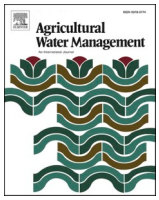
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Global meta-analysis of irrigation scheduling effects on water use efficiency, fruit quality, and yield in blueberry and strawberry

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ABSTRACT

Irrigation scheduling plays a critical role in improving water use efficiency (WUE), fruit quality, and yield of crops under increasing water scarcity and climate variability. A global meta-analysis was performed to assess WUE and crop performance of blueberry and strawberry under different irrigation scheduling approaches using climate and soil types as moderators. Irrigation scheduling was categorized as 1) over-irrigation (OI; >110% evapotranspiration (ET)), 2) full irrigation (FI) as control for comparison (90–100% ET), 3) moderate deficit irrigation (MDI; 65–90% ET), 4) severe deficit irrigation (SDI; <50%) 5) farmers practice irrigation and 6) Rainfed/no irrigation. Results indicated that irrigation scheduling across all treatments reduced blueberry and strawberry yield by −26.3% (SDI) and −40.4% (OI), respectively, while WUE improved by 17.5% and 14.2% under Rainfed conditions in blueberry and strawberry. Regarding climate types, yields were reduced by −8.0% and −2.0%, and WUE improved by 10.4% and 26.7% under MDI in semi-humid climates in blueberry and strawberry, respectively. Across soil types, blueberry yield was reduced by −6.8% and −8.3% in loamy and sandy soils under MDI. Strawberry yield was reduced by −6.1%, while WUE improved by 24.9% in loam soil under MDI. Yield was slightly reduced, while WUE improved in both crops under MDI in semi-humid climate with loamy and sandy soils. We also found that irrigation scheduling significantly influenced WUE and yield, with climate and soil type strongly affecting crop response. This highlights the need for irrigation management strategies to be established on a climate- and soil-specific basis. The results of this global meta-analysis suggest that MDI could be the best option to optimize blueberry and strawberry yield under semi-humid climate and loamy soil while improving WUE under limited water availability.

1. Introduction

Enhancing water use efficiency (WUE) is a central objective of modern irrigation management, particularly in regions experiencing increasing water scarcity (Alharbi et al., 2024). Global freshwater resources are under growing pressure due to rapid population growth, intensified agricultural production, and climate change-induced alterations in hydrological cycles (Ungureanu et al., 2020). Agriculture currently accounts for approximately 70% of global freshwater withdrawals, and a predicted 70% increase in food demand by 2050 is expected to raise agricultural water consumption by nearly 20% (FAO, 2017). These challenges are further exacerbated by climate change, which increases evapotranspiration rates and the frequency and severity of drought events (Borah, 2025). Therefore, optimizing irrigation management has become a critical strategy for sustaining agricultural productivity and water security under future climate change scenarios (Leghari et al., 2024, 2026).

Berry crops, particularly blueberry (*Vaccinium* spp.) and strawberry (*Fragaria* × *ananassa*), are among the most economically important horticultural commodities worldwide and are predominantly cultivated under irrigated conditions (Menzel, 2025; Pinzon et al., 2026). In the United States, blueberry production was valued at approximately 713 million USD, contributing approximately 5% of the total fruit production value. Strawberries generated more than 2 billion USD in annual farm-gate sales, representing nearly 12% of total fruit production value and ranking as the third most valuable fruit after grapes and apples (Yeh et al., 2023). In 2020, global strawberry production was valued approximately at 14 billion USD (FAO, 2021). Both crops are characterized by shallow root systems with limited capacity to access water from deeper soil layers, making them highly sensitive to soil moisture

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fluctuations. In blueberry, fine hairless roots concentrated in the upper soil profile restrict hydraulic conductivity and exacerbate vulnerability to water stress, particularly during critical growth stages such as flowering, fruit set, and berry ripening (Ru et al., 2024). Similarly, strawberries possess a shallow and dense root system, a short cultivation cycle, and large leaf area, resulting in high transpiration demand and pronounced sensitivity to both water deficit and excess throughout the growing season (Xu et al., 2023). Therefore, suboptimal irrigation management in these crops can lead to substantial yield losses, reduced fruit quality, and inefficient water use.

Irrigation scheduling involves the application of water at the appropriate time and in optimal quantities to maximize crop productivity while improving WUE and supporting plant growth (Dong, 2023). Effective irrigation scheduling is particularly critical for optimizing WUE in blueberry and strawberry production systems, as it aligns water applications with crop water requirements, soil conditions, and climatic factors (Janssens et al., 2022). Through this, it reduces water losses associated with evaporation, runoff, and deep percolation (Surve et al., 2024). Conventional irrigation practices, often based on fixed intervals or grower experience, often fail to account for temporal variability in weather conditions and soil moisture dynamics, leading to inefficient water use through over- or under-irrigation (Katimbo et al., 2023). In contrast, data-driven scheduling approaches such as those based on crop evapotranspiration or real-time soil moisture monitoring have been shown to significantly improve WUE and irrigation efficiency compared with conventional methods (Schlank et al., 2024). Soil-based approaches, including the use of tensiometers, capacitance sensors, and time-domain reflectometry, provide real-time information on soil moisture status within the root zone and enable more precise irrigation decisions once sensory placement is optimized (Singh et al., 2023). Plant-based indicators, such as leaf water potential, stomatal conductance, and canopy temperature, offer direct insights into crop water status and have been successfully applied to improve irrigation management in berry crops (Espinoza et al., 2017).

Deficit irrigation is an agricultural water management strategy in which the amount of water applied is intentionally maintained below the crop full water requirement (Teshome et al., 2023). It can improve WUE and increase crop productivity and quality by reducing the irrigation amount during less sensitive growth stages (Chai et al., 2016; Palai et al., 2025). Deficit irrigation has emerged as a practical and cost-effective approach for sustaining agricultural production under water-limited conditions (Hu et al., 2026). When water becomes limited or costly, producers may adopt stress management strategies to reduce water use by implementing controlled deficit irrigation (Kullberg et al., 2017). Plants respond to water deficit through physiological, biochemical, and molecular changes that directly or indirectly affect yield and quality (Wahab et al., 2022). To effectively evaluate deficit irrigation, it is important to consider the soil water retention capacity. Sandy soils induce rapid water stress, whereas fine-textured, deep soils allow plants more time to adapt, making deficit irrigation more successful and profitable in such conditions (Endalu Tura and Tolossa, 2020).

Despite advancements in irrigation technologies and management strategies, optimizing WUE in blueberry and strawberry production systems remains challenging due to variability in climatic conditions and soil characteristics. Differences in irrigation approaches across studies have led to inconsistent findings, hindering the development of universally applicable irrigation guidelines. Although existing studies provide valuable insights into the effects of irrigation on fruit yield, physiological responses, and quality traits, translating these findings to generalized recommendations across diverse production systems remains difficult. Therefore, the objective of this study is to conduct a quantitative synthesis of the available literature through meta-analysis to evaluate the overall impacts of irrigation scheduling on yield, fruit quality, physiological traits, and WUE in blueberry and strawberry under varying irrigation regimes, soil types, and climatic conditions. Furthermore, this study aims to identify key moderating factors that provide critical insights for optimizing irrigation strategies, improve crop performance and strengthen resilience to increasing water scarcity.

2. Materials and methods

2.1. Literature search and data collection

Original studies for this meta-analysis were collected through keyword searches in relevant literature databases prior to 31 March 2025. Peer-reviewed studies were searched in Scopus, Web of Science, and Google Scholar. The keywords used for literature search were “blueberry” or “strawberry” and “irrigation scheduling” and “irrigation management” and “yield” and “fruit quality” for Web of Science and “Irrigation scheduling” “irrigation management” “yield” “fruit quality” “blueberry” or “strawberry” for Scopus and Google Scholar. The total number of publications that were identified through Scopus, Web of Science and Google Scholar were 193, 182, and 186, respectively, from which duplicates were excluded.

2.2. Data curation

Data curation was performed following the same approach used in our previous meta-analyses (Ali et al., 2024; Dick and VanderWeide, 2025). The studies included in this meta-analysis were selected using predefined inclusion criteria to ensure comparability among crop type, irrigation treatments, and response variables. Studies reporting blueberry or strawberry responses under clearly defined irrigation regimes that matched the treatment categories used in this meta-analysis were included. The self-defined inclusion criteria for the list of collected publications were: a) contains irrigation scheduling and management based on evapotranspiration (ET), b) irrigation treatment > 2, c) the study was performed using field-grown plants, d) the study contains data on fruit weight, yield, fruit quality traits (firmness, total sugar, total soluble solids, and titratable acidity), leaf physiological parameters (photosynthesis rate, stomatal conductance and transpiration rate), irrigation water used (mm), and/or water use efficiency for blueberry and/or strawberry. Studies that were duplicated or showed overlapping results by year, location, or dataset, as well as those with inadequate data, conference abstracts, review papers, or research focusing on other fruits, were excluded for further statistical analysis (313 studies). Relevant data were extracted from tables and figures through GetData Graph Digitizer software. The study followed PRISMA guidelines regarding study identification, screening, and inclusion. Of the initial 561 studies identified, 313 studies were screened and excluded and 130 studies included in the meta-analysis (Supplemental 1 and 2). The geographic distribution of the experimental locations, trend in the number of publications, the year- and country-wise distribution of the studies included is shown in Fig. 1.

2.3. Screening process

The search was designed to acquire a wide range of studies while ensuring that the selected literature was relevant and reliable for the study objectives. Several articles were identified initially and subsequently screened by title and abstract, followed by full-text assessment based on data accessibility to check their suitability for inclusion in meta-analysis.

2.4. Moderator variables and analysis

In irrigation scheduling studies, numerous explanatory (moderator) variables affect the relationship between the independent variable (irrigation scheduling) and the dependent variables (yield, fruit quality attributes, plant physiological traits, and WUE). WUE was calculated as the ratio of yield to total water input, which, in Rainfed conditions, consisted only of effective rainfall. Irrigation treatments were

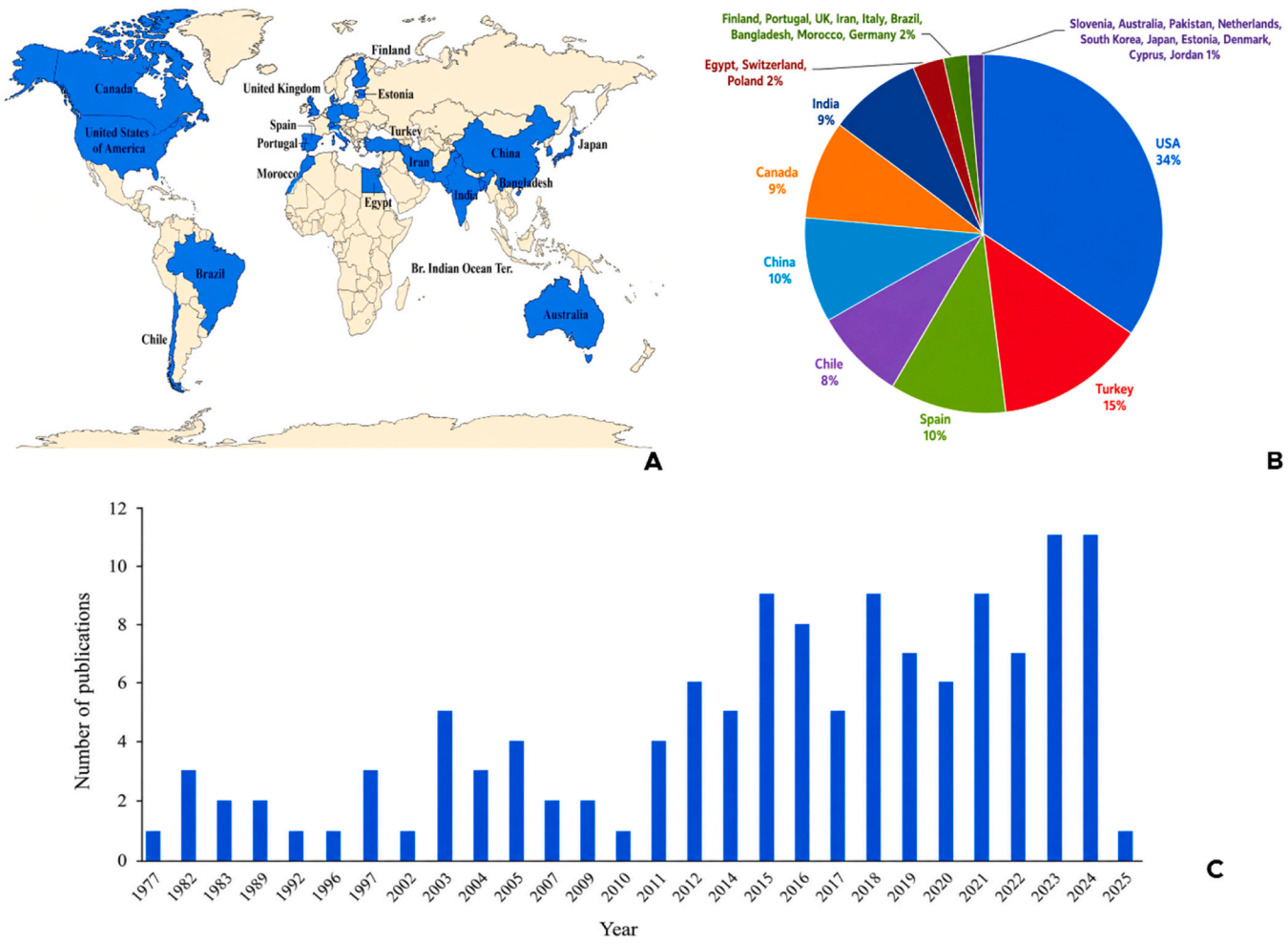


Fig. 1. The (**A**) geographical distribution of experimental sites from publications included in the meta-analysis, (**B**) proportion of published studies included in the meta-analysis by country, and (**C**) trend in the number of peer-reviewed publications included in the meta-analysis by publication year.

categorized as 1) over-irrigation (OI) (irrigation application exceeding 110% ET requirements, indicating water inputs greater than crop demand), 2) full irrigation (FI) (90–100% ET) or identified as control/FI), 3) moderate deficit irrigation (MDI) (65–90% ET), 4) severe deficit irrigation (SDI) (below 50%) and 5) Rainfed conditions/no irrigation. Additionally, farmer-practiced irrigation (FP) was also considered based on individual study representing irrigation levels typically applied by growers under real field conditions.

The explanatory variables considered in the meta-analysis included irrigation scheduling treatments, climate classification and soil type which represented key factors that influence the relationship between soil water availability and response variables. Additional moderators such as soil and climate types were included, as these factors can significantly impact yield, quality, and water use efficiency under varying irrigation schedules (Ali et al., 2024). Soil types were classified based on dominant particle composition into sand, silt, clay and loam. Similarly, climates were categorized according to annual average precipitation for each study location: arid (≤250 mm), semi-arid (250–400 mm), semi-humid (400–800 mm), and humid (>800 mm). This classification is based on observed daily precipitation from 1950 to 2013 obtained from the Rainfall Estimates on a Gridded Network dataset developed by (Contractor et al., 2020). Collectively, these categories allowed soil and climate to be evaluated as key moderating factors affecting irrigation responses across studies.

2.5. Meta-analysis and statistical evaluation

For dependent variables the natural logarithm response ratio (LnR) was used to quantify the effect size (Hedges et al., 1999) by calculating the ratio between the treatment group and the control group under different irrigation scheduling practices (Equation 1).

$$\mathrm{LnR} = Ln\left(\frac{xi}{xc}\right) = lnxi - lnxc \quad (1)$$

where *xi* represents the mean value of the treatment group and *xc* represents the mean value of the control group. In cases where standard deviation (SD) was not reported but standard error (SE) was, SD was calculated using the relationship $SD = SE \times \sqrt{n}$, where n is the number of replicates. When SD values were missing, they were estimated as 10% of the reported means to enable inclusion of the data in the meta-analysis. A sensitivity analysis was conducted by excluding studies with imputed SD values, and the overall conclusions remained unchanged, indicating that the results were robust to this assumption. The variance of the effect size (VLnR) was calculated using the following equation (Benítez-López et al., 2017):

$$VLnR = \left(\frac{Si^2}{ni.xi^2} + \frac{Sc^2}{(nc.xc^2)}\right) \quad (2)$$

where *Si* and *Sc* represent the standard deviations of the treatment and control groups, respectively, and *ni* and *nc* denote the corresponding sample sizes.

Each study was weighted by the inverse of its variance (Equation 3), and the overall effect size (LnRR++) was calculated using a weighted mean approach (Equation 4). The 95% confidence interval (CI) was determined using Eq. (5):

$$Wi = \frac{1}{Vi} \tag{3}$$

$$LnRR_{++} = \frac{\sum \ wiLnRi}{\sum \ wi} \tag{4}$$

$$95\%CI = LnRR_{++} \pm 1.96 * \sqrt{\frac{1}{\sum \ wi}} \tag{5}$$

where *Vi* represents the variance associated with each study and includes both within-study and between-study variance. The mean effect size (MES) for all irrigation treatments and response variables was subsequently converted to percentage change. Data merging, classification, processing, and statistical analyses were performed using Microsoft Excel. OpenMEE software was used to calculate effect sizes, generate forest plots, estimate 95% confidence intervals and perform random effects meta-analysis using the DerSimonian–Larid method (Wallace et al., 2017). GraphPad Prism 10 software was used for figure preparation (Motulsky, 2007).

3. Results

3.1. Blueberry

3.1.1. Irrigation scheduling impact on blueberry yield, fruit quality, leaf gas exchange, and water use efficiency

Irrigation scheduling significantly influenced yield, fruit quality attributes, leaf gas exchange parameters, and WUE (Fig. 2). An overall but non-significant reduction of −3.8% in fruit weight was observed under different irrigation scheduling strategies, with an effect size (ES) of −0.038 (95% confidence interval (CI): −0.001 to −0.076) (Fig. 2A). Among irrigation scheduling treatments, Rainfed conditions caused the greatest reduction in fruit weight (−6.6%), followed by SDI (−6.5%) and MDI (−4.1%). In contrast, OI promoted an increase in fruit weight (3.1%). Yield was more sensitive to irrigation scheduling than fruit weight. The overall analysis indicated a negative trend (ES: −0.128; 95% CI: −0.239–0.017) of irrigation scheduling on yield (Fig. 2B). Yield declined most significantly under OI (−9.3%) SDI (−26.0%), and Rainfed conditions (−11.8%), while it increased under MDI (4.0%) compared to FI.

Fruit firmness was not impacted by deficit irrigation with an overall ES of 0.005 (95% CI: −0.081–0.092) (Fig. 2C). SDI, MDI and Rainfed conditions enhanced fruit firmness by 4.7%,3.6% and 10%, respectively. In contrast, OI led to a significant reduction in fruit firmness (−17.7%), Total soluble solids were only significantly increased by 3.4% under SDI with an overall ES of 0.005 (95% CI: −0.125–0.033) (Fig. 2D). Conversely, total soluble solids were reduced by −2.5% and −3.6% under OI and Rainfed conditions, respectively. Titratable acidity was not significantly influenced by irrigation scheduling with an overall ES of −0.07 (95% CI: −0.019–0.054) (Fig. 2E). Titratable acidity significantly decreased by SDI (−17.9%) and Rainfed conditions (−14.1%), while MDI produced a moderate increase (3.9%).

Leaf gas exchange was markedly affected by irrigation scheduling. The photosynthesis rate decreased significantly under deficit irrigation, with an ES of −0.152 (95% CI: −0.223 to −0.081) (Fig. 2F). Photosynthesis rate was significantly reduced by −31.9%, −21.7% and −32.4% under OI, MDI and SDI, respectively. Similarly, stomatal conductance significantly declined under deficit irrigation (Fig. 2G). The

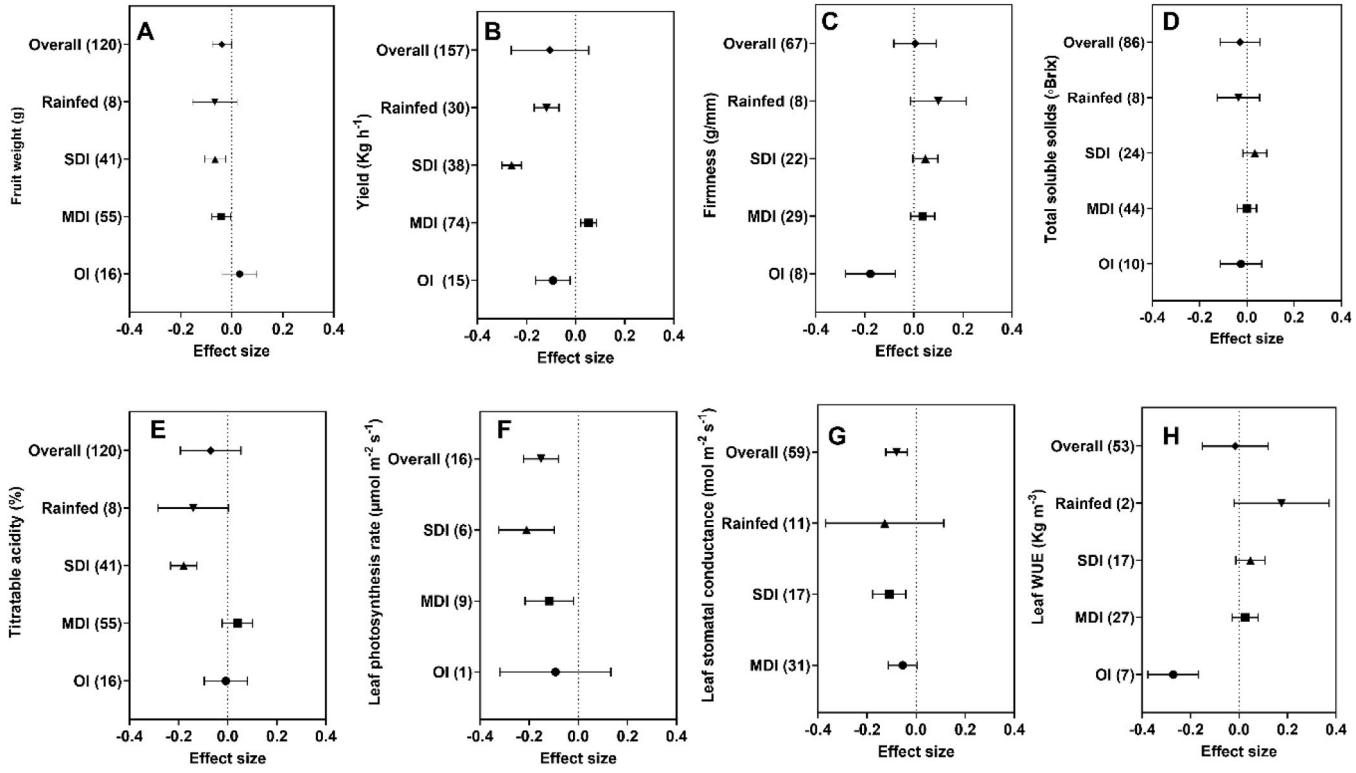


Fig. 2. Forest plot displaying the effect size of irrigation scheduling on A) fruit weight (g), B) yield (Kg ha^{-1}), C) fruit firmness (g/mm), D) total soluble solids (°Brix), E) titratable acidity (%), F) leaf photosynthesis rate (µmol m^{-2} s^{-1}), G) leaf stomatal conductance (mol m^{-2} s^{-1}), and H) leaf water use efficiency (Kg m^{-3}) in blueberry. Error bars represent 95% confidence interval (CI), and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% evapotranspiration (ET)); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET).

overall ES was −0.046 (95% CI: −0.119–0.028). Stomatal conductance was significantly reduced under MDI (−5.5%), SDI (−10.9%) and Rainfed conditions (−12.0%). The overall ES for WUE was 0.003 (95% CI: −0.034–0.039) (Fig. 2H). WUE showed an overall non-significant trend under deficit irrigation. WUE improved under MDI (2.5%), SDI (4.7%) and Rainfed conditions (17.5%), while significantly reduced under OI (−27.2%).

3.1.2. *Climate classification influence on blueberry yield, fruit quality, leaf gas exchange, and water use efficiency*

Climate classification impacted yield, fruit quality attributes, physiological performance, and WUE under different irrigation scheduling strategies. The climate classifications considered in this meta-analysis included humid, semi-humid, and semi-arid regions, which differ in annual precipitation and evaporative demand, thereby regulating crop responses to irrigation scheduling (Fig. 3).

Fruit weight exhibited a consistent declining trend under irrigation scheduling across all climate types (Fig. 3 $A_{a\text{-}c}$). In humid climates, OI had non-significant effect, while fruit weight was significantly reduced under MDI (−25.3%), SDI (−12.1%). In semi-humid climates, fruit weight was lower under MDI (−30.6%) and SDI (−51.6%). In semi-arid climates, the decrease in fruit weight was −18.2% under SDI, while MDI had non-significant effect. Yield was significantly affected by irrigation scheduling across all climate types (Fig. 3 $B_{a\text{-}c}$). In humid climates, yield reduction was observed under OI (−15.1%), MDI (−5.3%), and SDI (−11.2%). In semi-humid climates, a significant decrease in yield was noted under OI (−8.1%), MDI (−8.0%) and SDI (−18.0%). In semi-arid climates, yield declined significantly under MDI and SDI by −13.6% and −24.6%, respectively.

Fruit firmness responded positively to deficit irrigation, particularly under humid and semi-humid climate; a significant increase in fruit firmness was observed for MDI (27.2%) and SDI (20.4%) (Fig. 3 $C_{a\text{-}c}$). Semi-humid climates exhibited significant improvement in fruit firmness under SDI (−16.9%) while MDI and OI did not affect fruit firmness. In semi-arid climates, fruit firmness responses for MDI and SDI were 6.2% and 4.4%, respectively. Total soluble solids demonstrated climate-dependent responses to irrigation scheduling as well (Fig. 3 $D_{a\text{-}c}$). In humid climates, total soluble solids response to irrigation regimes was non-significant. In semi-humid climates MDI and OI did not influence total soluble solids while SDI exhibited a more pronounced

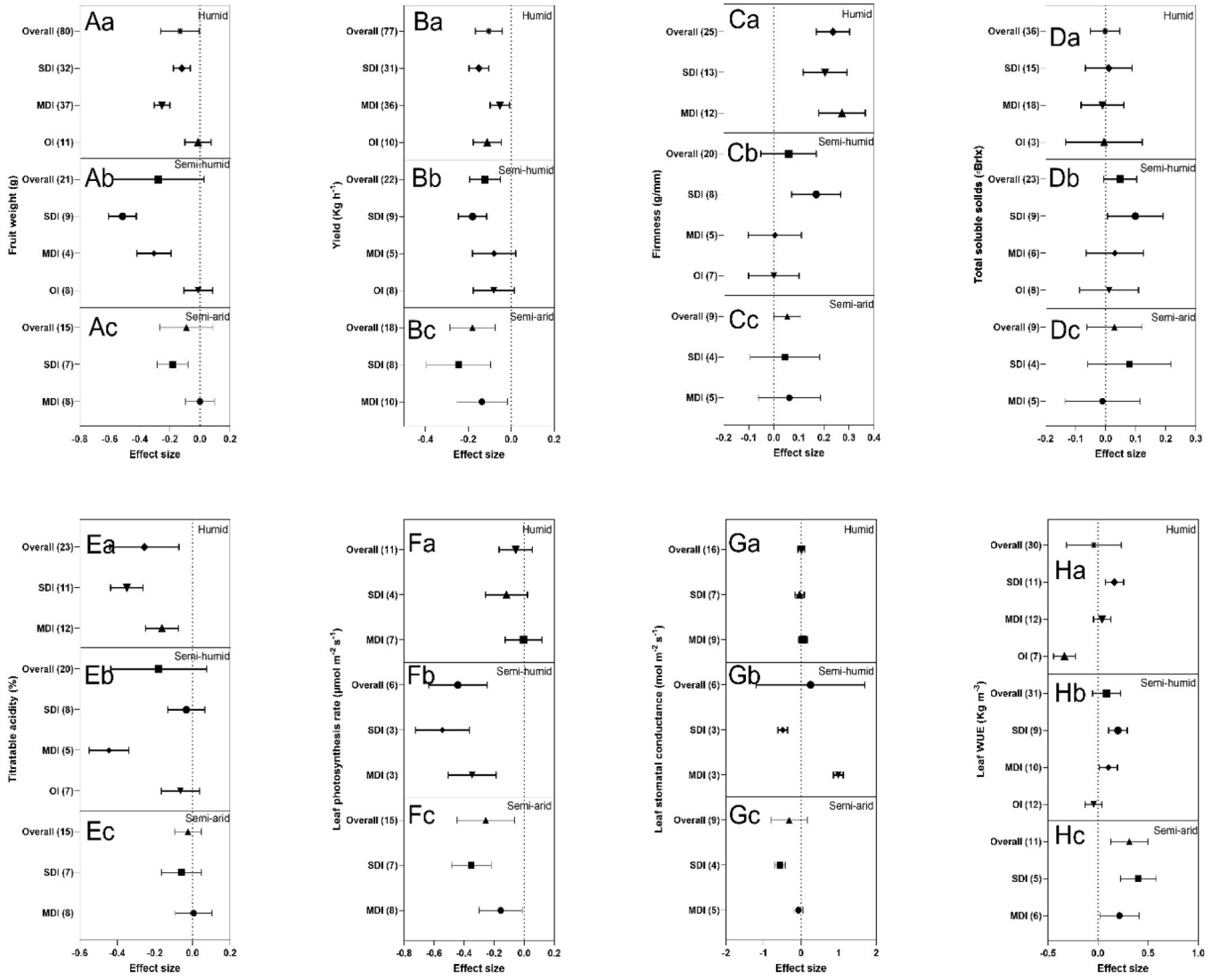


Fig. 3. Forest plot displaying the effect size of irrigation scheduling on ($A_{a\text{-}c}$) fruit weight (g), ($B_{a\text{-}c}$) yield (Kg ha^{-1}), ($C_{a\text{-}c}$) fruit firmness (g/mm), ($D_{a\text{-}c}$) total soluble solids (°Brix), ($E_{a\text{-}c}$) titratable acidity (%), ($F_{a\text{-}c}$) leaf photosynthesis rate (µmol m^{-2} s^{-1}), ($G_{a\text{-}c}$) leaf stomatal conductance (mol m^{-2} s^{-1}), and ($H_{a\text{-}c}$) leaf water use efficiency (Kg m^{-3}) in blueberry under different climatic conditions. Error bars represent 95% confidence interval (CI) and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% ET); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET).

improvement of 9.8%. Similarly, in semi-arid climates, SDI improved total soluble solids by 7.9%, while MDI had no effect on total soluble solids. Titratable acidity was significantly influenced by irrigation scheduling under humid climate (Fig. 3 E_{a-c}). In humid climates, titratable acidity decreased significantly under MDI (−16.2%) and SDI (−35.0%). In semi-humid climates, titratable acidity reduced under OI, MDI and SDI by −44.5%, −6.4% and −3.3%, respectively. In semi-arid climates, titratable acidity was reduced by SDI (−5.9%), whereas MDI and OI had non-significant effects.

Physiological responses showed strong dependence on climate type. The leaf photosynthesis rate declined in humid climates under SDI by −11.8%, while MDI had non-significant effect (Fig. 3 F_{a-c}). Similarly, in semi-humid climates, photosynthesis was reduced significantly under MDI and SDI by −18.6% and −36.5%, respectively. Similarly, in semi-arid climates, photosynthesis was reduced significantly under both MDI (−34.6%) and SDI (−54.4%). Stomatal conductance was reduced under deficit irrigation (Fig. 3 G_{a-c}). In humid climates, SDI did not impact stomatal conductance, whereas MDI increased stomatal conductance by 5.3%. The semi-humid climates exhibited comparable stomatal limitations under SDI (−36.0%), while in contrast MDI increased stomatal conductance by 11.2%. In semi-arid climate, stomatal conductance significantly decreased under MDI (−21.0%) and SDI (−48.9%).

WUE responded positively to deficit irrigation under different climate types. In humid climates, WUE decreased under OI (−33.5%) but improved slightly under MDI (4.0%) and more so by SDI (16.4%) (Fig. 3 H_{a-c}). In semi-humid climates, MDI and SDI significantly enhanced WUE by 10.4% and 19.8%, respectively. The strongest improvement in WUE was observed in semi-arid climates, where MDI and SDI increased WUE by 31.2% and 40.2%, respectively.

3.1.3. *Soil type as moderator for irrigation scheduling impact on yield, quality and physiological parameters and water use efficiency*

Soil texture, as a key explanatory variable, played a critical role in regulating fruit yield, quality attributes, physiological responses, and water use efficiency under different irrigation scheduling strategies. The soil classes considered in this meta-analysis included sand, loam, silt, and clay soils, which differ significantly in water-holding capacity and infiltration rate, thereby influencing crop responses to OI, MDI, and SDI (Fig. 4).

Fruit weight exhibited strong soil-dependent responses to irrigation scheduling (Fig. 4 A_{a-d}). In clay soil, fruit weight declined under MDI

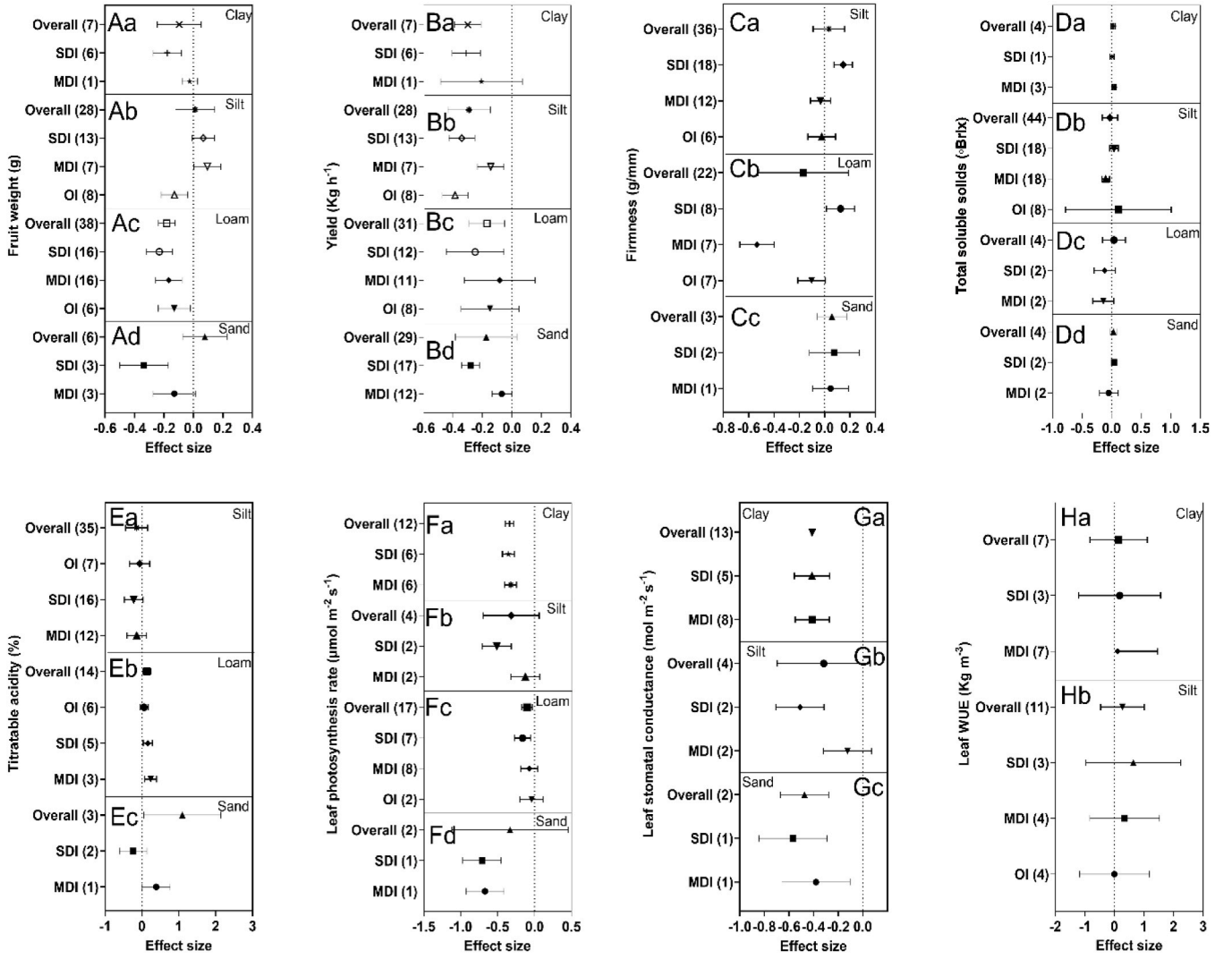


Fig. 4. Forest plot displaying the effect size of irrigation scheduling on (A_{a-d}) fruit weight (g), (B_{a-d}) yield (Kg ha^{-1}), (C_{a-c}) fruit firmness (g/mm), (D_{a-d}) total soluble solids (°Brix), (E_{a-c}) titratable acidity (%), (F_{a-d}) leaf photosynthesis rate (µmol m^{-2} s^{-1}), (G_{a-c}) leaf stomatal conductance (mol m^{-2} s^{-1}), and ($H_{a\&b}$) leaf water use efficiency (Kg m^{-3}) in blueberry under different soil types. Error bars represent 95% confidence interval (CI) and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% ET); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET).

(−2.5%) and SDI (−17.7%). In silt soil, fruit weight showed a more pronounced reduction, particularly under OI (−21.8%), while MDI and SDI showed non-significant effects. In loam soil, fruit weight was significantly reduced across both MDI (−16.7%) and SDI (−23.1%). Similarly, in sand soil, fruit weight reduced significantly under MDI (−6.85%) and SDI (−28.1%), with an overall ES of 0.173 (95% CI: −0.095 − 0.154). Fruit yield was strongly affected by soil type (Fig. 4 B_{a-d}). Yield was significantly reduced under MDI (−8.3%) and SDI (−25.0%) in loam soil with (ES: −0.63; 95% CI: −0.91 − 0.35). In silt soil, yield significantly declined under MDI (−14.5%), SDI (−34.0%) and OI (−38.6%). Similarly, the clay soil yield was reduced significantly under MDI (−20.7%) and SDI (−31.1%). In sandy soil yield reduced significantly under SDI (−28.1%).

Fruit firmness responded differently depending on soil texture (Fig. 4 C_{a-c}). In silt soils, fruit firmness was significantly enhanced by SDI (14.7%), whereas OI and MDI reduced fruit firmness by −2.3% and −3.2%, respectively. In loam soil, fruit firmness declined under OI (−10.3%) and MDI (−53.5%) but increased under SDI (12.6%). In contrast, fruit firmness was enhanced by both MDI (4.7%) and SDI (7.7%) in sandy soil. Soil types significantly influenced the response of total soluble solids to irrigation scheduling (Fig. 4 D_{a-d}). In clay soil, irrigation scheduling had a minimal influence on total soluble solids, as both MDI and SDI showed a near-zero effect size. Similarly, sandy soil exhibited negligible changes in total soluble solids under both MDI and SDI. In contrast, in silt soil, OI and SDI resulted in a noticeable increase in total soluble solids of 4.3% and 11.6% respectively, while decreased under MDI (−10.0%). In loam soil, TSS exhibited a moderate reduction under both MDI (−14.0%) and SDI (−11.5%). Titratable acidity in silt soil decreased significantly under OI (−36.0%), MDI (−43.0%) and SDI (−51.0%) (Fig. 4 E_{a-c}). In contrast, in loam soil titratable acidity was significantly increased by OI (5.5%), MDI (23.7%) and SDI (15.9%). Similarly, in sandy soil, titratable acidity increased significantly under MDI (20.0%) and SDI (5.7%).

Physiological responses were strongly influenced by soil texture. The photosynthesis rate declined substantially under deficit irrigation across all soil types (Fig. 4 F_{a-d}). In clay soil, SDI reduced photosynthesis rate by −35.4%, whereas in silt and loam soils the reduction was −25.0% and 34.0%, respectively. The greatest decline in photosynthesis was observed in sandy soil under SDI (−71.3%). Stomatal conductance exhibited consistent reductions under deficit irrigation across all soil textures (Fig. 4 G_{a-c}). Clay soil showed moderate reductions under MDI (−41.0%) and SDI (−41.3%), while silt soil exhibited stronger stomatal limitations of −7.4% and −56.0% across MDI and SDI respectively. Similarly, sandy soil showed a significant reduction in stomatal conductance under MDI (−38.1%) and SDI (−56.8%).

WUE showed contrasting responses depending on soil texture (Fig. 4 H_{a-b}). In clay soil, WUE improved under MDI (10.8%) and SDI (17.7%). Similarly, in silt soil, improvement in WUE was observed under MDI (34.4%) and SDI (64.0%), whereas OI decreased WUE. Overall, these findings demonstrated that soil texture acts as a main moderator of irrigation scheduling effectiveness, with loam and silt soils providing optimal conditions for improving yield, quality and WUE. Conversely, sandy soil was highly susceptible to yield, and physiological deterioration under deficit irrigation conditions, which highlighted the need for soil-specific scheduling strategies to achieve optimal blueberry production.

3.2. Strawberry

3.2.1. Irrigation scheduling impact on strawberry yield, fruit quality, leaf gas exchange, and water use efficiency

Irrigation scheduling significantly influenced strawberry yield, fruit quality attributes, leaf gas exchange traits and WUE (Fig. 5). The number of fruit plant^{-1} exhibited a non-significant response to irrigation scheduling, with an overall effect size (ES) of −0.02 (95% CI: −0.08–0.046) (Fig. 5A). A slight reduction in fruit number was recorded

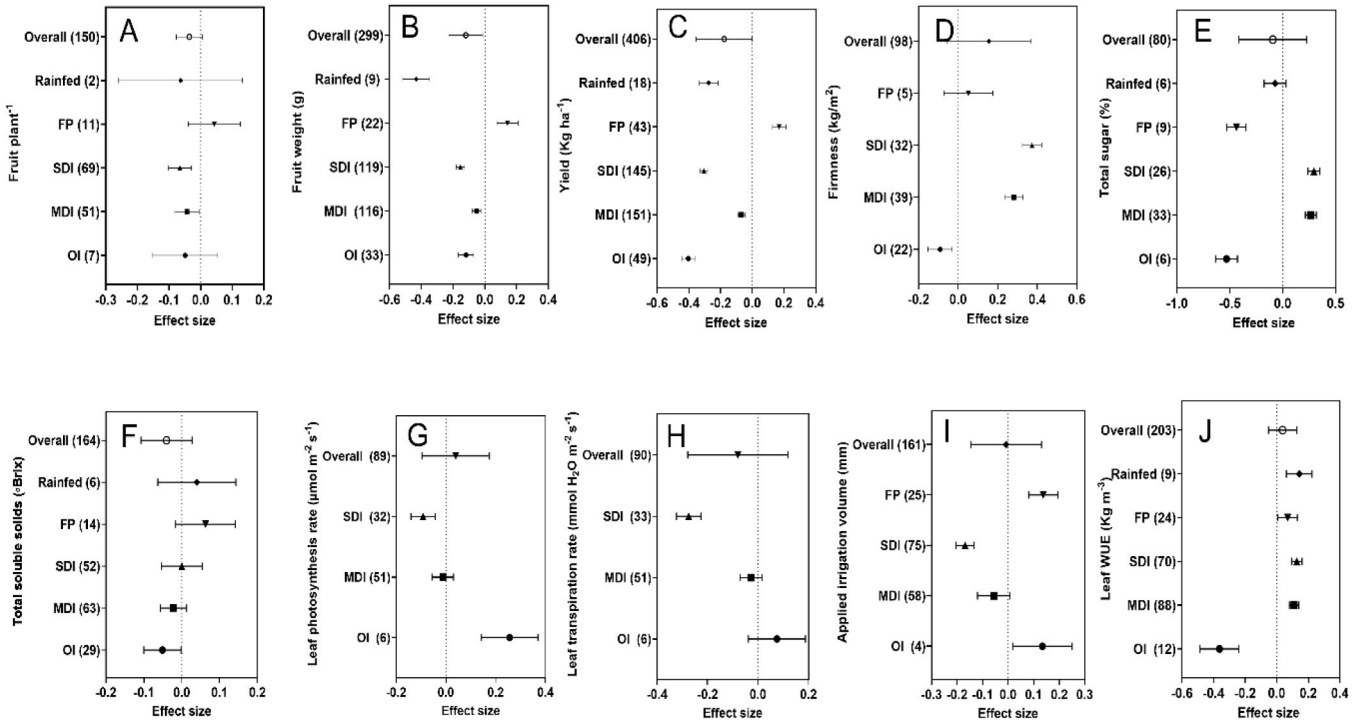


Fig. 5. Forest plot displaying the effect size of irrigation scheduling effect on (A) fruit plant^{-1}, (B) fruit weight (g), (C) yield (Kg ha^{-1}), (D) fruit firmness (g/mm), (E) total sugar (%), (F) total soluble solids (° Brix), (G) leaf photosynthesis rate (μmol m^{-2} s^{-1}), (H) leaf transpiration rate (mmol m^{-2} s^{-1}), (I) applied irrigation volume (mm), and (J) leaf water use efficiency (Kg m^{-3}) in strawberry. Error bars represent 95% confidence interval (CI) and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% ET); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET); FP, farmers practice irrigation.

for OI (−4.9%), MDI (−4.4%), SDI (−6.6%), and Rainfed conditions (−6.4%), while FP treatment increased fruit per plant by 4.3%. A significant reduction in fruit weight was observed under MDI (−5.2%), OI (−11.9%), SDI (−15.4%), and Rainfed conditions (−43.0%) with an overall ES of −12 (95% CI: −0.23 to −0.01) (Fig. 5B). In contrast, fruit weight was increased by FP treatment (14.2%). Similarly, yield was significantly reduced under OI (−40.4%), MDI (−6.9%), SDI (−30.5%), and Rainfed conditions (−27.6%), (Fig. 5C). In contrast, FP treatment significantly improved yield by 17.0%.

Fruit firmness was not impacted by deficit irrigation with an overall ES of 0.155 (95% CI: −0.06 – 0.369) (Fig. 5D). Both MDI and SDI significantly increased firmness by 28.0% and 37.3%, respectively, while FP treatment had non-significant effects. In contrast, firmness was significantly reduced under OI by −9.2%. Total sugar showed a strong increasing trend under deficit irrigation (Fig. 5E). SDI significantly enhanced total sugar by 29.5%, followed by MDI (26.5%), whereas FP treatment and OI resulted in a marked reduction of −43.8% and −53.2%, respectively. Total soluble solids were not significantly affected by irrigation scheduling (ES: −0.01 and 95% CI: −0.05 – 0.033) (Fig. 5F). OI reduced total soluble solids by −9.0%, while MDI decreased total soluble solids slightly (−2.2%). In contrast, Rainfed conditions and FP treatment increased total soluble solids by 4.0% and 6.3%, respectively.

The photosynthesis rate declined under increasing deficit irrigation, with MDI causing a moderate decline (−5.5%) and SDI leading to a significant reduction (−14.1%) (Fig. 5G). In contrast, OI increased the photosynthesis rate by 14.0% with an overall (ES: 0.039 and 95% CI: −0.1 – 0.175). Transpiration rate was reduced under deficit irrigation with (ES: −0.08 and 95% CI: −0.28 – 0.199) (Fig. 5H). OI significantly reduced transpiration by −3.8%, followed by MDI (−7.1%) and SDI (−32.3%).

Applied irrigation volume differed markedly among treatments (Fig. 5I). Both MDI and SDI significantly reduced applied irrigation volume by −11.0% and −16.9%, respectively, while OI and FP showed a greater applied irrigation volume of 13.4% and 13.7%, respectively. WUE was not impacted by deficit irrigation strategies (ES: 0.036 and 95% CI: −0.05 – 0.125) (Fig. 5J). A significant improvement in WUE was noticed under FP (6.9%), MDI (11.0%), SDI (12.7%), and Rainfed conditions (14.2%), while WUE decreased under OI (−36.3%).

3.2.2. *Climate classification influence on strawberry yield, fruit quality, leaf gas exchange, and water use efficiency*

Climate classification played a significant role in regulating strawberry yield, fruit quality attributes, physiological responses, and WUE

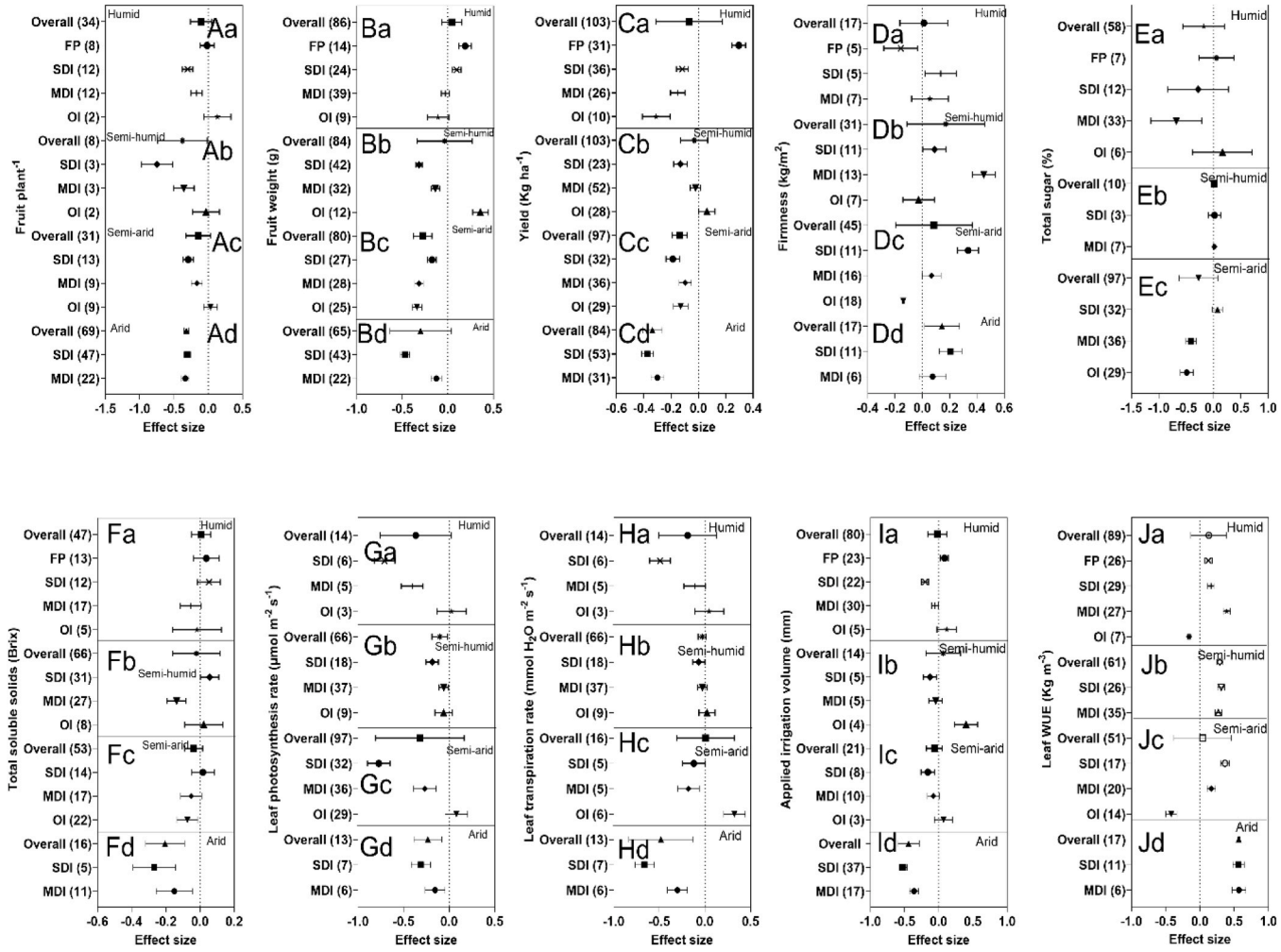


Fig. 6. Forest plot displaying the effect size of irrigation scheduling on (A $_{a-d}$) fruit plant $^{-1}$, (B $_{a-d}$) fruit weight (g), (C $_{a-d}$) yield (Kg ha^{-1}), (D $_{a-d}$) fruit firmness (g/mm), (E $_{a-c}$) total sugar (%), (F $_{a-d}$) total soluble solids (°Brix), (G $_{a-d}$) leaf photosynthesis rate (μmol m^{-2} s^{-1}), (H $_{a-d}$) leaf transpiration rate (mmol m^{-2} s^{-1}), (I $_{a-d}$) applied irrigation volume (mm), and (J $_{a-d}$) leaf water use efficiency (Kg m^{-3}) in strawberry under different climatic conditions. (bars represent 95% confidence interval (CI) and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% ET); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET); FP, farmers practice irrigation.

under different irrigation scheduling (Fig. 6).

Regarding yield parameters, fruit plant^{-1} in humid climates showed a significant reduction under MDI (−16.9%) and SDI (−30.0%), whereas OI increased the fruit number by 13.5% (Fig. 6 A_{a-d}). In semi-humid climates, SDI and MDI resulted in a significant reduction of −35.6% and −74.7%, respectively, whereas OI showed a smaller decline. In semi-arid climates, fruit plant^{-1} was reduced under MDI (−16.6%) and SDI (−29.2%), whereas slightly increased under OI (3.3%). The largest decline in fruit plant^{-1} was observed under arid climates, where MDI and SDI reduced fruit plant^{-1} by −30.6% and −33.3%, respectively. Fruit weight declined significantly in humid climates under OI (−10.7%), while FP treatment slightly improved fruit weight by 19.0% (Fig. 6 B_{a-d}). In semi-humid climates, MDI and SDI resulted in significant reductions of 13.6% and 31.5%, respectively in fruit weight. In semi-arid climates, fruit weight decreased moderately under OI (−33.8%), MDI (−31.6%) and SDI (−17.4%). Under arid climates, the strongest reduction in fruit weight was observed, with MDI (−18.4%) and SDI (−51.9%). The yield in humid climates was significantly reduced under OI (−30.9%), MDI (−15.1%) and SDI (−11.2%), whereas FP treatment increased yield by 29.5% (Fig. 9 C_{a-d}). In semi-humid climates, SDI resulted in a marked reduction in yield (−13.1%), while MDI caused a smaller decline. In semi-arid climates, yield declined significantly under OI (−33.8%), MDI (−31.6%) and SDI (−17.4%). Under arid climates, yield was most severely affected, with MDI and SDI significantly reducing yield by −18.4% and −51.9%, respectively.

In quality attributes, fruit firmness improved significantly in humid climates, under MDI (5.6%) and SDI (13.5%), while reduced under FP treatment (−15.7%) (Fig. 6 D_{a-d}). In semi-humid climates, MDI and SDI resulted in a noticeable increase in fruit firmness (44.9% and 8.9%, respectively), while OI slightly decreased fruit firmness. Similarly, in semi-arid climates, MDI and SDI increased fruit firmness by 6.7% and 33.5% respectively, while decreased under OI (−13.9%). In arid climates, fruit firmness increased by 7.6% and 20.6% under MDI and SDI, respectively. Total sugar decreased slightly in humid climates under MDI (−68.0%) and SDI (−28.2%), whereas it increased under OI (16.3%) and FP (5.4%) (Fig. 6 E_{a-c}). In semi-humid climates, MDI and SDI showed a moderate increase in total sugar. In semi-arid climates, sugar concentration increased modestly under SDI (7.1%), while it decreased under OI (−48.8%) and MDI (−40.9%). In humid climates, total soluble solids increased significantly under MDI (7.3%) and SDI (11.6%) (Fig. 6 F_{a-d}). In semi-humid climates, SDI significantly enhanced total soluble solids by 19.8%, while MDI resulted in a smaller improvement. In semi-arid climates, TSS increased by approximately 14.2% under SDI. Under arid climates, total soluble solids were most severely affected, with SDI and MDI reduced total soluble solidsby −15.1% and −26.8%, respectively.

Leaf photosynthesis rate declined moderately under MDI (−40.5%) and SDI (−70.8%), whereas there was a slight increase under OI in humid climates (Fig. 6 G_{a-d}). In semi-humid climates, SDI reduced leaf photosynthesis rate by −18.6%, while MDI caused a smaller decline. In semi-arid climates, leaf photosynthesis rate decreased by −26.7% and −77.2% under MDI and SDI respectively, whereas increased under OI. Similarly, in arid climates, leaf photosynthesis rate was reduced under MDI (−15.5%) and SDI (−31.1%). The leaf transpiration rate in humid climates decreased under MDI (−11.2%) and SDI (−49.2%) (Fig. 6 H_{a-d}). In semi-humid climates, SDI caused a reduction of −6.9%, while MDI led to a smaller decline in leaf transpiration rate. In semi-arid climates, transpiration decreased by −18.1% under MDI and −12.3% under SDI. Under arid climates, a significant reduction of leaf transpiration rate was observed under MDI (−30.2%) and SDI (−66.1%).

Across all climates, applied irrigation volume was reduced under deficit irrigation (Fig. 6 I_{ad}). In humid climates, applied irrigation volume decreased by −5.6% under MDI and −20.0% under SDI, whereas it increased under FP treatment (8.3%) and OI (11.7%). In semi-humid climates, a slight reduction of −4.4% and −12.7% were observed under MDI and SDI. Similarly, in semi-arid climates, applied irrigation volume decreased by −7.9% under MDI and −16.0% under SDI. A significant reduction in applied irrigation volume was recorded under arid climates, where MDI decreased applied irrigation volume by −36.0% and SDI by −51.9%. WUE in humid climates improved moderately under FP (12.3%), SDI (16.0%) and MDI (39.1%), whereas reduced under OI (−15.9%) (Fig. 6 J_{ad}). In semi-humid climates, significant enhancement in WUE was observed under MDI (32.4%) and SDI (41.7%). In semi-arid climates, WUE increased by 16.6% under MDI and 36.5% under SDI, whereas decreased under OI (−41.8%). In arid climates, a significant improvement in WUE was noticed, with MDI and SDI increased WUE by 56.3% and 56.8%, respectively.

3.2.3. *Soil type as moderator for irrigation scheduling impact on yield, quality and physiological parameters and water use efficiency*

Soil type significantly influenced the effectiveness of irrigation scheduling in regulating strawberry growth, yield, fruit quality, physiological responses, and WUE. Fig. 7 illustrates strawberry response to irrigation scheduling with soil type as moderator across clay, silt, loam, and sandy soils.

The overall effect of irrigation scheduling on fruits plant^{-1} showed a declining trend across soil types in relation to water holding capacity (Fig. 7 A_{a-d}). In clay soil, a significant reduction in fruit plant^{-1} was observed under MDI (−11.1%), SDI (−25.5%), and OI (−50.1%). In silt soil, fruit plant^{-1} was reduced under SDI (−15.8%), FP (−16.9%) and slightly decline in MDI (−9.9%). Loam soil also showed the same trend of reduced fruit plant^{-1} under OI (−16.7%), MDI (−24.3%) and SDI (−30.3%). In sand soil, FP, SDI and MDI reduced fruit plant^{-1} by −4.9%, −5.3% and 10%. Fruit weight was significantly reduced in clay soil under MDI (−8.3%) SDI (−16.7%), while OI improved fruit weight by 19.4% (Fig. 7 B_{a-d}). In silt soil, MDI and SDI resulted in −23.7% and −28.6% significant reductions in fruit weight, whereas FP reduced fruit weight by 7.0%. Similarly, in loam soil a significant reduction in fruit weight was observed under MDI (−12.3%) and SDI (−14.7%), whereas OI and FP slightly increased fruit weight. Yield was significantly reduced in clay soil under OI (−9.3%), MDI (−15.6%) and SDI (−20.3%) yield (Fig. 7 C_{a-d}). In silt soil, MDI, SDI and FP resulted in significant yield reductions of −9.9%, −15.8% and −16.9%, respectively. In loam soil, a significant reduction in yield was observed under OI (−16.7%), MDI (−24.3%) and SDI (−30.3%). In sand soil, yield was significantly reduced under SDI (−10.3%), FP (−11.5%) and MDI (−16.7%), whereas OI had a non-significant effect.

Fruit firmness in clay soil showed a slight improvement under MDI (3.9%) and SDI (8.0%), while OI resulted in a minor reduction (−5.2%) (Fig. 7 D_{a-d}). Similarly, in silt soil, SDI and MDI enhanced fruit firmness by 20.3% and 7.9%, whereas OI reduced fruit firmness by −7.3%. In sand soil, fruit firmness was enhanced markedly by MDI (9.5%) and SDI (7.7%), while reduced slightly under OI and FP. Total sugar in clay soil was significantly reduced under OI (−32.8%), MDI (−16.8%) and SDI (−24.5%) (Fig. 7 E_{a-d}). In silt soil, a significant reduction in total sugar was observed under MDI (−19.5%), FP treatment (−29.7%) and SDI (−16.8%). In loam soil, total sugar reduced significantly under OI (−31.9%) and MDI (−65.6%), whereas increased under SDI (32.7%). In sand soil, total sugar showed high variability, with significant reduction under MDI (−8.8%) and increased under SDI (15.8%) and FP (26.5%). For total soluble solids, no significant differences were observed for irrigation regimes in clay soil (Fig. 7 F_{a-d}). In silt soil, MDI resulted in a significant decrease in total soluble solids by (−10.5%), whereas MDI had a moderate positive effect. In sand soil, total soluble solids response was inconsistent, with a significant improvement under MDI (6.9%) and FP (9.5%), whereas decreased under OI (−7.7%).

The leaf photosynthesis rate declined significantly under MDI (−44.4%) and SDI (−14.3%) in clay soil (Fig. 7 G_{a-d}). In silt soil, OI, MDI, and SDI significantly reduced leaf photosynthesis rate by −13.1%, −12.6%, and −13.8%, respectively. In loam soil, the leaf photosynthesis rate declined under MDI (−22.6%) and SDI (−47.8%), while slightly increased under OI (2.6%). Similarly, in sand soil, leaf photosynthesis

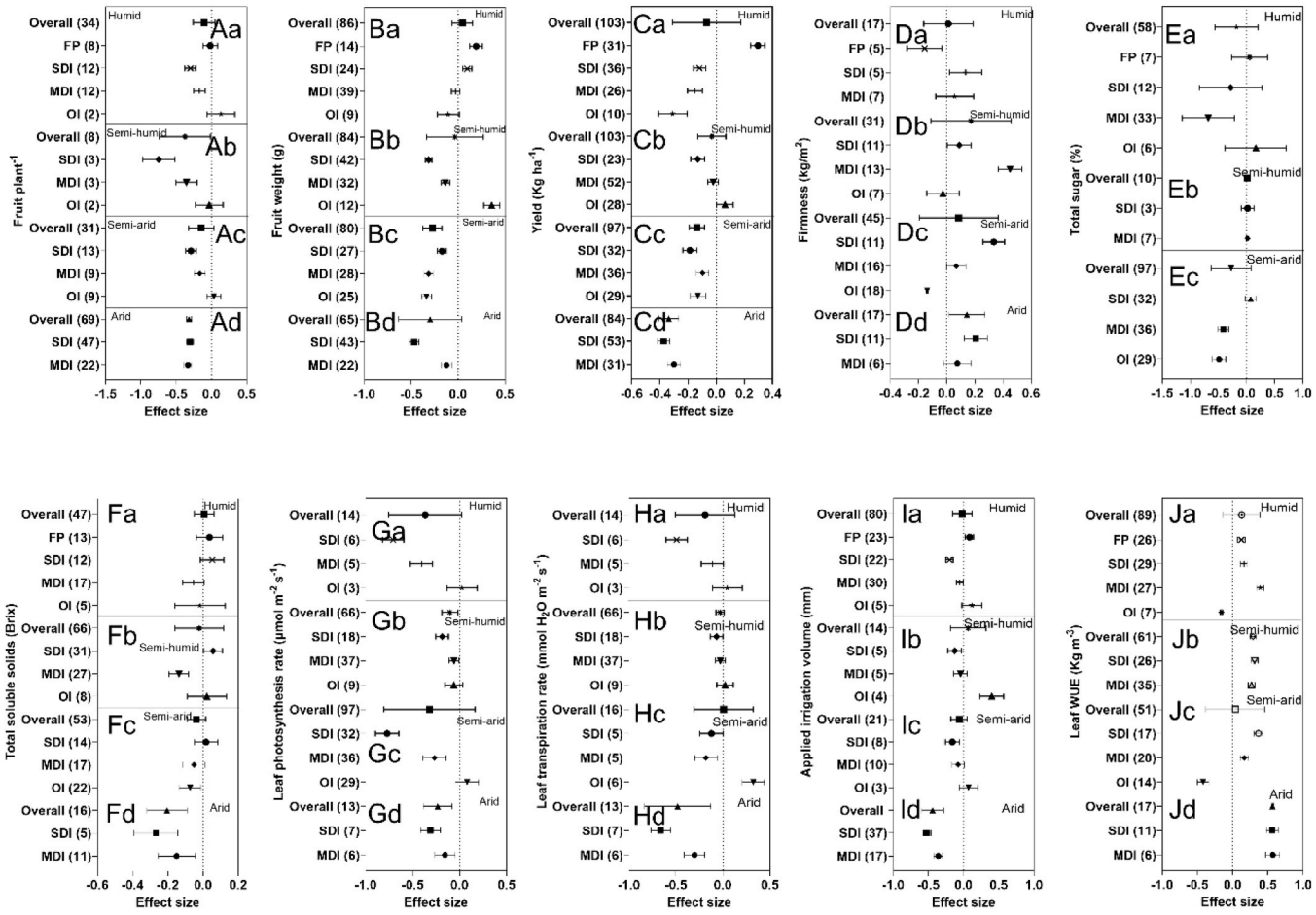


Fig. 7. Forest plot displaying the effect size of irrigation scheduling on (A $_{a\text{-}d}$) fruit plant $^{-1}$, (B $_{a\text{-}d}$) fruit weight (g), (C $_{a\text{-}d}$) yield (Kg ha^{-1}), (D $_{a\text{-}c}$) fruit firmness (g/mm), (E $_{a\text{-}d}$) total sugar (%), (F $_{a\text{-}c}$) total soluble solids (ºBrix), (G $_{a\text{-}d}$) leaf photosynthesis rate (μmol m^{-2} s^{-1}), (H $_{a\text{-}d}$) leaf transpiration rate (mmol m^{-2} s^{-1}), (I $_{a\text{-}d}$) applied irrigation volume (mm), and (J $_{a\text{-}d}$) leaf water use efficiency (Kg m^{-3}) of strawberry under different soil types. Error bars represent 95% confidence interval (CI) and vertical dotted line indicates Hedges = 0). The effect size for each irrigation scheduling treatment is considered significant if either of the error bars representing the 95% CI does not cross zero. OI, over-irrigation (>110% ET); MDI, moderate deficit irrigation (65–90% ET); SDI, severe deficit irrigation (below 50% ET); FP, farmers practice irrigation.

rate was reduced under MDI (−4.5%) and SDI (−21.0%), while enhanced under OI (19.9%). Leaf transpiration rate decreased significantly under MDI (−28.9%) and SDI (−66.1%) in clay soil (Fig. 7 $H_{a\text{-}d}$). Similarly, silt soil reduced leaf transpiration rate by −12.6% and −13.1% under MDI and SDI, respectively. In loam soil, leaf transpiration rate decreased by −32.3% under MDI and −41.9% under SDI, whereas increased under OI (30.1%). Similar trends were observed in sand soil, where MDI and SDI decreased leaf transpiration rate by −3.7% and −43.8%, respectively, while OI increased leaf transpiration rate by 33.1%.

Across all soil types, applied irrigation volume was reduced under deficit irrigation strategies, and increased under over irrigation (Fig. 7 $I_{a\text{-}d}$). In clay soil, applied irrigation volume was reduced by −30% under MDI and −20.6% under SDI. In silt soil, reductions of −8.5% and −48.1% in applied irrigation volume were observed under MDI and SDI, respectively. Similarly, in loam soil, applied irrigation volume decreased under MDI (−2.5%) and SDI (−25.3%). The reduction in applied irrigation volume was recorded in sand soil, under MDI (−17.6%) and SDI -(37.4%). WUE increased significantly in clay soil under MDI (19.5%) and SDI (60.4%), whereas decreased under OI (−66.7%) (Fig. 7 $J_{a\text{-}d}$). In silt soil, MDI, FP and SDI improved WUE by 8.5%, 13.9% and 16.7%, respectively. In loam soil, a significant enhancement in WUE was observed under MDI (24.9%) and SDI (45.7%). Similarly, in sand soil, WUE improved by 3.3% under MDI and 14.1% under SDI.

4. Discussion

4.1. Irrigation scheduling affects leaf gas exchange, WUE, yield, and fruit quality traits

Irrigation scheduling has become a critical decision-making process for achieving efficient and economically sustainable water use in agricultural systems (Saggi and Jain, 2022). Inefficient irrigation practices result in over- or under-irrigation, which can substantially reduce water use efficiency (WUE) and compromise crop performance (Umutoni and Samadi, 2024). Therefore, real-time irrigation scheduling plays a vital role in optimizing water application by aligning irrigation inputs with crop water requirements (Bwambale et al., 2022).

The present meta-analysis demonstrated that leaf gas exchange, WUE, and yield were among the most significantly altered parameters by irrigation scheduling for both blueberry and strawberry. In blueberry, MDI and SDI decreased photosynthesis rate and stomatal conductance and increased WUE, while Rainfed conditions and SDI resulted in yield losses. In strawberry, only SDI reduced photosynthesis and transpiration, while OI, MDI, SDI, and Rainfed conditions increased WUE and reduced yield. These contrasting results reflect the challenge of maximizing yield and WUE simultaneously through irrigation scheduling. WUE in plants reflects the balance between leaf photosynthesis and stomatal conductance or transpiration and is therefore closely linked to yield formation. Strategies that improve WUE (e.g. deficit

irrigation) often involve tighter stomatal regulation, which reduces water loss but also constrains CO_2 uptake (Rho et al., 2012). This can potentially limit photosynthesis, leading to a reduction in biomass accumulation and yield (Ali et al., 2024). Several studies included in this meta-analysis reported this negative relationship between WUE and yield (Ali et al., 2024; Weber et al., 2017). However, under severe water deficit, loss of cell turgor and cellular damage can override these effects, ultimately reducing fruit firmness. In both blueberry and strawberry, total soluble solids was minimally impacted by irrigation scheduling. However, in strawberry, total sugars increased in fruits under MDI and SDI and decreased by FP and OI. Deficit irrigation increases sugar concentration primarily through reduced fruit water content and limited dilution during growth (Janssens et al., 2022). Although soluble sugars can also increase under water deficits to serve as osmolytes to maintain a low osmotic potential in fruit tissues (Ru et al., 2024). Meanwhile, over-irrigation promotes rapid fruit expansion and dilution of soluble carbohydrates, leading to lower sugar concentrations. TSS can remain unchanged across treatments because it reflects the combined contribution of sugars, organic acids, and other soluble compounds, which may respond differently to irrigation regimes and offset changes in sugar concentration (Kader, 2008). In blueberry, TAC was moderately responsive to deficit irrigation; values were only decreased by SDI and Rainfed conditions. This reduction is primarily associated with the enhanced utilization of organic acids as respiratory substrates during stressful conditions, which results in greater acid degradation and lower organic acid accumulation in fruit tissues (Etienne et al., 2013).

Although both OI and FP applied similarly maximum irrigation amounts in strawberry, their effects on crop performance differed markedly. OI consistently reduced yield, firmness, and WUE in both blueberry and strawberry, likely due to excessive soil moisture causing reduced root aeration, increased nutrient leaching, and reduced physiological function (Zhang et al., 2025). OI can reduce crop yield by causing soil waterlogging, reduced root-zone oxygen availability, nutrient leaching, and increased susceptibility to root diseases. Excess soil moisture may also induce stomatal closure, restrict root growth, and reduce water and nutrient uptake, ultimately limiting plant productivity and yield (Irmak Suat, 2014). In contrast, FP improved FW, yield, TSS, and WUE in strawberry, indicating that these practices involve more adaptive and responsive water management rather than simply higher water application (Ibrahim et al., 2023). Unlike OI, FP likely reflects irrigation timing, frequency, and adjustments based on crop demand, soil moisture conditions, or grower experience, which help maintain optimal root-zone moisture without inducing waterlogging. This balance allows sustained photosynthesis and assimilates partitioning toward fruit development, thereby enhancing yield and quality. Overall, the contrast highlights that how water is applied is more critical than how much is applied, with FP treatment achieving better outcomes through improved synchronization between irrigation and plant water needs.

4.2. Irrigation scheduling was impacted by climate classification

Climate classification strongly moderated the effects of irrigation scheduling on fruit yield, quality, physiological traits, and WUE of blueberry and strawberry (Fig. 6 and 9). Irrigation scheduling under different climatic conditions serves as a key guide for irrigation system construction and operation and for regional water distribution (Linker et al., 2018).

In blueberry, yield reduction under deficit irrigation was more noticeable in semi-arid climates, while yield reductions were smaller under semi-humid and humid climates. Similarly, in strawberry, yield reductions and physiological stress responses under deficit irrigation were less pronounced in humid climates compared to drier climates (Du et al., 2018). Our results are in line with (Ali et al., 2024), who reported that yield reduction was higher in semi-arid climate compared to semi-humid and humid climates in apple. An explanation for these differences across climate classification is the contribution of precipitation and ET demand to existing water stress conditions Yield reduction under deficit irrigation is more pronounced in semi-arid climates due to low precipitation and high ET demand, which increases plant water stress and restrain photosynthesis and fruit development (Cholula et al., 2026; Emami et al., 2026). In contrast, semi-humid and humid climates provide supplemental rainfall and reduced ET demand, buffering soil moisture deficits and mitigating yield losses (Rashidi et al., 2026).

WUE under deficit irrigation was consistently higher in semi-arid climates as compared to humid and semi-humid climates. Reducing irrigation to boost WUE at the expense of yield is not advisable (Yu et al., 2020). These results were in accordance with the findings of (Cheng et al., 2021), who reported that deficit irrigation strategies are more effective for improving WUE in semi-arid regions in apple and grape. Irrigation scheduling in arid and semi-arid climate results in higher WUE compared to the humid regions (Ali et al., 2024). According to Zhang et al. (2021), the areas with humid climates can attain maximum return in terms of yield and WUE than drier climates due to lower vapor pressure deficit, which reduces plant water stress. This suggests that both blueberry and strawberry grown in wetter climates have greater resilience to irrigation reductions.

Deficit irrigation effects on fruit quality were strongly climate-dependent on both blueberry and strawberry. Total soluble solids and total sugar increased more consistently in humid and semi-humid climates under SDI and MDI, where moderate stress and partial moisture availability supported sugar accumulation. Deficit irrigation has been widely reported to advance fruit maturity and increase total soluble solids in fruit crops (Costa et al., 2007), while well-watered conditions or excessive vegetative growth can delay ripening due to shading within the canopy, resulting in lower total soluble solids (Marsal et al., 2000). In contrast, fruit firmness was higher in semi-arid and arid climates, likely due to reduced cell expansion and lower fruit water content under deficit irrigation. This increase in firmness under deficit irrigation has been attributed to cell-wall remodeling processes, including pectin methyl esterification and xyloglucan acetylation, which enhance structural rigidity (Gribaa et al., 2013; Toumi et al., 2022). In addition, fruit cell walls are rich in pectin, and calcium–pectin cross-linking plays a key role in strengthening cell wall structure, thereby increasing firmness (Hocking et al., 2016). Titratable acidity declined across all climates, with more pronounced reductions in humid and semi-humid regions. Overall, moderate climates favored sweetness, while drier climates enhanced firmness, highlighting a climate-driven trade-off in fruit quality under deficit irrigation.

Physiological responses such as photosynthesis rate and transpiration rate are highly sensitive to environmental conditions (Rett-Cadman and Vander Weide, 2026). Both parameters were reduced in deficit irrigation in arid climate as compared to humid climates. Soil moisture and vapor pressure deficit are the key drivers of transpiration at both local and global scales (Kimm et al., 2020; Liu et al., 2020). In wet soil, hydraulic conductivity is high, and water flow is primarily controlled by root hydraulic conductivity (Cai et al., 2022). As soils dry, hydraulic conductivity declines sharply, limiting water movement to the roots and eventually limiting the plant capacity to maintain high transpiration rates (Cai et al., 2024). The climate strongly governed the trade-off between yield preservation and water savings for both crops. Deficit irrigation was the most effective for improving WUE in arid and semi-arid climates, but needs proper management to avoid excessive yield loss, whereas semi-humid and humid climates allowed greater flexibility in irrigation reduction with minimal productivity penalties (He and Rosa, 2023).

4.3. Soil type influenced irrigation scheduling

Soil types significantly influenced the effectiveness of irrigation scheduling. Soil physio-chemical properties determine soil water retention capacity, infiltration rate, and availability of water in the root

zone for plant uptake. Among these, soil texture is important in regulating crop response to irrigation management. Rooting depth and water-extraction capacities of crops are impacted by the texture of the soil, which influences plant resistance to water stress (Zhang et al., 2004). Differences in field water capacity and permanent wilting point among soil types changed the duration and intensity of water stress under deficit irrigation, thereby determining crop response. Clay soil generally has a higher water-holding capacity, while sandy soil exhibits rapid drainage and limited moisture retention, requiring frequent irrigation to maintain adequate soil moisture. Loam soils, due to their balanced texture, provide comparatively favorable conditions for strawberry production under different irrigation strategies (Zhang et al., 2004). Blueberries are commonly grown on sandy loam soils to limit waterlogging (Tucker et al., 2025). In blueberry, across all soil types, sandy soils exhibited the greatest sensitivity to irrigation reduction. Yield parameters declined significantly under deficit irrigation in sand soil due to rapid drainage and low water-holding capacity. This soil type accelerates soil moisture reduction, exposing plants to frequent water stress events. These findings align with previous findings that coarse-textured soils increase drought stress and reduce yield under deficit irrigation (Tucker et al., 2025). Although yield reductions were greatest in sandy soils, WUE improved due to significant reductions in soil moisture under deficit irrigation because water savings from ET were proportionally larger than the corresponding yield losses (Yu et al., 2020). In contrast, clay soil resulted in smaller yield declines due to higher water retention. However, excessive irrigation in clay soil reduced WUE, likely because of reduced soil aeration and inefficient water use, as reported in earlier studies on fine-textured soils (Blanco et al., 2019). Loam soil provided the most balanced response, maintaining yield stability while achieving significant enhancement in WUE under moderate deficit irrigation (Cheng et al., 2021). Fruit quality attributes such as firmness, total soluble solids, and titratable acidity remained largely unaffected across soil types, indicated that blueberry fruit quality is comparatively resilient to soil-mediated water stress. Physiological responses in blueberry were reduced significantly in sandy soil compared to loam and clay soil.

Strawberry responses to irrigation scheduling were strongly soil-dependent and more pronounced than those observed for blueberry. Sandy soil showed the greatest reductions in strawberry fruits plant^{-1}, yield, and physiological activity under deficit irrigation, reflecting limited water availability and high susceptibility to drought stress. Similarly, soil-driven yield reductions in strawberry have been attributed to rapid soil drying and restricted root water uptake in sandy soil (Küçükyumuk, 2024). Loam soil consistently supported the highest WUE improvements with comparatively lower yield reduction. Moderate water retention and adequate aeration in loam soil allowed efficient water to use while maintaining physiological function, confirming that loam soil offers ideal conditions for deficit irrigation strategies (Assi et al., 2019). Clay soil reduced the severity of yield losses under deficit irrigation but showed lower improvements in WUE under high irrigation. Fruit quality traits were influenced by irrigation scheduling across soil types. Total soluble solids, total sugar, and firmness generally increased in loam and clay soils, where better water retention allowed moderate stress to enhance quality. In contrast, sandy soil showed weaker responses due to rapid moisture loss. Titratable acidity declined across all soils under deficit irrigation, with greater reductions in finer-textured soils. Overall, soil with higher water-holding capacity improved quality, highlighting the importance of soil texture in optimizing irrigation strategies and enhancing fruit quality under deficit irrigation.

5. Conclusions

This meta-analysis provides a comprehensive evaluation of irrigation scheduling effects on yield, fruit quality, leaf gas exchange, and WUE of blueberry and strawberry, with climate and soil type identified as key moderating factors. Across both crops, irrigation scheduling had a more significant effect on yield and WUE than on fruit quality, indicating that yield and WUE are more sensitive to water availability than fruit quality traits. Results indicated that blueberry and strawberry yields decreased significantly under OI, MDI, SDI, and Rainfed conditions compared to FI, with strawberry exhibiting greater sensitivity to irrigation stress than blueberry. Deficit irrigation strategies significantly reduced applied irrigation volume and improved WUE compared to full or excessive irrigation. WUE improved under MDI, SDI, and Rainfed conditions, with greater improvement observed in strawberry, whereas OI reduced WUE in both crops. Across both crops, MDI generally represented the most balanced strategy, achieving substantial water savings while limiting yield reduction, whereas SDI resulted in noticeable yield. OI and FI provided limited yield benefits and regularly reduced WUE, highlighting inefficient water use.

Climate classification strongly influenced crop response to irrigation scheduling. Deficit irrigation strategies significantly reduced blueberry yield under semi-arid, semi-humid, and humid climates, while improving WUE compared with FI. In strawberry, deficit irrigation strategies significantly reduced yield under arid and semi-arid climates and slightly reduced yield under semi-humid and humid climates, while improving WUE across all climate conditions. These findings highlight that climate-specific irrigation strategies are crucial to improve yield and WUE under increasing climate variability. Soil texture further regulated irrigation scheduling efficacy by controlling soil water retention and plant-available water. In blueberry, yield was significantly reduced under sand, loam, silt and clay soil compared to FI, whereas WUE improved under clay and silt soil. In strawberry yield reduced under sand, loam, silt and clay soil compared to FI, whereas WUE was improved under loam, silt and clay soil and decreased slightly under sandy soil. Overall, this study demonstrated that optimized irrigation scheduling, particularly MDI, can enhance WUE of blueberry and strawberry without yield decline. These results therefore supported the adoption of climate and soil-specific irrigation management approaches as a critical way toward sustainable berry production, improved water conservation, and resilience of crops under future water scarcity and climate change.

CRediT authorship contribution statement

Joshua VanderWeide: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Younsuk Dong:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Conceptualization. **Nawab Ali:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Jalal Bayar:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2026.110667.

Data availability

Data will be made available on request.

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