

REVIEW ARTICLE

Influence of Agroecological Practices on the Yield and Water Use Efficiency of Irrigated Vegetables: A Global Meta-Analysis

Mègnissè Zohoun¹  | Sissou Zakari¹  | André Adjogboto¹  | Pierre Gbènoukpo Tovihoudji¹  | Joost Wellens²  | P. B. Irénikatché Akponikpè^{1,3} 

¹Laboratory of Hydraulics and Environmental Modeling (HydroModE-Lab), Faculty of Agronomy, University of Parakou (UP), Parakou, Benin | ²TERRA Teaching and Research Centre, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium | ³Institute For Science And Innovation In Africa (ISTI-Africa), Parakou, Benin

Correspondence: Mègnissè Zohoun (inozohoun@gmail.com)

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ABSTRACT

Yield and irrigation water use efficiency (IWUE) are key indicators to evaluate water consumption in irrigated vegetable systems. This meta-analysis assessed three agroecological practices (water, biotic and nutrient management) to increase yield and IWUE under water-stressed (WS) and overwatering (OW) conditions. Response ratios were calculated for 871 yield and 814 IWUE observations from 84 peer-reviewed publications using random-effects models. Statistical analyses and graphics (forest plots) were performed using R 4.5.2. The yield was 15% lower, and the IWUE was 24% higher under WS than under full irrigation; however, the IWUE was 16% lower under OW. The highest yield and lowest IWUE occurred under severe OW for subsurface drip versus sprinkler and furrow systems. Under WS, the yield response was 6% lower for organic straw and 9% lower for plastic mulch than for unmulched soil (−18%), and the response was less negative under mixed organic–inorganic fertilisers than under sole sources. IWUE increased by 26% for manual weeding but decreased by 28% for herbicide use and increased by 60% for pesticides despite negative yield impacts. Under OW, bulb and root yields were improved under mixed fertilisation. Findings highlight the need to integrate agroecological practices to enhance yield and IWUE under synergistic management conditions.

RÉSUMÉ

Le rendement et l'efficacité d'utilisation de l'eau d'irrigation (EUEI) sont des indicateurs clés dans les systèmes maraîchers irrigués. Cette méta-analyse évalue trois pratiques agroécologiques (gestion de l'eau, des nuisibles et des nutriments) en vue d'accroître le rendement et l'EUEI sous stress hydrique (SH) et sur-irrigation (SI). Les ratios de réponse ont été calculés pour 871 observations de rendement et 814 d'EUEI issues de 84 publications à travers des modèles à effets aléatoires. Les analyses statistiques et les graphiques (forest plots) ont été réalisés sous le logiciel R 4.5.2. Le rendement était inférieur de 15% et l'EUEI supérieure de 24% en SH; l'EUEI était inférieure de 16% en SI. Le rendement maximal et EUEI minimale ont été observés en SI sévère sous l'irrigation goutte-à-goutte souterraine, comparativement aux systèmes par aspersion et l'irrigation par raie. En SH, la réponse du rendement était inférieure de 6% pour le paillage organique et de 9% pour le paillage plastique par rapport aux

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sols non paill  s (  18%); et moins n  gative sous la fertilisation mixte organo-min  rale. L'EUEI a augment   de 26% en SH avec le d  sherbage manuel, mais diminu   de 28% avec l'usage des herbicides et a augment   de 60% avec l'utilisation de pesticides malgr   des impacts n  gatifs sur le rendement. En SI, les rendements des cultures mara  ch  res    bulbes et    racines se sont am  lior  s sous la fertilisation mixte. Ces r  sultats soulignent l'importance de l'int  gration des pratiques agro  cologiques pour am  liorer le rendement et l'EUEI en gestion synergique des ressources agricoles.

1 | Introduction

Irrigated vegetable crops are essential for food security and provide crucial nutrients to populations worldwide (Radovich 2018). As water-sensitive crops, vegetables are heavily reliant on irrigation water to sustain both yields and quality (Du et al. 2017). In fact, efficient water management directly affects crop yield and irrigation water use efficiency (IWUE), defined as crop yield per unit of applied water, which are essential to ensure a consistent food supply in regions facing water scarcity exacerbated by climate change (Perry et al. 2009; Li et al. 2021). Drip and deficit irrigation strategies have proven effective under limited water supply (Wang et al. 2006; Sonawane and Shrivastava 2022). For instance, drip irrigation has outperformed sprinkler irrigation in both crop and economic water productivity for tomato, cabbage, sweet pepper and melon under groundwater-limited conditions (Al-Said et al. 2012) and increased yields by up to 8% relative to furrow irrigation and 2% relative to sprinkler irrigation (Yang et al. 2023). Similarly, optimised microsprinkler irrigation strategies have been shown to maintain yields comparable to conventional full irrigation while substantially improving crop water productivity across different cropping systems (Wu et al. 2024).

Several agroecological practices have demonstrated positive effects on vegetable yield and water use efficiency as sustainable alternatives to conventional methods (Wezel et al. 2014). Mulching and organic fertilisation enhance soil water retention and reduce evapotranspiration (Wu et al. 2017; Xu et al. 2024). Crop diversification strategies such as rotation and intercropping, combined with biological pest and weed management, further contribute to biodiversity and system productivity (Gebru 2015; Puissant et al. 2021). Beyond irrigation, vegetable production systems are also characterised by high pest pressure and intensive pesticide use, raising concerns about human health and environmental contamination (Williamson et al. 2008), which further underlines the relevance of agroecological pest and disease management strategies.

Sustainable vegetable production therefore requires integrated management of water, soil nutrients and pests, as water management plays a critical role in nutrient mobilisation, disease control and system profitability (Viets and Frank 1967; Dutta et al. 2020; Vishwakarma et al. 2024). In this context, irrigation management influences the effectiveness of agroecological practices by affecting soil moisture, nutrient cycling and pest dynamics, whereas agroecological practices enhance crop responses to irrigation through improved soil water retention, soil fertility and system resilience. Most of the abovementioned findings are based on field experiments, whereas previous meta-analyses have primarily focused on the effects of irrigation regimes on crop yield and water productivity. For instance, Cheng et al. (2021) and Singh

et al. (2021) investigated yield and water use efficiency responses to deficit irrigation across several crops, including vegetables, and Sounon Orou et al. (2025) assessed yield and water use efficiency responses to agroecological practices in lowland rice. However, few studies have synthesised quantitative evidence on how agroecological practices interact with water stress and overwatering conditions in irrigated vegetable systems. The practices targeted in this study are defined based on ecological principles of land practices (water and permanent soil cover), diversity (biological weed, pest and disease control as biotic control) and soil nutrient management. Vegetable types may respond differently to water management, fertilisation and pest resistance, which further complicates the integration of such practices into irrigation strategies (Li et al. 2021; Sultana et al. 2022). While agroecological practices have been studied in other crop systems, their application to irrigated vegetables remains insufficiently explored, particularly in integrated management systems.

This meta-analysis evaluates the potential of three agroecological practices to increase vegetable yield and IWUE under water stress and overwatering conditions. Meta-analysis allows for the statistical combination of quantitative study results, providing a more precise estimate of the effects (Grant and Booth 2009). Specifically, the study addresses the following research questions: (1) Which irrigation schemes and soil cover practices affect the yield and IWUE of irrigated vegetables under water stress and overwatering? (2) Do agroecological practices of weed, pest and disease control contribute to yield and IWUE improvements? (3) Which nutrient management practices are most effective in improving irrigated vegetable yield and IWUE under varying irrigation conditions?

2 | Methods

2.1 | Data Search and Collection

Peer-reviewed research papers published between 2000 and 2025 were retrieved from the Web of Science and Scopus databases using the following keywords: ((irrigation OR water) AND (WUE OR water productivity OR water use efficiency OR yield) AND (vegetable OR market garden*)). Searches were applied to titles and abstracts and then screened following PRISMA guidelines (<https://www.prisma-statement.org/>), ensuring that the process remains transparent and reproducible (Figure 1). Screening was performed in three steps mainly using Excel: duplicate removal, title and abstract reading and full-text reading. Duplicate removal was applied to the titles. For title and abstract reading, a subsample of 100 articles was independently checked by two coauthors to calibrate the screening process. For full-text reading, a subsample of five articles was checked by the abovementioned coauthors to calibrate article selection and data extraction from selected

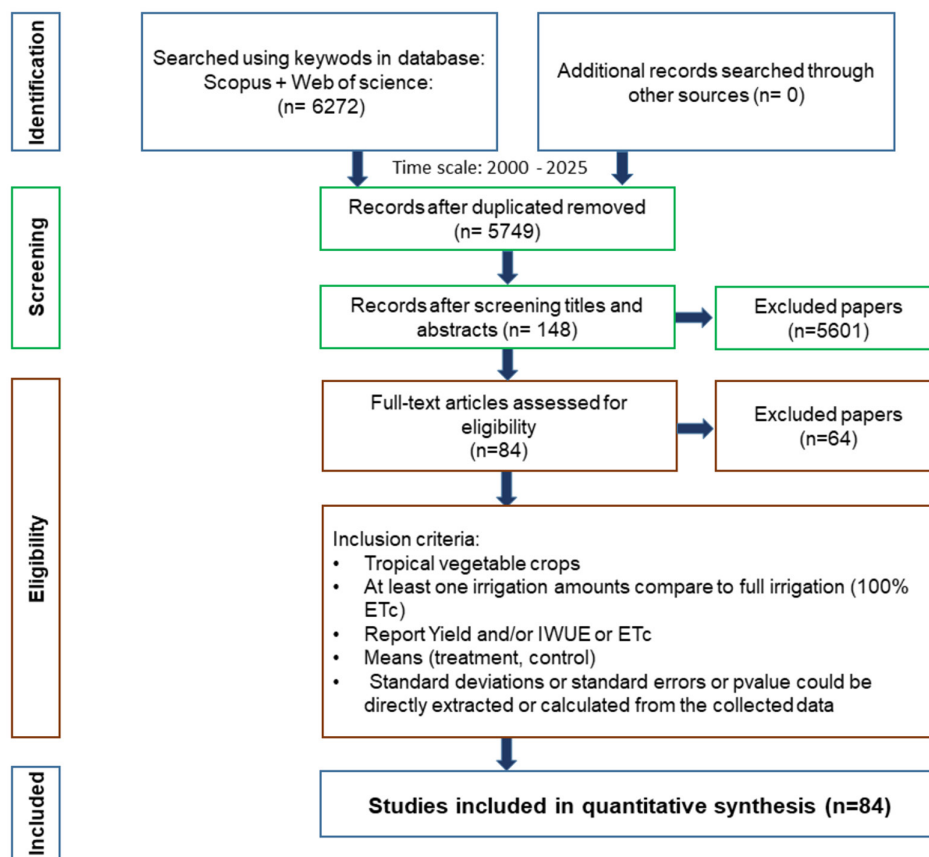


FIGURE 1 | Flowchart of the literature search and data collection.

articles using the inclusion and exclusion criteria. Disagreements were resolved by discussion and consensus. Then, the first author further read the remaining full-text articles and conducted the data extraction. Studies were included if they reported vegetable yield and/or IWUE or maximum crop evapotranspiration (ET_c), allowed IWUE calculation, included at least one irrigation treatment expressed as a proportion of ET_c relative to a full irrigation control (100% ET_c) and provided sufficient statistical information to compute effect sizes. Data were extracted from tables or digitised from figures using WebPlotDigitizer 4.5.0. For each study, metadata on crop productivity, experimental location, year and measurement units were extracted for both control and treatment conditions. Categorical variables were grouped into functionally comparable classes (Table 1). Yield and IWUE were standardised to tonnes per hectare (tha⁻¹) and kilogrammes per cubic metre (kg m⁻³), respectively.

2.2 | Data Analysis

2.2.1 | Response Variables and Moderators

The primary response variables were vegetable yield and IWUE. Yield is defined as harvested fresh aboveground biomass for leafy vegetables and fresh products in the form of fruits, roots or bulbs (Schiattone et al. 2018; Yang et al. 2018). Moderators encompassed agroecological practices related to water management (irrigation schemes and soil cover), biotic control (weed, pest and disease management) and soil nutrient management. Practices were

classified as agroecological or conventional based on established criteria (Table 1, Figure 2 and Supporting Information S1). The effects of water stress and overwatering were analysed relative to full irrigation, whereas agroecological practices were compared against their conventional counterparts.

2.2.2 | Irrigation Amount Classifications

Irrigation water stress and overwatering were classified as percentages of full irrigation. Water stress thresholds followed those established for vegetable production (El-Mageed and Semida 2015; Abdelkhalik et al. 2020; Mattar et al. 2021): severe ($\leq 50\%$ ET_c), moderate (50%–65% ET_c), low (65%–80% ET_c) and very low (80%–100% ET_c). Overwatering was grouped assuming that irrigation beyond the optimal ET_c range does not increase yield and reduces IWUE (Steduto et al. 2012): moderate (100%–125% ET_c) and severe ($> 125\%$ ET_c). These classes reflect typical yield and IWUE responses to irrigation amounts across vegetable systems.

2.2.3 | Effect Sizes and Variances

The natural log of the response ratio (lnRR) was calculated as effect size, following Hedges et al. (1999), and variance, following Luo et al. (2006) (see Supporting Information S2 for equations and definitions). In short, R_Y refers to the response ratio of crop yield, and R_{IWUE} refers to the response ratio of IWUE.

TABLE 1 | Group of agricultural management practices and their corresponding agroecological and conventional practices.

Managements	Agroecological practices		Conventional practices	
	Practices	%	Practices	%
Water management				
Irrigation schemes	Surface drip	80	Hand watering	5
	Subsurface drip	5	Sprinkler irrigation	5
			Furrow irrigation	5
Soil cover	Organic straw	7	Unmulched soils	73
	Plastic mulch	21		
Weed, pest and diseases management				
Weed management	Manual weeding	71	Applied herbicides	22
	Mulching	6		
Pest and diseases management	Biopesticide	NA	Applied pesticides for pest control	20
			Applied pesticides for disease control	16
Soil nutrient management				
Fertiliser source	Organic	6	Inorganic	65
	Mixed (organic + inorganic)	29		
Fertiliser application methods	Incorporation organic	66	Broadcasting organic	34
	Incorporation inorganic	9	Broadcasting inorganic	15
			Fertigation inorganic	69
			Hill placement inorganic	7

Note: Organic straw included date palm biochar, pistachio biochar, ricestraw biochar, biochar + compost, compost, compost + neemcake and crop residue; plastic mulch was a polyethylene plastic film. Percentages indicate the relative frequency of occurrence of each practice among the total observations included in the review. Abbreviation: NA, not available.

2.2.4 | Treatment of Missing Values

Missing standard deviations were derived from standard errors and sample size. Missing IWUE values were calculated as the ratio of yield over irrigation amount applied. When irrigation was based on soil water content or full irrigation data were unavailable, ETc was estimated using climatic data extracted from FAO's CLIMWAT 2.0 based on experimental site coordinates. We then incorporated papers-provided or FAO's 56 guidelines (Allen et al. 1998) information on crop species, sowing date, growth cycle duration, development stages and root depth, along with soil texture, into CROPWAT 8.0 (Smith 1992). When full-irrigation yield data were not reported, yields were fitted using polynomial, logarithmic or power regressions to estimate predicted values and standard errors (see Supporting Information S3). These estimations were applied only when necessary to preserve comparability across studies rather than generating new primary data.

2.2.5 | Statistical Analysis

Statistical analyses were performed using the package 'metafor' (Viechtbauer 2010) in R Version 4.5.2 (R Core Team 2025). Random-effects models were fitted to account

for heterogeneity across studies. Forest plots were used to synthesise pooled study outcomes (Borenstein et al. 2009), with submeta-analysis performed for each factor level. Each effect size was represented by a diamond, with upper and lower bounds corresponding to the 95% confidence interval. The diamond size corresponds to the weight assigned to the factor level, whereas the width indicates the precision of the estimate. Only moderator levels with at least three observations were included. Treatment effects were considered significant when the 95% confidence interval of lnRR did not include zero. If lnRR < 0, water stress had a negative effect on yield and IWUE; if lnRR > 0, the effect was positive. Heterogeneity was assessed using the Q statistic and I^2 index (Viechtbauer 2010), and moderators were introduced when heterogeneity was significant ($p < 0.05$).

3 | Results and Discussion

3.1 | Overview of the Collected Data

Data were collected from 84 papers reporting studies on 20 vegetable species across 17 countries worldwide (Figure 3). In total, 871 and 814 observations of yield and IWUE, respectively, were collected. Most yield-related observations

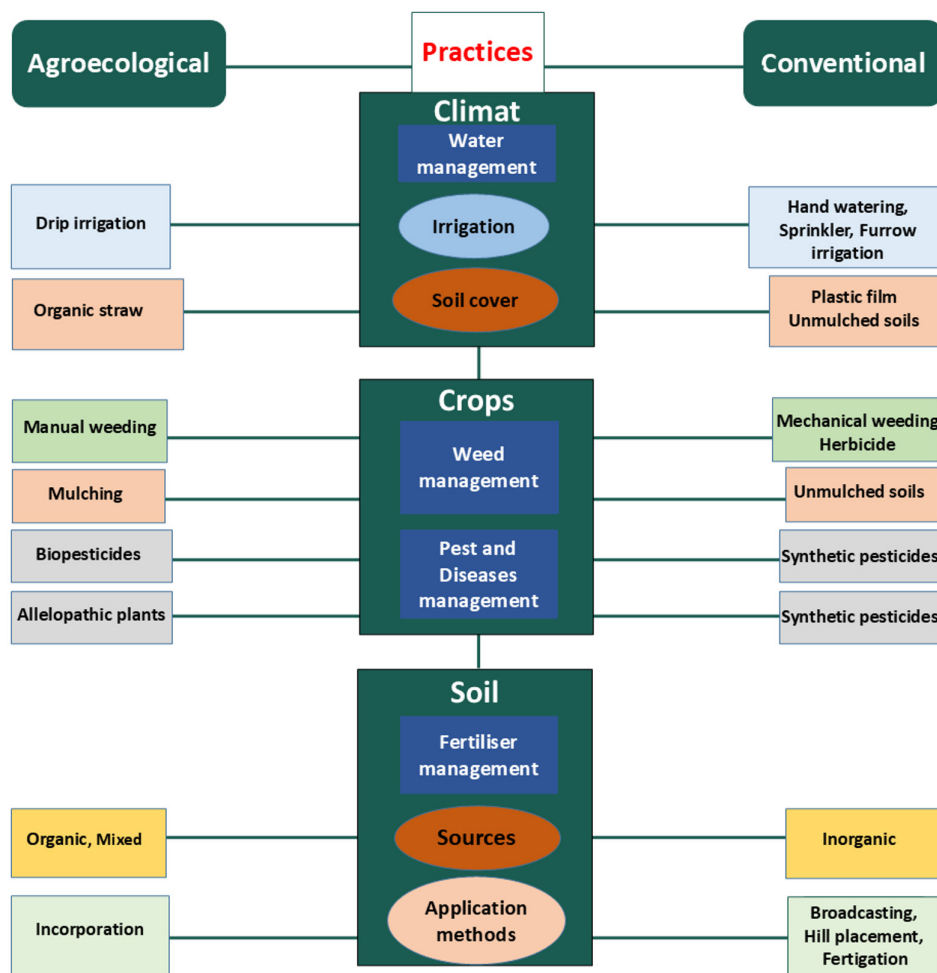


FIGURE 2 | Agroecological practices vs. conventional practices.

concerned tomato, with a relative frequency of 25%, followed by potato (18%), onion (11%), cucumber (10%) and sweet pepper (9%) (Table S1). The reported vegetable types were fruits (50%), roots (20%), bulbs (13%) and leaves (17%). The most represented countries were China (39%), Egypt (10%) and Iran (10%). The observed practices covered water management, nutrient management and pest control, with their relative frequencies of occurrence detailed in Table 1.

3.2 | Overall Response of Vegetable Crop Yield and IWUE to Water Stress and Overwatering

Yield was mainly 15% lower under water stress than under full irrigation ($p < 0.001$), and the effect of water stress on yield decreased from -7% to -33% with increasing water stress ($p < 0.001$) (Figure 4). The opposite trend occurred for IWUE, which was 24% higher under water stress ($p < 0.001$) and increased from 12% to 64% ($p < 0.001$). The IWUE was lower under overwatering than under full irrigation and decreased from -13% to -25% with increasing overwatering. In summary, water stress reduced vegetable yield but enhanced IWUE, highlighting a clear trade-off between production and irrigation efficiency.

3.3 | How Do Agroecological Practices Moderate the Response of Yield and IWUE to Water Stress and Overwatering?

3.3.1 | Influence of Irrigation Schemes

3.3.1.1 | Response of Yield to Irrigation Schemes. Yield was significantly higher under full irrigation than under water stress for sprinklers (-14% , $p < 0.001$), surface drip (-16%), subsurface drip (-21%) and hand watering (-25%), but not for furrow irrigation (-0.8% , $p = 0.682$), where the highest RRY occurred under very low water stress. RRY was more negative under severe (-28%) and moderate water stress (-22%) than under low (-7%) and very low water stress (-9%) for surface drip and more negative under severe water stress (-45%) relative to each of the other stress levels (-15% , -4% and -4%) for subsurface drip. The RRY did not significantly differ between low and moderate water stress for sprinkler and hand watering. These different responses can be attributed to differences in water application efficiency and distribution uniformity among irrigation schemes. The absence of significant yield reduction under water stress in furrow irrigation may be explained by compensation from conveyance losses along the furrow. Furrow irrigation involves substantial seepage and deep percolation

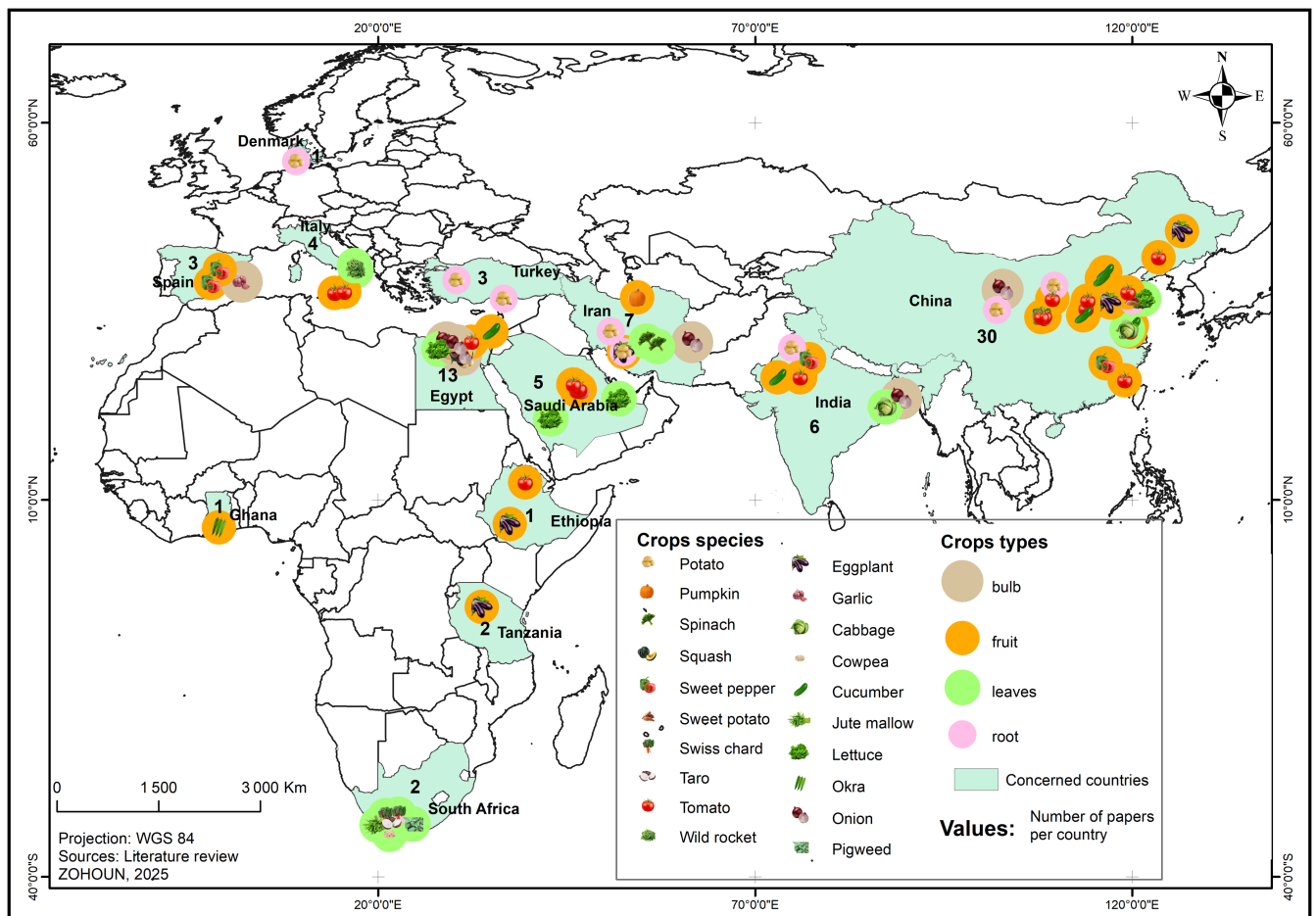


FIGURE 3 | Geographic distribution of included studies, crop species and types per country.

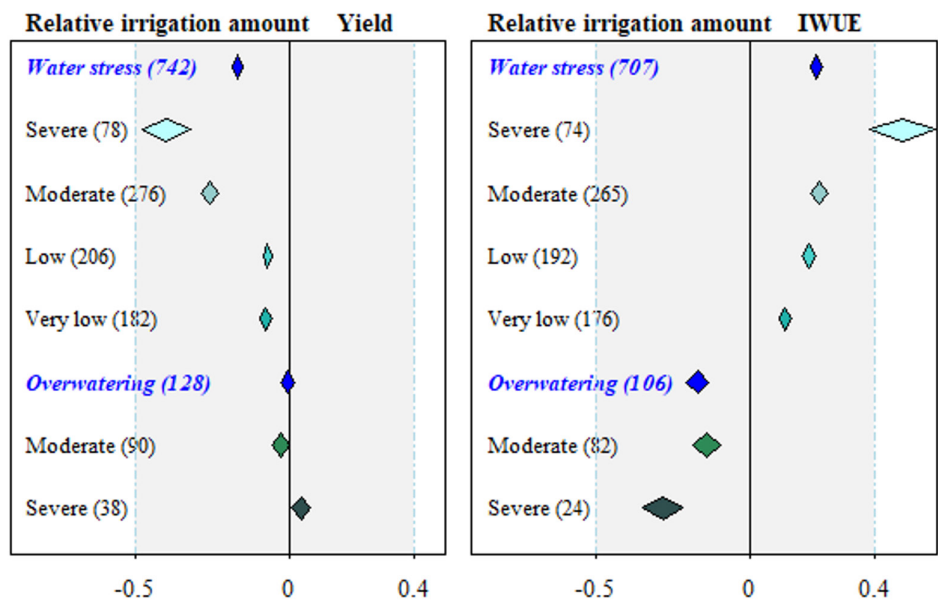


FIGURE 4 | Yield and IWUE response ratios for different irrigation amounts. Blue diamonds represent summary effect sizes. Individual water stress and overwatering levels are displayed using sequential colour gradients from light to dark to reflect increasing treatment intensity. Values in parentheses are the number of observations.

during surface flow (Araujo et al. 2019). Consequently, actual plant water availability may approach or exceed scheduled amounts because conveyance losses infiltrate the root zone along the furrow, even under nominal water stress treatments. By comparison, pressurised systems (drips and sprinklers) deliver water with high precision and minimal losses (Ayars et al. 1999), ensuring that stress treatments accurately reflect plant water status. This precision accounts for the significant and consistent yield reductions under water stress in all pressurised irrigation methods.

Subsurface drip was the only irrigation scheme for which yield was significantly higher under overwatering than under full irrigation (largest increase: +26%, $p < 0.001$ under severe overwatering conditions). Consequently, subsurface drip, an agro-ecological irrigation scheme, was the only system that showed a clear full gradient of R_Y (water stress < full irrigation < overwatering). It sustained yield gains beyond full irrigation, but it also showed greater sensitivity to water stress than the other

irrigation schemes (Figure 5). This yield advantage of subsurface drip under overwatering is likely due to the subsurface placement of emitters, which prevents surface waterlogging, hence maintaining adequate oxygen diffusion in the upper soil layers and thus supporting root respiration (Ayars et al. 2015). Additionally, part of the additional water may redistribute dissolved nutrients towards deeper root zones that remain within the active root system, thereby sustaining or even enhancing nutrient uptake efficiency rather than causing pure leaching losses (Callau-Beyer et al. 2024). No prior meta-analysis has documented this yield advantage of subsurface drip under overwatering. Excessive irrigation typically increases nutrient leaching, soil salinity and crop disease risk, with little or no yield benefit (Nwosisi et al. 2019; Etikala et al. 2021).

3.3.1.2 | Response of IWUE to Irrigation Schemes. IWUE increased by 34% under water stress but decreased by 11% under overwatering for subsurface drip. Similarly, surface drip irrigation resulted in a 23% increase in IWUE

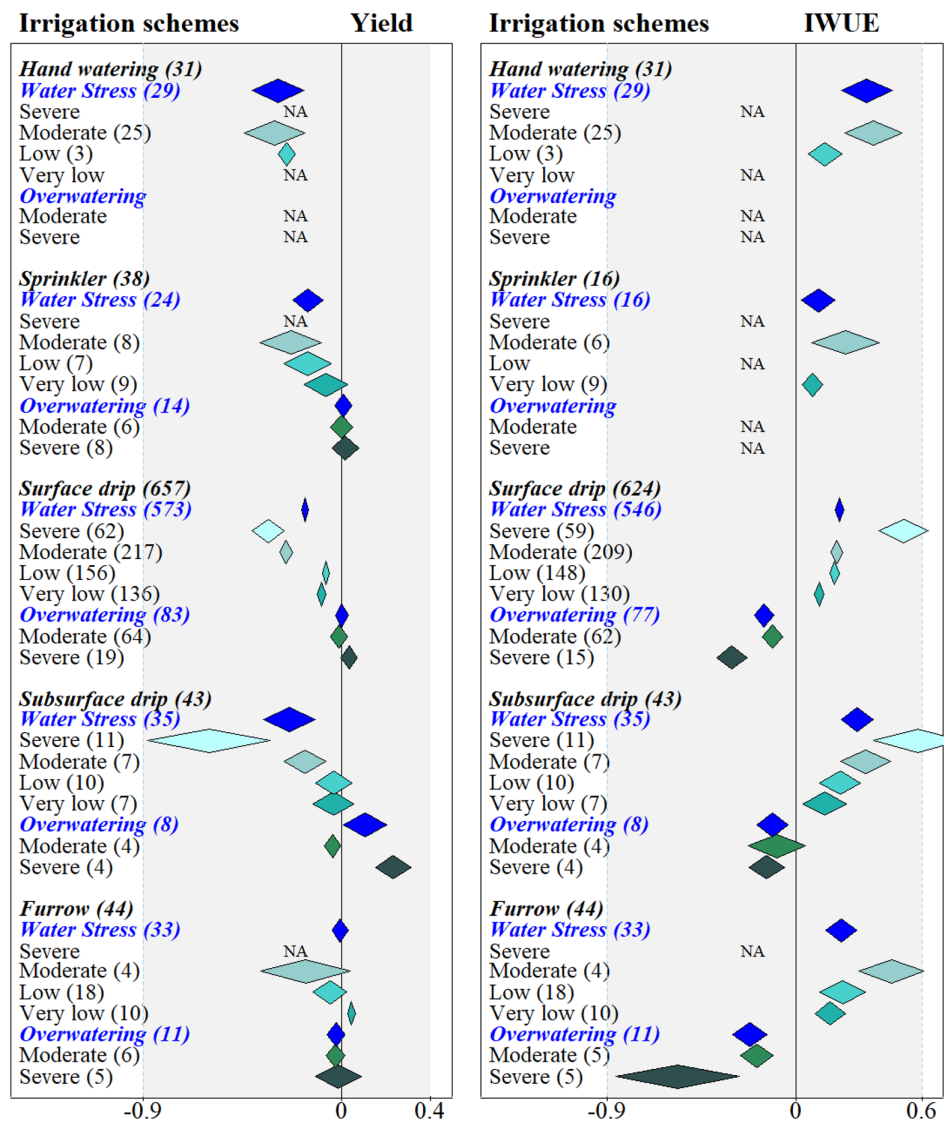


FIGURE 5 | Yield and IWUE response ratios for different irrigation schemes. Blue diamonds represent summary effect sizes. Individual water stress and overwatering levels are displayed using sequential colour gradients from light to dark to reflect increasing treatment intensity. Values in parentheses are the number of observations.

under water stress and a 14% decrease under overwatering, whereas furrow irrigation increased IWUE by 24% under water stress but reduced it by 21% under overwatering. Furrow irrigation showed the most negative RR_{IWUE} under severe overwatering (-43%), but RR_{IWUE} was similar among subsurface drip (-4%), surface drip (-1%) and furrow irrigation (-0.9%) under moderate overwatering. Moreover, IWUE increased progressively from very low to severe water stress across all irrigation schemes before the decline from moderate to severe overwatering (Figure 5). Similar water use efficiency responses across water stress intensities were reported by Welde et al. (2019). Drip irrigation systems maintained higher IWUE than conventional practices, particularly under water stress. The lower performance of furrow irrigation resulted from substantial evaporation and nutrient losses through seepage and deep percolation compared to pressurised systems (Yazar et al. 2002). Although water stress reduced yields relative to full irrigation across irrigation schemes ($RR_y = -0.172$, $p < 0.001$), it substantially improved IWUE ($RR_{IWUE} = +0.214$). Overwatering consistently reduced IWUE ($RR_{IWUE} = -0.159$, $p < 0.001$) and provided no significant yield benefit ($RR_y = 0.003$, $p = 0.827$).

3.3.2 | Influence of Soil Cover With Mulching Materials

3.3.2.1 | Response of Yield to Soil Cover. The effect of water stress on crop yield was significantly influenced by mulching materials (Figure 6). The yield was reduced overall under water stress (-15.49% , $p < 0.001$), and this reduction was greatest for unmulched soils (-18.01%). Both plastic mulch and organic straw maintained yields under low to very low water stress, with no significant difference from full irrigation. Organic straw was the only mulch material to produce a positive yield response under very low water stress, suggesting a superior moisture conservation capacity at moderate stress levels, likely through improved soil structure and water-holding capacity from gradual decomposition (Huo et al. 2017; Demo and Asefa Bogale 2024). Both mulch materials reduce soil evaporation, stabilise soil temperature and preserve soil organic carbon and nitrogen fractions in the critical topsoil layer where feeder roots are concentrated (Dong et al. 2018). Evaporation control emerges as the dominant factor that determines yield under moderate stress, regardless of mulching material, a finding consistent with previous studies (Kader et al. 2017; Gu et al. 2020).

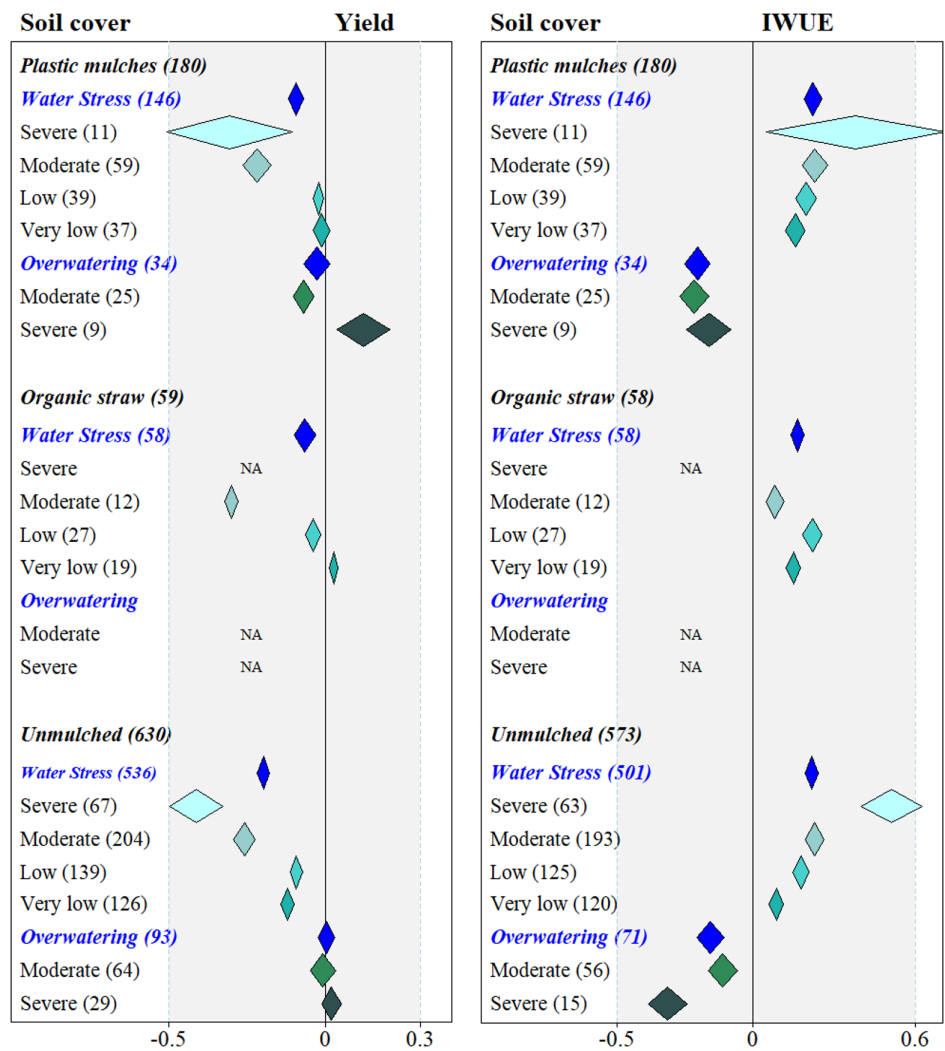


FIGURE 6 | Yield and IWUE response ratios for different soil covers with mulching materials. Blue diamonds represent summary effect sizes. Individual water stress and overwatering levels are displayed using sequential colour gradients from light to dark to reflect increasing treatment intensity. Values in parentheses are the number of observations.

Unexpectedly, plastic mulch was the only mulch material to show a significant yield increase under severe overwatering (+13%, $p=0.005$). We hypothesised that three nonexclusive mechanisms: (1) Plastic impermeability may facilitate lateral runoff, thereby preventing prolonged waterlogging; (2) soil temperature moderation under plastic mulch could maintain root metabolic activity despite excess water (Zhang et al. 2019); and (3) the physical barrier may suppress fungal pathogens and weed growth that typically proliferate in saturated soils (Nwosisi et al. 2019). Overall, across all mulching conditions, RRy followed the pattern water stress < full irrigation $\approx$ overwatering.

3.3.3.2 | Response of IWUE to Soil Cover. IWUE showed an opposite trend to the yield under water stress (+24%, $p<0.001$), increasing progressively from the lowest to the most severe water stress levels. This result suggests that crops used water more efficiently when the water supply is limited because they rely on stomatal regulation and osmotic adjustment (Petrik et al. 2023). Across all mulching conditions, IWUE decreased by 16% ($p<0.001$) under overwatering, with the greatest reduction in unmulched soils under severe overwatering (−27%, $p<0.001$).

This may reflect additional nonproductive evaporation losses in the absence of soil cover. Overall, $RRiwue$ followed the opposite pattern to RRy : water stress > full irrigation > overwatering (Figure 6).

3.3.3 | Influence of Weed, Pest and Disease Control

3.3.3.1 | Response of Yield to Biotic Control. Crop yield was consistently lower under water stress than under full irrigation across weed (−19%), pest (−17%) and disease control (−17%), but the control method strongly influenced the magnitude of this reduction (Figure 7). Herbicide application exacerbated yield reductions under water stress (−30%, $p=0.0002$), as did pesticide treatments for pest (−28%, $p<0.001$) and disease control (−25%, $p=0.125$). This likely reflects an additive stress effect, where chemical inputs further impair root function and soil microbial activity under drought (Shah et al. 2025).

Manual weeding was the only control method for which overwatering significantly increased yield (+9%, $p=0.021$), whereas pest

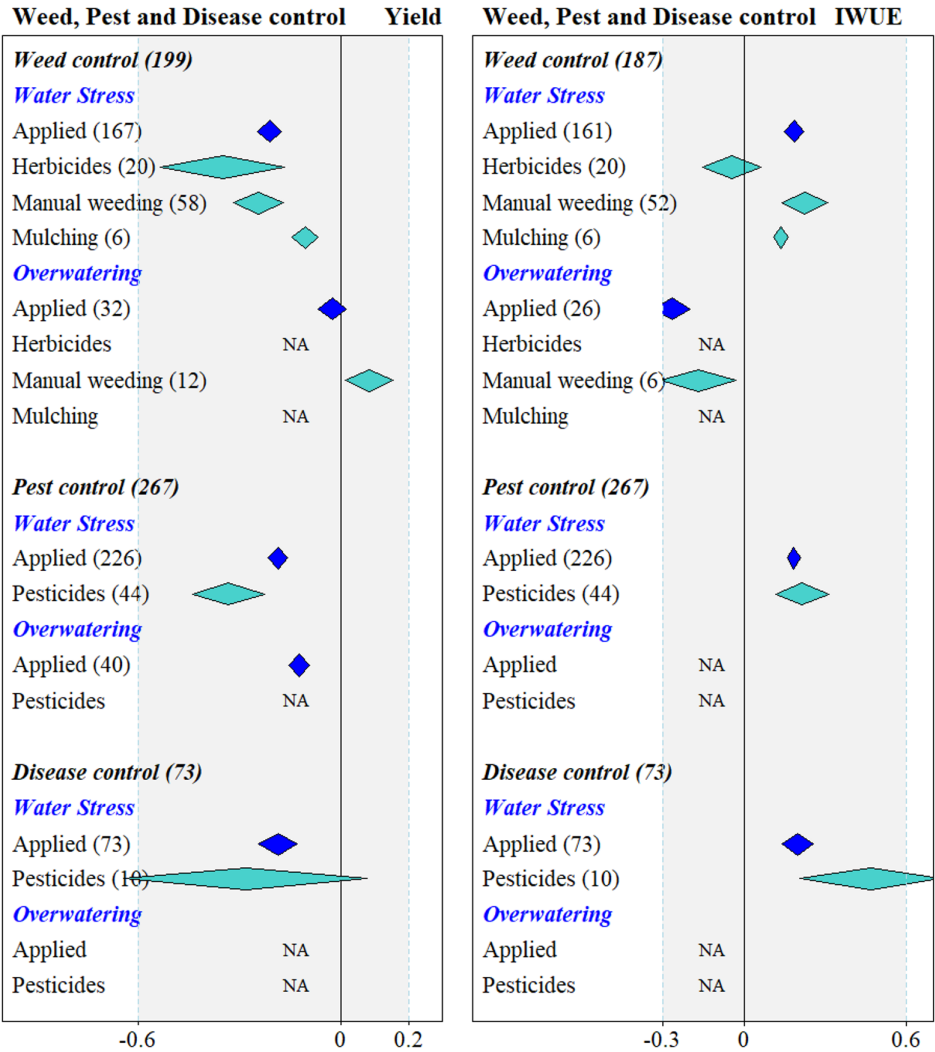


FIGURE 7 | Yield and IWUE response ratios for weed, pest and disease control. Blue diamonds represent summary effect sizes for the applied control under water stress or overwatering. Turquoise diamonds represent individual control methods within each category. Values in parentheses are the number of observations.

control significantly reduced yield under overwatering (-12% , $p < 0.001$). This exception may reflect the absence of chemical stress and improved root aeration in saturated soils under manual weeding (Kumar et al. 2024). However, from a practical standpoint, manual weeding entails high labour costs (~ 2500 USD/ha, Gianessi and Reigner 2007) compared to herbicide application, creating a strong economic barrier in industrialised systems (Bhagat et al. 2024). This suggests that in high-value vegetable crops under marginal water conditions, the yield and IWUE benefits of manual weeding may nonetheless offset these costs.

3.3.3.2 | Response of IWUE to Biotic Control. IWUE was significantly higher under water stress than under full irrigation across most weed (+20%), pest (+20%) and disease control methods (+22%), with the exception of herbicide application, which showed no significant difference from full irrigation (-4% , $p = 0.421$) (Figure 7). Herbicide application may therefore have compromised the plant's ability to improve IWUE under water stress. However, IWUE decreased by 23% ($p < 0.001$) under overwatering compared to full irrigation, even when weed control was implemented. These results suggest that

manual weeding is the most water-efficient management option under both water stress and overwatering conditions.

3.3.4 | Influence of Fertiliser Sources

3.3.4.1 | Response of Yield to Fertiliser Sources. R_{RY} followed a consistent pattern across most fertiliser sources: water stress < overwatering < full irrigation (Figure 8). Yield was reduced under water stress across all fertiliser sources, with mean reductions of -17% for inorganic sources, -18% for organic sources and -10% for mixed sources (all $p < 0.001$). Inorganic fertilisers showed progressive yield reductions with increasing stress severity, ranging from -8% to -34% , with additional sensitivity to overwatering (-4% , $p = 0.027$). This likely reflects their critical dependence on adequate soil moisture for nutrient dissolution and uptake, potentially exacerbated by osmotic stress from soluble salt accumulation in the root zone (Badr et al. 2012), which further reduces water availability to plants (Yang et al. 2020). Mixed fertilisers most effectively mitigated yield reductions under very low water stress (-4% ,

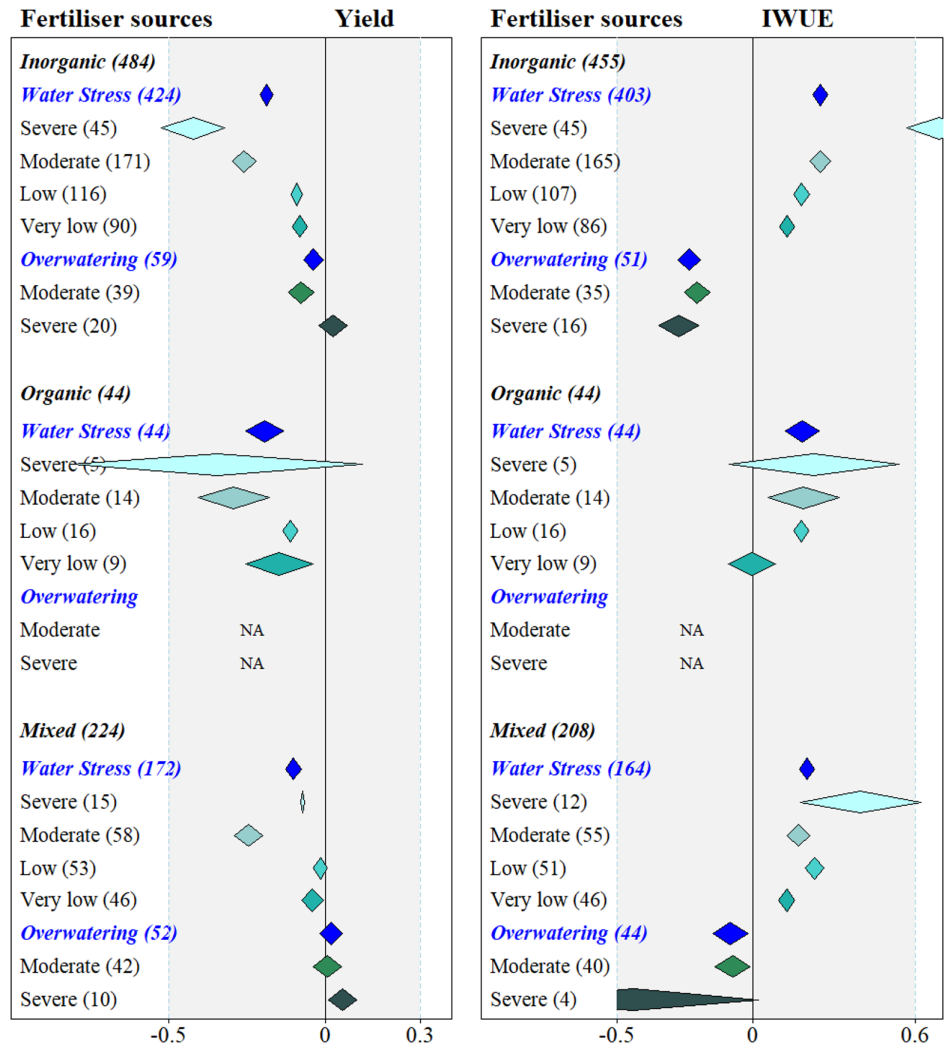


FIGURE 8 | Yield and IWUE response ratios for different fertiliser sources. Blue diamonds represent summary effect sizes. Individual water stress and overwatering levels are displayed using sequential colour gradients from light to dark to reflect increasing treatment intensity. Values in parentheses are the number of observations.

$p=0.015$) and were the only source that showed a significant yield increase under severe overwatering (+5%, $p=0.021$), in contrast to the pattern observed for the other sources. Such a buffering effect may stem from improved soil water retention, gradual nutrient release and better drainage (Kumar et al. 2018; Roba 2018; Singh et al. 2019) (Figure 8).

3.3.4.2 | Response of IWUE to Fertiliser Sources. The RR_{IWUE} showed the opposite pattern to RR_Y : overwatering < full irrigation < water stress (Figure 8). IWUE was higher under water stress than under full irrigation across all fertiliser sources: inorganic (+28%), mixed (+22%) and organic (+20%). For inorganic fertilisers, IWUE increased substantially with stress intensity, from +13% to +99%. Under overwatering, inorganic fertilisers showed the highest reduction in IWUE (−21%), compared with −8% for mixed fertilisers. This negative response was more attenuated under moderate overwatering for mixed fertilisers (−7%, $p=0.024$) than for inorganic sources (−19%, $p<0.001$). Under water stress, organic and mixed fertilisers showed more moderate and variable responses than inorganic fertilisers, a pattern that partly reflects reduced soil microbial activity, which constrains organic nutrient release under water stress (Liu et al. 2022). Such attenuation, under both water stress and overwatering, may point to a buffering effect from organic matter incorporation.

3.3.5 | Influence of Fertiliser Application Methods

3.3.5.1 | Response of Yield to Fertiliser Application Methods. Water stress significantly reduced yield relative to full irrigation across all fertiliser application methods (−14%, $p<0.001$) (Figure 9). The RR_Y values were comparable between surface applications (inorganic and organic broadcasting) and soil-incorporated applications (inorganic incorporation, fertigation and organic incorporation). Both inorganic and organic broadcasting showed positive yields under very low water stress, challenging conventional recommendations that prioritise hill placement or fertigation under all conditions (Li et al. 2021). Reduced irrigation under mild water stress can limit nutrient leaching and concentrate nutrients in the active root zone, which may explain why broadcasting sometimes shows a relative yield advantage under slightly restricted irrigation (Chai et al. 2016). Only inorganic hill placement (+7%, $p=0.039$) and organic incorporation (+9%, $p<0.001$) improved yield under overwatering, whereas other methods remained statistically comparable (Figure 9). These gains likely stem from deeper nutrient positioning below waterlogged surface layers for placement methods and improved soil aeration from organic matter incorporation (Zhou et al. 2022). However, the modest effect sizes (<10%) suggest limited practical benefit from intentional overwatering.

3.3.5.2 | Response of IWUE to Fertiliser Application Methods. IWUE increased consistently under water stress across all application methods (+20%, $p<0.001$), although the magnitude varied substantially (Figure 9). Inorganic hill placement achieved the greatest IWUE enhancement under moderate water stress (+64%, $p<0.001$), and it exceeded the gains

from inorganic broadcasting at the same stress level (+7%). Concentrated nutrient availability near roots under water-limited conditions may explain this wide margin between methods. Inorganic hill placement (−11%, $p<0.001$) and fertigation (−10%, $p=0.006$) resulted in a reduced IWUE under overwatering, whereas organic incorporation increased IWUE under moderate overwatering (+6%, $p=0.025$) but became ineffective under severe overwatering. This divergence suggests that organic incorporation improves drainage capacity under moderate excess water but becomes ineffective under severe overwatering, where oxygen limitation constrains root function (Kou et al. 2022). The IWUE reduction observed for fertigation is also noteworthy, as excess water promotes nutrient leaching despite its capacity for precision delivery (Li et al. 2021; Wu et al. 2022).

3.4 | How Does Crop Type Influence Yield and IWUE Responses to Water Stress and Overwatering Under Agroecological Practices?

3.4.1 | Case of Irrigation Schemes

Water stress reduced yield across all crop types relative to full irrigation, with the magnitude varying by irrigation scheme (Figure 10). This reduction was most pronounced for root crops under furrow irrigation (−36%, $p=0.003$), whereas bulb crops demonstrated a near-neutral response ($RR_Y=0.025$, $p=0.056$). Under overwatering, yield was improved for root crops under surface drip (+11%, $p<0.001$) and for fruit crops under subsurface drip (+19%, $p<0.001$). These contrasting responses are consistent with distinct physiological mechanisms: osmotic regulation through storage organs in bulb crops (Sansan et al. 2024) and improved water retention in root systems (Holz et al. 2024).

IWUE increased under water stress exceeded full irrigation across all crop types, with leaf crops showing the greatest enhancement (+57%, $p<0.001$), followed by bulb (+22%), fruit (+19%) and root crops (+16%). Under overwatering, by contrast, IWUE decreased for fruit (−22%), leaves (−19%) and bulbs (−19%), especially under surface drip irrigation. This reflects their specialised stomatal regulation minimising water loss under limited supply (Maseko et al. 2019) (Figure 10).

3.4.2 | Case of Soil Cover With Mulching Materials

Consistent with the irrigation scheme findings, yield remained lower under water stress across most crop types and mulching conditions. Bulb crops under organic straw were the only exception, with no significant difference from full irrigation. Under overwatering, root crops instead showed a significant yield increase in unmulched soils ($RR_Y=0.103$, $p<0.001$). Soil moisture retention and reduced nutrient leaching under organic straw may partially compensate for water deficits in shallow-rooted systems (Zhao et al. 2014; Rasool et al. 2019). Excessive watering, meanwhile, may stimulate vegetative growth while maintaining root nutrient supply, as reported for sweet potato by Siqinbatu et al. (2013). Leaf crops showed the greatest enhancement in IWUE under water stress, particularly under unmulched conditions (+59%, $p<0.001$). Overall, IWUE was higher under water stress than under full irrigation

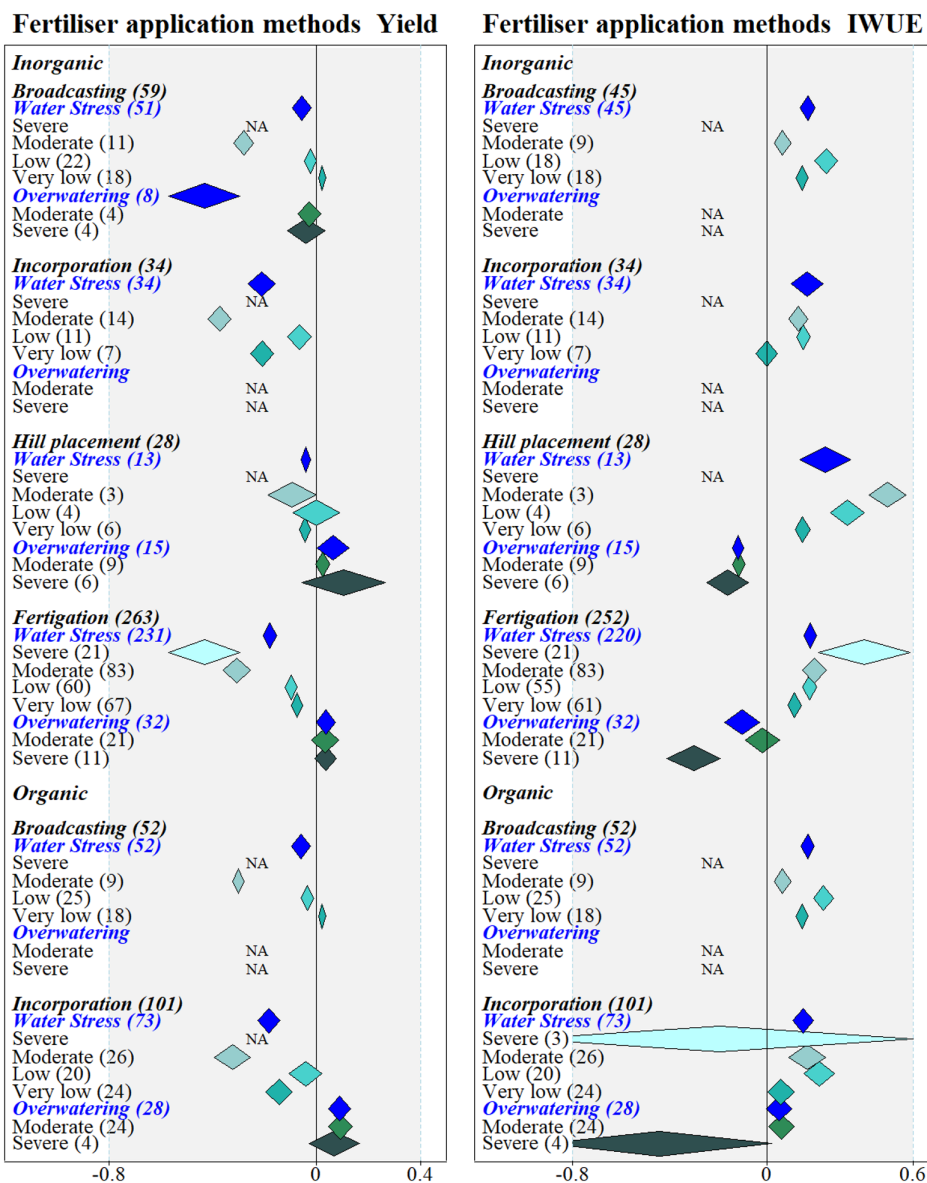


FIGURE 9 | Yield and IWUE response ratios for different fertiliser application methods. Blue diamonds represent summary effect sizes. Individual water stress and overwatering levels are displayed using sequential colour gradients from light to dark to reflect increasing treatment intensity. Values in parentheses are the number of observations.

across all crop types. Leafy vegetables adjust stomatal conductance to minimise water loss, despite increased evaporative demand (Petrik et al. 2023).

3.4.3 | Case of Weed, Pest and Disease Control

Similarly, water stress reduced yield across all crop types, although bulb crops showed the smallest reductions under weed control (−10%) and pest control (−7%). Root crops showed no significant yield difference from full irrigation, specifically under manual weeding and disease control. Under overwatering, leaf crops were the only exception, with a significant yield increase under manual weeding (+9%, $p = 0.021$) (Figure 10). Bulb resilience reflects storage organ physiology, whereby bulbs act as hydraulic capacitors, buffering short-term water deficits through

remobilisation of stored assimilates and water (Melchior and Steudle 1993). Manual weeding appears to preserve soil moisture by eliminating competitor transpiration, whereas disease control maintains root hydraulic conductivity (Zwieniecki et al. 2001). WUE increased most for leaf crops under disease control (+147%, $p < 0.001$) but was generally higher under water stress than under full irrigation across other control methods. However, the IWUE decreased for leaf crops with herbicide application (−31%, $p < 0.001$). The gain for leaf crops under disease control may reflect restored photosynthetic capacity combined with stress-induced stomatal restriction (Chakraborty and Newton 2011). The decline under herbicide application, on the other hand, is consistent with adverse effects of herbicide stress on stomatal conductance and photosynthetic efficiency, further intensified by restricted herbicide translocation under water stress (Singh et al. 2022).

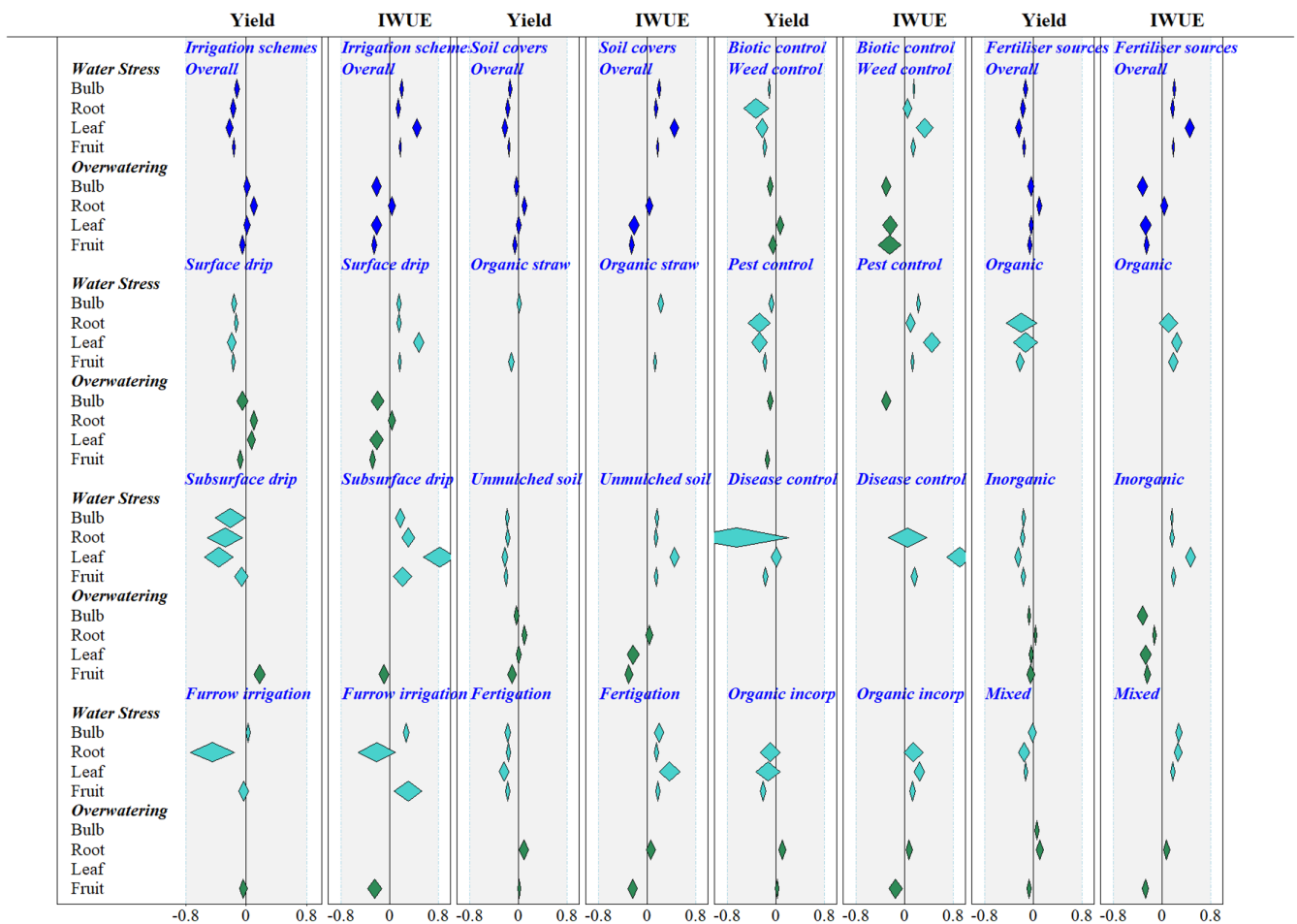


FIGURE 10 | Yield and IWUE response ratios for different crop types across all moderators: irrigation schemes, soil cover, biotic control (weed, pest and disease control), fertiliser sources, fertigation application methods and organic fertiliser incorporation. Blue diamonds represent summary effect sizes, whereas turquoise and green diamonds represent water stress and overwatering subcategories, respectively.

3.4.4 | Case of Fertiliser Sources and Application Methods

As observed across other management practices, yield decreased under water stress, except for bulb crops under mixed fertilisers (-1% , $p=0.696$) and leaf crops under organic sources (-12% , $p=0.226$), both of which were nonsignificant (Figure 10). IWUE exceeded full irrigation under water stress across all crop types, most prominently for leaf crops with inorganic fertilisers ($+61\%$, $p<0.001$) and for root crops with inorganic fertiliser incorporation ($+74\%$, $p<0.001$). Root crops were also the only crop type to show an IWUE increase under overwatering relative to full irrigation, with organic incorporation ($+8\%$, $p=0.005$). The high IWUE enhancement for root crops under inorganic fertiliser incorporation is consistent with deep nutrient placement matching root distribution patterns (Wu et al. 2022).

Together, these results demonstrate that bulb and root crops showed greater resilience to water stress when paired with appropriate management practices, whereas leaf crops achieved exceptional water use efficiency under optimal biotic stress control.

3.5 | Limitations and Implications

This meta-analysis did not fully address several factors that may affect crop responses to water stress, including soil texture, water source quality, irrigation frequency, crop growth stage, fertiliser application rates and cultivar-specific traits. Fertiliser sources were also classified broadly without accounting for specific NPK or C:N ratios, which may influence nutrient availability under water-limited conditions. Limited observations for pest and disease management restricted deeper interaction analysis with irrigation schemes. The long-term effects of water stress and fertilisation on yield stability and IWUE also remain under-explored. These limitations highlight key directions for future research: long-term field trials integrating irrigation management with tailored fertilisation strategies across diverse crop types, incorporating economic feasibility and environmental co-benefits to support adaptive vegetable production under variable water availability. Expanding research on synergies between biotic stress management and deficit irrigation could further reveal opportunities for resource-efficient intensification in water-limited environments.

4 | Conclusion

We studied the influence of agroecological practices on the yield and IWUE of irrigated vegetables using a global meta-analysis. Yield was negatively affected under water stress and overwatering compared to full irrigation, whereas IWUE responded inversely under water stress. Yield losses under water stress were approximately 25 times greater than those under overwatering. Irrigation amounts between 80% and 100% ETc provided the best trade-off, limiting yield losses (−7%) while maintaining a positive IWUE response (+12%). Only subsurface drip irrigation and mixed fertiliser sources showed significantly higher yields under overwatering than under full irrigation. Applying low to very low water stress most effectively optimised both yield and IWUE while minimising water wastage. Mixed fertilisers outperformed sole organic or inorganic sources under water stress, whereas subsurface drip irrigation and plastic or organic mulching emerged as the most resilient strategies, with 15%–26% yield advantages over furrow systems. Crop selection should prioritise bulb crops for drought tolerance, and root crops under manual weeding, avoiding herbicide use. Agroecological practices mainly underperformed conventional practices under water stress; but they outperformed under overwatering. In gravity-fed or resource-limited irrigation systems, where precise water control remains difficult to achieve, the resilience of agroecological practices over conventional practices remains particularly relevant, a point that does not diminish the priority given to water-saving efforts in agroecological management. Where labour constraints limit agroecological practices, carefully timed minimal chemical inputs combined with precise irrigation may offer an effective compromise.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Identified vegetable species.