrigation water use efficiency. In the current study, up to 50% WP gains were observed at 50 – 70% ETc under wheat and tomato, reflecting their ability to maintain biomass production and physiological activity under reduced water supply. Moreover, DI at 80% ETc improved WP without significant yield loss, reinforcing its practical relevance for farmers to balance productivity and water conservation (Li et al., 2022). Climate strongly influenced WP outcomes. In the current study, semi-arid regions exhibited greater WP gains than humid regions. This might be due to stronger dependence on irrigation and plant adaptation to water stress in the semi-arid regions (Zhang et al., 2024). Soil pH also influenced WP responses. Acidic soils showed non-significant WP improvements. This might be due to several factors, including nutrient constraints, and build-up of toxic elements which hamper root growth, and reduced microbial activity under water limited conditions (Msimbira and Smith, 2020; Prakash et al., 2024) or small sample size. In general, severe DI disrupts the synchronization of water and nutrient availability to plants, leading to reduced water use efficiency (Ullah et al., 2021).

The combined yield and WP responses observed in the current study have potential relevance to similar water-limited smallholder systems indicating broader relevance. The average yield reduction (24%) and WP improvement (22%) due to DI observed in this meta-analysis aligned with global estimates reported by Singh et al. (2021). According to Singh et al. (2021), yield reductions of crops and vegetables ranged from 6.9 to 51% with 8 – 30% WP gains under DI, corroborating our findings. This convergence suggests that crop water relationships identified here can be transferable across regions. For example, wheat, tomato, and sesame maintained acceptable yields under moderate to severe DI in the current study, which is consistent with studies reported from semi-arid regions in Zimbabwe, Senegal, and Morocco (Diedhiou et al., 2024; Kouighat et al., 2023; Mugabe and Nyakatawa, 2000; Muroyiwa et al., 2023). Such consistency across diverse agroecological zones indicates that these crops possess inherent drought resilience traits that make them suitable candidates for DI based intensification worldwide. Additionally, DI could offer significant opportunities for irrigation expansion through water reallocation. In Sub-Saharan Africa, where less than 10% of cultivated land is irrigated (Burney et al., 2013; You et al., 2011), water saved through DI could be redirected to expand irrigated area (Asmamaw et al., 2023), potentially increasing overall food production and enhancing resilience to climate variability. Overall, this study demonstrated that DI is a flexible, scalable, and globally applicable irrigation strategy. Its success depends not on location alone but on informed crop selection, appropriate deficit levels, soil and climate conditions, and clearly defined management objectives that balance yield stability with water use efficiency. Additionally, the findings offer

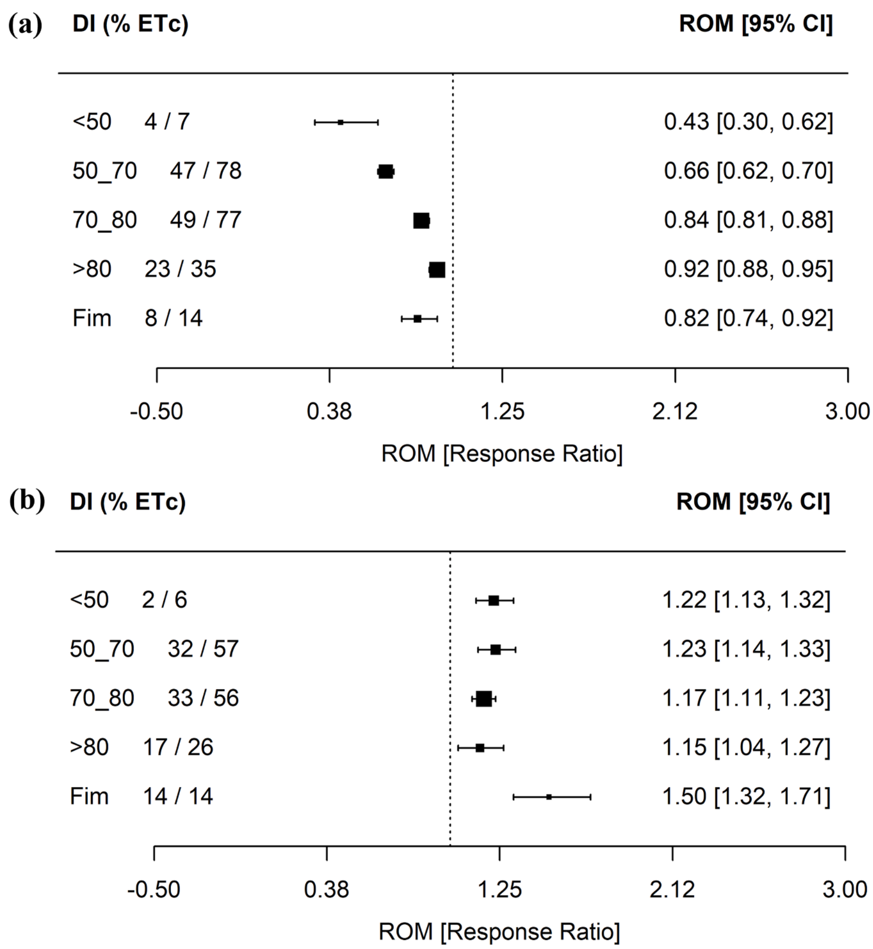

Fig. 8. Forest plot showing: (a) yield comparison and (b) WP comparison between full irrigation and DI across irrigation methods. Fim is a notation used to indicate furrow irrigation methods (alternate furrow and fixed furrow irrigation) managed at full irrigation amount. The vertical dotted line denotes the line of no effect (null hypothesis). The square shapes represent the estimated effect size. The size of the squares represents the weight of each effect size. Error bars indicate the 95% confidence interval (CI). The two numbers separated by a backslash on the left represent the number of studies and the number of observations, respectively. Overlapping CI indicates statistical non-significance and vice versa.

valuable insights for decision-makers in developing effective water management strategies by balancing productivity and water conservation. These strategies enhance food production and income among smallholder farmers in water-scarce regions, with relevance beyond Ethiopia by addressing the underrepresentation of Ethiopian highland agro-ecological zones in previous global meta-analyses of deficit irrigation. Furthermore, to enhance water productivity and support sustainable water resource management, deficit irrigation strategies should be integrated with strategic crop allocation across regions, as suggested by Liu et al. (2026).

5. Conclusion

This study evaluated the impact of deficit irrigation (DI) on yield and water productivity (WP) across eight major crops cultivated in the Ethiopian highlands. The overall yield reduction due to DI application was found 24% with a 22% overall increment in WP. Soil texture, climate, soil pH level, irrigation method, crop type, and deficit irrigation level were the potential moderators explaining the variation in effect size between studies. This study found that irrigating crops at 80–100% ETc gave statistically comparable yield as the full irrigation across all potential moderators. Moreover, in water-scarce areas having potential irrigable land resources, wheat and tomato can be irrigated at half of their crop water requirement. Similarly, vegetables can be irrigated up to 70% ETc with moderate yield loss, except for pepper. Sesame was found to be adaptable to severe water deficits. As sesame is one of the cash crops, farmers can produce more with less water consumption. These responses are supported by drought adaptation mechanisms such as osmotic adjustment, antioxidant defense, stomatal regulation, root system modification, and hormonal signaling, which collectively enhance crop resilience and sustain productivity under water stress.

The findings provide practical guidance for irrigation planning in Ethiopia. Irrigation authorities, development programs, and extension services may consider promoting DI at approximately 80% ETc as a sustainable water-saving strategy to balance yield loss and water conservation. Moreover, this study contributes to the achievement of Sustainable Development Goal 2 (Zero Hunger) by supporting sustainable crop production and improved food security under water-limited conditions. It also contributes to Sustainable Development Goal 6 (Clean Water and Sanitation) by identifying irrigation strategies that improve water productivity and promote more efficient use of scarce freshwater resources. For a better understanding of the impact of DI on yield and WP in the Ethiopian highlands, one can consider the potential impact of other explanatory variables like electrical conductivity, bulk density, organic matter, fertilizer rate, planting density and tillage practice as potential moderators. Additionally, one can consider the potential impact of stage-wise deficit irrigation on yield and water productivity. Moreover, to better classify climate regions, the aridity index should be considered. Although this study was limited to datasets from Ethiopia and crop representation varied across the available literature, the findings provide practical guidance for irrigation management across diverse Ethiopian agroecological conditions and may also offer useful insights for regions with similar agro-climatic conditions and cropping systems.

Funding

This research was funded by the VLIR-UOS project through the Institutional University Cooperation (IUC) with Bahir Dar University (Ethiopia).

CRediT authorship contribution statement

Seifu A Tilahun: Writing – review & editing, Supervision. **Tewodros T. Assefa:** Writing – review & editing. **Abebech Abera Beyene:** Writing – review & editing, Supervision. **Mekete Dessie:** Resources, Project administration. **Kristine Walraevens:** Writing – review & editing, Resources, Project administration. **Enyew Adgo Tsegaye:** Writing – review & editing, Funding acquisition. **Amaury Frankl:** Writing – review & editing, Project administration. **Wim Cornelis:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Abdu Yimer Yimam:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Desale Kidane Asmamaw:** Writing – review & editing, Supervision. **Margaret Chen:** Supervision, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The first author acknowledges Dr. Lin Wang for her technical guidance on the use of R package.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2026.110555.

Data availability

Data will be made available on request.

References

Abdelkhalik, A., Pascual, B., Nájera, I., Domene, M., Baixauli, C., Pascual-Seva, N., 2020. Effects of deficit irrigation on the yield and irrigation water use efficiency of drip-irrigated sweet pepper (Capsicum annuum L.) under Mediterranean conditions. Irrig. Sci. 38, 89–104. https://doi.org/10.1007/s00271-019-00655-1.

Adu, M.O., Yawson, D.O., Abano, E.E., Asare, P.A., Armah, F.A., Opoku, E.K., 2019. Does water-saving irrigation improve the quality of fruits and vegetables? Evidence from meta-analysis [Review]. Irrig. Sci. 37 (6), 669–690. https://doi.org/10.1007/s00271-019-00646-2.

Aleminew, A., Alemayehu, M., 2020. Soil fertility depletion and its management options under crop production perspectives in Ethiopia: A review. Agric. Rev. 41 (2), 91–105.

Al-Ghobari, H.M., Dewidar, A.Z., 2018. Integrating deficit irrigation into surface and subsurface drip irrigation as a strategy to save water in arid regions. Agric. Water Manag. 209, 55–61.

Allakonon, M.G.B., Zakari, S., Tovihoudji, P.G., Fatondji, A.S., Akponikpè, P.B.I., 2022. Grain yield, actual evapotranspiration and water productivity responses of maize crop to deficit irrigation: A global meta-analysis [Review] (Article). Agric. Water Manag. 270, 107746. https://doi.org/10.1016/j.agwat.2022.107746.

Amare, D., 2020. Review on effect of different irrigation method on water use efficiency, yield productivity and nitrogen application. J. Biol. Agric. Health 10 (8), 1–9. https://doi.org/10.7176/JBAH/10-8-01.

Araz, O., Ekinci, M., Yildirim, E., 2025. Physiological, Biochemical and Molecular Response of Pepper Genotypes Exposed to Water Deficit. J. Crop. Health 77 (1), 46.

Arslan, A., Floress, K., Lamanna, C., Lipper, L., Rosenstock, T.S., 2022. A meta-analysis of the adoption of agricultural technology in Sub-Saharan Africa. PLOS Sustain. Transform. 1 (7), e0000018.

Asmamaw, D.K., Janssens, P., Dessie, M., Tilahun, S.A., Adgo, E., Nyssen, J., Walraevens, K., Assaye, H., Yenehun, A., Nigate, F., 2023. Effect of deficit irrigation and soil fertility management on wheat production and water productivity in the Upper Blue Nile Basin, Ethiopia. Agric. Water Manag. 277, 1–12. https://doi.org/10.1016/j.agwat.2022.108077.

Asres, L.A., 2023. Alternative techniques of irrigation water management for improving crop water productivity. Rev. Agric. Sci. 11, 36–53.

Avazdahandeh, S., Khalilian, S., 2021. The effect of urbanization on agricultural water consumption and production: the extended positive mathematical programming approach. Environ. Geochem. Health 43 (1), 247–258.

Baghery, M.A., Kazemitabar, S.K., Dehestani, A., Mehrabanjoubani, P., 2023. Sesame (Sesamum indicum L.) response to drought stress: susceptible and tolerant genotypes exhibit different physiological, biochemical, and molecular response patterns. Physiol. Mol. Biol. Plants 29 (9), 1353–1369.

Bayisa, G.D., Ayana, M., Dinka, M.O., Hordofa, T., Mekonnen, B., 2024. Effect of Deficit Irrigation on Wheat (Triticum aestivum L.) Yield and Water Use Efficiency in the Semi-Arid Region of Awash Basin, Ethiopia. Air Soil. Water Res. 17, 11786221241274019.

Belay, A.M., Assefa, T.T., Belay, S.A., Yimam, A.Y., 2023. Evaluating the performance of small-scale irrigation schemes in subhumid Ethiopian highlands. Irrig. Drain. 72 (1), 224–239.

Berhe, G.T., Baartman, J.E., Veldwisch, G.J., Grum, B., Ritsema, C.J., 2022. Irrigation development and management practices in Ethiopia: a systematic review on existing problems, sustainability issues and future directions. Agric. Water Manag. 274, 107959.

Borenstein, M., Higgins, J.P., Hedges, L.V., Rothstein, H.R., 2017. Basics of meta-analysis: I2 is not an absolute measure of heterogeneity. Res. Synth. Methods 8 (1), 5–18. https://doi.org/10.1002/jrsm.1230.

Borenstein, M., Hedges, L.V., Higgins, J.P., Rothstein, H.R., 2021. Introduction to meta-analysis. John Wiley & Sons.

Bracken, M.B., 2019. Random-effects assumption in meta-analyses, 81-81 JAMA 322 (1). https://doi.org/10.1001/jama.2019.5443.

Burney, J.A., Naylor, R.L., Postel, S.L., 2013. The case for distributed irrigation as a development priority in sub-Saharan Africa. Proc. Natl. Acad. Sci. 110 (31), 12513–12517.

Champaneri, D.D., Desai, K.D., Sharma, V., Madane, D.A., More, S.J., 2024. A synoptic review of deficit irrigation methods: sustainable water-saving strategies in vegetable cultivation. Water Supply 24 (9), 3132–3147.

Cheeseman, J., 2016. Food security in the face of salinity, drought, climate change, and population growth. Halophytes for food security in dry lands. Elsevier, pp. 111–123.

Cohen, J.F., Chalumeau, M., Cohen, R., Korevaar, D.A., Khoshnood, B., Bossuyt, P.M., 2015. Cochran's Q test was useful to assess heterogeneity in likelihood ratios in studies of diagnostic accuracy. J. Clin. Epidemiol. 68 (3), 299–306. https://doi.org/10.1016/j.jclinepi.2014.09.005.

Diedhiou, S., Maiga, A., Himbane, P.B., Iboko, M.P., Ndiaye, L.G., Diedhiou, I., 2024. The Biochar Amendment Improves Tomato Growth and Yield under Deficit Irrigation in Sandy Loam Soil in Senegal. Sci. World J. 2024 (1), 9945354.

du Plessis, A., 2023. Water resources from a global perspective. South Africa's Water predicament: Freshwater's unceasing decline. Springer, pp. 1–25.

El-Hendawy, S., Mohammed, N., Al-Suhaibani, N., 2024. Enhancing wheat growth, physiology, yield, and water use efficiency under deficit irrigation by integrating foliar application of salicylic acid and nutrients at critical growth stages. Plants 13 (11), 1490. https://doi.org/10.3390/plants13111490.

Eshete, D.G., Sinshaw, B.G., Legese, K.G., 2020. Critical review on improving irrigation water use efficiency: Advances, challenges, and opportunities in the Ethiopia context. Water-Energy Nexus 3, 143–154.

Eshetu, A.A., Yimer, H., 2024. Determinants of smallholder farmers' adaptation to the effects of climate extremes: evidence from Legambo district in northcentral Ethiopia. Environ. Dev. Sustain. 1–29.

Fan, J., Halpern, M., Yu, Y., Zuo, Q., Shi, J., Fan, Y., Wu, X., Yermiyahu, U., Sheng, J., Jiang, P., 2022. The mechanisms responsible for N deficiency in well-watered wheat under elevated CO2. Front. Plant. Sci. 13, 801443.

Fenta, H.M., Aynalem, D.W., Malmquist, L., Haileslassie, A., Tilahun, S.A., Barron, J., Adem, A.A., Adimassu, Z., Zimale, F.A., Steenhuis, T.S., 2024. A critical analysis of soil (and water) conservation practices in the Ethiopian Highlands: Implications for future research and modeling. Catena 234, 107539.

Gebremedhin, M.A., Kahsay, G.H., Fanta, H.G., 2018. Assessment of spatial distribution of aridity indices in Raya valley, northern Ethiopia. Appl. Water Sci. 8 (8), 1. https://doi.org/10.1007/s13201-018-0868-6.

Gebul, M., 2021. Trend, status, and challenges of irrigation development in Ethiopia—a review. Sustainability 13 (10), 5646 (In).

Golla, B., 2021. Agricultural production system in arid and semi-arid regions. Int. J. Agric. Sci. Food Technol. 7 (2), 234–244.

Golzardi, F., Baghdadi, A., Afshar, R.K., 2017. Alternate furrow irrigation affects yield and water-use efficiency of maize under deficit irrigation. Crop. & Pasture Sci. 68 (8), 726–734.

Haftom, H., Haftu, A., Goitom, K., Meseret, H., 2019. Agroclimatic zonation of Tigray region of Ethiopia based on aridity index and traditional agro-climatic zones. J. Agrometeorol. 21 (2), 176–181. https://doi.org/10.54386/jam.v21i2.229.

Haghpanah, M., Hashemipetroudi, S., Arzani, A., Araniti, F., 2024. Drought tolerance in plants: physiological and molecular responses. Plants 13 (21), 2962.

Hall, C., Dawson, T., Macdiarmid, J., Matthews, R., Smith, P., 2017. The impact of population growth and climate change on food security in Africa: looking ahead to 2050. Int. J. Agric. Sustain. 15 (2), 124–135.

Hashem, M.S., Guo, W., Qi, X.-B., Li, P., She, Y.-j, Cui, J., Li, T., 2023. Effect of using reclaimed water via furrow and subsurface drip systems under alternate partial root-zone irrigation mechanism on crops growth and soil properties. Irrig. Sci. 42 (2024), 1–18. https://doi.org/10.1007/s00271-023-00883-6.

Hedges, L.V., Pigott, T.D., 2001. The power of statistical tests in meta-analysis. Psychol. Methods 6 (3), 203. https://doi.org/10.1037//1082-989X.6.3.203.

Hedges, L.V., Vevea, J.L., 1998. Fixed-and random-effects models in meta-analysis. Psychol. Methods 3 (4), 486..

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80 (4), 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2.

Hemkemeyer, M., Schwalb, S.A., Berendonk, C., Geisen, S., Heinze, S., Joergensen, R.G., Li, R., Lövenich, P., Xiong, W., Wichern, F., 2024. Potato yield and quality are linked to cover crop and soil microbiome, respectively. Biol. Fertil. Soils 60 (4), 525–545.

Higgins, J.P., Thompson, S.G., Deeks, J.J., Altman, D.G., 2003. Measuring inconsistency in meta-analyses. bmj 327 (7414), 557–560.

Jackson, D., Turner, R., 2017. Power analysis for random-effects meta-analysis. Res. Synth. Methods 8 (3), 290–302. https://doi.org/10.1002/jrsm.1240.

Jahan, M., Nassiri-Mahallati, M., 2022. Modeling the response of sesame (Sesamum indicum L.) growth and development to climate change under deficit irrigation in a semi-arid region. PLoS. Clim. 1 (6), 1–20. https://doi.org/10.1371/journal.pclm.0000003.

Jalilibal, Z., Amiri, A., Castagliola, P., Khoo, M.B., 2021. Monitoring the coefficient of variation: A literature review. Comput. & Ind. Eng. 161, 107600. https://doi.org/10.1016/j.cie.2021.107600.

Jiang, L., Wu, F., Liu, Y., Deng, X., 2014. Modeling the impacts of urbanization and industrial transformation on water resources in China: an integrated hydro-economic CGE analysis. Sustainability 6 (11), 7586–7600.

Johnson, J.-M., Becker, M., Kaboré, J.E.P., Dossou-Yovo, E.R., Saito, K., 2024. Alternate wetting and drying: a water-saving technology for sustainable rice production in Burkina Faso? Nutr. Cycl. Agroecosyst. 129 (1), 93–111.

Kassaye, A.Y., Shao, G., Wang, X., Shifaw, E., Wu, S., 2021. Impact of climate change on the staple food crops yield in Ethiopia: implications for food security. Theor. Appl. Climatol. 145 (1), 327–343.

Khalid, M.F., Huda, S., Yong, M., Li, L., Li, L., Chen, Z.-H., Ahmed, T., 2023. Alleviation of drought and salt stress in vegetables: crop responses and mitigation strategies. Plant. Growth Regul. 99 (2), 177–194. https://doi.org/10.1007/s10725-022-00905-x.

Kifle, M., Gebremicael, T., Girmay, A., Gebremedihin, T., 2017. Effect of surge flow and alternate irrigation on the irrigation efficiency and water productivity of onion in the semi-arid areas of North Ethiopia. Agric. Water Manag. 187, 69–76.

Kouighat, M., Nabloussi, A., Kettani, R., Fakhour, S., El Fechtali, M., Hamdani, A., 2023. Drought-tolerant sesame mutant lines assessed by physiological traits and stress indices under water deficit conditions. J. Agric. Food Res. 14, 100842.

Lakhiar, I.A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., Han, Y., Wang, B., Bao, R., Syed, T.N., 2024. A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. Agriculture 14 (7), 1141.

Lee, D.K., In, J., Lee, S., 2015. Standard deviation and standard error of the mean. Korean J. Anesthesiol. 68 (3), 220–223.

Li, Q., Chen, Y., Sun, S., Zhu, M., Xue, J., Gao, Z., Zhao, J., Tang, Y., 2022. Research on crop irrigation schedules under deficit irrigation—A meta-analysis. Water Resour. Manag. 36 (12), 4799–4817.

Lin, L., Chu, H., Murad, M.H., Hong, C., Qu, Z., Cole, S.R., Chen, Y., 2018. Empirical comparison of publication bias tests in meta-analysis. J. General. Intern. Med. 33, 1260–1267. https://doi.org/10.1007/s11606-018-4425-7.

Liu, W., Fan, Y., Yu, T.E., 2026. Optimizing Crop Planting Structures for Water Savings and Grain Revenue in China Considering Different Spatial Scales. Resour. Environ. Sustain., 100323

Lu, J., Shao, G., Gao, Y., Zhang, K., Wei, Q., Cheng, J., 2021. Effects of water deficit combined with soil texture, soil bulk density and tomato variety on tomato fruit quality: A meta-analysis [Article] (Article). Agric. Water Manag. 243, 106427. https://doi.org/10.1016/j.agwat.2020.106427.

McKenzie, F.C., Williams, J., 2015. Sustainable food production: constraints, challenges and choices by 2050. Food Secur. 7, 221–233.

Meskelu, E., Woldemichael, A., Hordofa, T., 2017. Effect of moisture stress on yield and water use efficiency of irrigated wheat (Triticum aestivum L.) at Melkassa, Ethiopia. Acad. Res. J. Agric. Sci. Res. 5 (2), 90–97. https://doi.org/10.14662/ARJASR2016.055.

Msimbira, L.A., Smith, D.L., 2020. The roles of plant growth promoting microbes in enhancing plant tolerance to acidity and alkalinity stresses. Front. Sustain. Food Syst. 4, 106. https://doi.org/10.3389/fsufs.2020.00106.

Mugabe, F., Nyakatawa, E., 2000. Effect of deficit irrigation on wheat and opportunities of growing wheat on residual soil moisture in southeast Zimbabwe. Agric. Water Manag. 46 (2), 111–119.

Muroyiwa, G., Mashonjowa, E., Mhizha, T., Muchuweti, M., 2023. The effects of deficit irrigation on water use efficiency, yield and quality of drip-irrigated tomatoes grown under field conditions in Zimbabwe. Water Sa 49 (4), 363–373, 363–373.

Nakagawa, S., Cuthill, I.C., 2007. Effect size, confidence interval and statistical significance: a practical guide for biologists. Biol. Rev. 82 (4), 591–605. https://doi.org/10.1111/j.1469-185X.2007.00027.x.

Narayanan, K., Seid, M.M., 2015. Effect of deficit irrigation on maize under conventional, fixed and alternate furrow irrigation systems at Melkassa, Ethiopia. Int. J. Eng. Res. & Technol. (IJERT) 4 (11), 119–126.

Neupane, J., Guo, W., 2019. Agronomic basis and strategies for precision water management: A review. Agronomy 9 (2), 87.

Pabuayon, I.L.B., Singh, S., Ritchie, G.L., 2019. Effects of deficit irrigation on yield and oil content of sesame, safflower, and sunflower. Agron. J. 111 (6), 3091–3098.

Park, H.Y., Suh, C.H., Woo, S., Kim, P.H., Kim, K.W., 2022. Quality reporting of systematic review and meta-analysis according to PRISMA 2020 guidelines: results from recently published papers in the Korean Journal of Radiology. Korean J. Radiol. 23 (3), 355–369. https://doi.org/10.3348/kjr.2021.0808.

Prakash, N.B., Dhumgond, P., Goiba, P.K., Laxmanarayanan, M., 2024. The benefits of gypsum for sustainable management and utilization of acid soils. Plant. Soil. 1–24. https://doi.org/10.1007/s11104-024-06907-0.

Rai, A., Sarkar, S., Jha, P.K., 2022. Deficit irrigation: An optimization strategy for a sustainable agriculture. Soil-Water, Agriculture, and Climate Change: Exploring Linkages. Springer, pp. 163–181.

Ramaswwamyreddy, S., Basavaraju, P., TV, R.D., MA, N., 2021. Effect of Water and Soil Quality on Crop Productivity. Clean Water and Sanitation. Springer, pp. 1–27.

Sánchez-Tójar, A., Moran, N.P., O'Dea, R.E., Reinhold, K., Nakagawa, S., 2020. Illustrating the importance of meta-analysing variances alongside means in ecology and evolution. J. Evolut. Biol. 33 (9), 1216–1223. https://doi.org/10.1111/jeb.13661.

Sabir, R.M., Sarwar, A., Shoaib, M., Saleem, A., Alhousain, M.H., Wajid, S.A., Rasul, F., Adnan Shahid, M., Anjum, L., Safdar, M., 2024. Managing Water Resources for Sustainable Agricultural Production. Transforming Agricultural Management for a Sustainable Future: Climate Change and Machine Learning Perspectives. Springer, pp. 47–74.

Sadovski, A.N., 2019. Study on pH in water and potassium chloride for Bulgarian soils. Eurasia J. Soil. Sci. 8 (1), 11–16.

Sasson, A., 2012. Food security for Africa: an urgent global challenge. Agric. Food Secur. 1, 2 (In).

Singh, M., Singh, P., Singh, S., Saini, R.K., Angadi, S.V., 2021. A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation [Article] (Article). Sci. Rep. 11 (1), 22095. https://doi.org/10.1038/s41598-021-01433-w.

Solomon, N., Birhane, E., Tilahun, M., Schauer, M., Gebremedhin, M.A., Gebremariam, F. T., Gidey, T., Newete, S.W., 2024. Revitalizing Ethiopia's highland soil degradation: a comprehensive review on land degradation and effective management interventions. Discov. Sustain. 5 (1), 106.

Song, Z., Gui, Y., Hua, L., Yuan, S., Hu, R., 2025. Investigation of the Water Retention Characteristics and Mechanisms of Organic Clay. Water 17 (3), 286.

Suna, T., Kumari, A., Paramaguru, P.K., Kushwaha, N., 2023. Enhancing agricultural water productivity using deficit irrigation practices in water-scarce regions. Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches. Springer, pp. 177–206.

Temesgen, M., Hoogmoed, W., Rockstrom, J., Savenije, H., 2009. Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. Soil. Tillage Res. 104 (1), 185–191.

Temesgen, T., Ayana, M., Bedadi, B., 2018. Evaluating the effects of deficit irrigation on yield and water productivity of furrow irrigated onion (Allium cepa L.) in Ambo, Western Ethiopia. Irrig. & Drain. Syst. Eng. 7 (1), 1–6. https://doi.org/10.4172/2168-9768.1000203.

Tong, X., Wu, P., Liu, X., Zhang, L., Zhou, W., Wang, Z., 2022. A global meta-analysis of fruit tree yield and water use efficiency under deficit irrigation. Agric. Water Manag. 260, 107321. https://doi.org/10.1016/j.agwat.2021.107321.

Ullah, I., Mao, H., Rasool, G., Gao, H., Javed, Q., Sarwar, A., Khan, M.I., 2021. Effect of deficit irrigation and reduced N fertilization on plant growth, root morphology and water use efficiency of tomato grown in soilless culture. Agronomy 11 (2), 228. https://doi.org/10.3390/agronomy11020228.

Viechtbauer, W., 2010. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. 36 (3), 1–48. https://doi.org/10.18637/jss.v036.i03.

Wang, L., Blanchy, G., Cornelis, W., Garré, S., 2024. Changes in soil hydraulic and physio-chemical under treated wastewater irrigation: A meta-analysis. Agric. Water Manag. 295, 108752. https://doi.org/10.1016/j.agwat.2024.108752.

Wang, Y., Guo, T., Qi, L., Zeng, H., Liang, Y., Wei, S., Gao, F., Wang, L., Zhang, R., Jia, Z., 2020. Meta-analysis of ridge-furrow cultivation effects on maize production and water use efficiency. Agric. Water Manag. 234 (2020), 106144. https://doi.org/10.1016/j.agwat.2020.106144.

Wang, Z., Zhang, B., Li, J., Lian, S., Zhang, J., Shi, S., 2024. Effects of Deficit-Regulated Irrigation on Root-Growth Dynamics and Water-Use Efficiency of Winter Wheat in a Semi-Arid Area [Article] (Article). Water (Switz.) 16 (18), 2678. https://doi.org/10.3390/w16182678.

Worqlul, A.W., Dile, Y.T., Schmitter, P., Jeong, J., Meki, M.N., Gerik, T.J., Srinivasan, R., Lefore, N., Clarke, N., 2019. Water resource assessment, gaps, and constraints of vegetable production in Robit and Dangishta watersheds, Upper Blue Nile Basin, Ethiopia. Agric. Water Manag. 226, 105767.

Wubaye, G.B., Gashaw, T., Worqlul, A.W., Dile, Y.T., Taye, M.T., Haileslassie, A., Zaitchik, B., Birhan, D.A., Adgo, E., Mohammed, J.A., 2023. Trends in rainfall and temperature extremes in Ethiopia: Station and agro-ecological zone levels of analysis. Atmosphere 14 (3), 483. https://doi.org/10.3390/atmos14030483.

Wudil, A.H., Usman, M., Rosak-Szyrocka, J., Pilař, L., Boye, M., 2022. Reversing years for global food security: A review of the food security situation in Sub-Saharan Africa (SSA). Int. J. Environ. Res. Public. Health 19 (22), 14836.

Xu, Y., Hu, W., Zuo, Q., Shi, J., Fan, Y., Wu, X., Ben-Gal, A., 2026. Including water-salinity stress hysteresis and compensation to empirical root water uptake models. J. Hydrol., 135561

Yadav, D.S., Jaiswal, B., Gautam, M., Agrawal, M., 2020. Soil acidification and its impact on plants. Plant. Responses Soil. Pollut. 1–26.
Yadav, M., Vashisht, B., Jalota, S., Jyolsna, T., Singh, S.P., Kumar, A., Kumar, A., Singh, G., 2024. Improving Water Efficiencies in Rural Agriculture for Sustainability of Water Resources: A Review. Water Resour. Manag. 1–22.
Yang, P., Wu, L., Cheng, M., Fan, J., Li, S., Wang, H., Qian, L., 2023. Review on drip irrigation: impact on crop yield, quality, and water productivity in China. Water 15 (9), 1733. https://doi.org/10.3390/w15091733.
Yanqi, X., Qiang, Z., Jianchu, S., Yuchun, F., Xun, W., Alon, B.-G., 2025. Estimating groundwater depth in a coastal drained field using a process-and data-driven hybrid model. Pedosphere.
Yenesew, M., Tilahun, K., 2009. Yield and water use efficiency of deficit-irrigated maize in a semi-arid region of Ethiopia. Afr. J. Food Agric. Nutr. Dev. 9 (8).
You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun, Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 36 (6), 770–782.
Yu, L., Zhao, X., Gao, X., Siddique, K.H.M., 2020. Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis [Article] (Article). Agric. Water Manag. 228, 105906. https://doi.org/10.1016/j.agwat.2019.105906.
Zerssa, G., Feyssa, D., Kim, D.-G., Eichler-Löbermann, B., 2021. Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. Agriculture 11 (3), 192.
Zewdie, M.C., Van Passel, S., Moretti, M., Annys, S., Tenessa, D.B., Ayele, Z.A., Tsegaye, E.A., Cools, J., Minale, A.S., Nyssen, J., 2020. Pathways how irrigation water affects crop revenue of smallholder farmers in northwest Ethiopia: A mixed approach. Agric. Water Manag. 233, 106101.
Zhang, B.-C., Li, F.-M., Huang, G.-B., Gan, Y., Liu, P.-H., Cheng, Z.-Y., 2005. Effects of regulated deficit irrigation on grain yield and water use efficiency of spring wheat in an arid environment. Can. J. Plant. Sci. 85 (4), 829–837.
Zhang, T., Zuo, Q., Ma, N., Shi, J.C., Fan, Y.C., Wu, X., Wang, L.C., Xue, X.Z., Ben -Gal, A., 2023. Optimizing relative root-zone water depletion thresholds to maximize yield and water productivity of winter wheat using AquaCrop (Article). Agric. Water Manag. 286, 108391. https://doi.org/10.1016/j.agwat.2023.108391.
Zhang, T., Zuo, Q., Shi, J., Fan, Y., Zhang, S., Wu, X., Ben-Gal, A., 2025. Evaluation and improvement of crop root-water-uptake and transpiration in AquaCrop. Agric. Water Manag. 318, 109686.
Zhang, Y., Long, A., Zhang, P., Deng, X., Gu, X., 2024. Are water use efficiency and effectiveness relatively lower in arid zones? Comparative analyses of the water productivity of typical crops. Agronomy 14 (9), 2–18. https://doi.org/10.3390/agronomy14092153.