frontiers in Agronomy

TYPE Review
PUBLISHED 05 March 2026
DOI 10.3389/fagro.2026.1785544

OPEN ACCESS

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RECEIVED 11 January 2026
REVISED 11 February 2026
ACCEPTED 16 February 2026
PUBLISHED 05 March 2026

CITATION
Ng'eno V, Barrera W Jr., Thine C, Mbuge DO, Obiero JP, Dalla Marta A and Verdi L (2026) A systematic review on the combined effects of deficit irrigation and soil amendment with super-absorbent polymer on crop yield and water productivity.
Front. Agron. 8:1785544.
doi: 10.3389/fagro.2026.1785544

A systematic review on the combined effects of deficit irrigation and soil amendment with super-absorbent polymer on crop yield and water productivity

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Deficit irrigation (DI) and soil amendment with super-absorbent polymer (SAP) are viable strategies to reduce agricultural water demand. This review paper aims to discuss the *status quo* of research studies on this topic focusing on their effects on yield and water productivity (WP). Publications were retrieved from Scopus® database and relevant studies used for the analysis were selected following the PRISMA protocol. Findings indicate that SAP effectively increased yield and WP, particularly under field conditions and various levels of DI. Soil type with high water holding capacity (e.g. clay) showed higher WP when SAP was added in the soil while minimal effect was observed in soil types with lower water retention capacity (e.g. sandy, sandy clay, and sandy loam). The amount of SAP applied varied by crop type but not by irrigation strategy. In conclusion, crop yield and WP is affected by the amount of SAP and DI with some crop- and soil-specific responses. To maximize SAP effectiveness, it is recommended to apply it directly within the plant rooting depth, considering also the specific crop type. Furthermore, future research should adopt systematic irrigation scheduling and appropriate irrigation regimes to enhance SAP and DI efficiency.

KEYWORDS
crop yield, deficit irrigation, soil amendment, super absorbent polymer, water productivity

1 Introduction

Crop production is highly dependent on irrigation. About 70% of all global freshwater usage is accounted for by irrigated agriculture, which is the biggest user of freshwater (Aivazidou et al., 2016). However, about 40% of the irrigated water is lost to the environment either through evaporation, deep percolation, or runoff (Jägermeyr et al., 2017). These reasons combined with climate change and the increasing pressure on water scarcity necessitates increasing crop water productivity (WP).

Water productivity is defined as the ratio of crop yield to the amount of water consumed by plants through evapotranspiration (ET_c). Various irrigation management practices, such as deficit irrigation (DI) and the use of soil conditioners like super-absorbent polymers (SAPs) have been employed to enhance WP and mitigate water loss from runoff and deep percolation.

Deficit irrigation is an irrigation strategy aimed at increasing crop WP (Abdalhi and Jia, 2018; Yang et al., 2022). It involves supplying crops with less irrigation water than what is required to achieve maximum evapotranspiration (ET_{max}) (English, 2002; Kiyan et al., 2022; Wale et al., 2022; Li et al., 2022). It is vital to understand how crop respond to water stress across phenology before implementing DI, which could be during specific growth phases i.e. regulated deficit irrigation, or the entire growing cycle i.e. standard deficit irrigation (Geerts and Raes, 2009). In addition, water retention capacity of soil types should also be taken into consideration when implementing DI.

SAPs have been used in agriculture primarily for soil water retention, positively altering the physical and chemical properties of soil by enhancing water absorption and release. They are characterized by hydrophilic networks that are able to absorb and retain large amount of water about thousand times their original weight. The retained water is released to the soil when the osmotic pressure in the root cells is lower than the surrounding soil medium (Kong et al., 2019). SAP reduce soil surface temperature during the day, enhancing soil moisture levels and fostering a healthier microbial community structure (Han et al., 2013). In addition, SAPs play a crucial role in various aspects of plant growth. They contribute to crop water conservation, drought resistance and fertilizer retention, increasing yield per unit area (Bai et al., 2010; Hazem and Ippolito, 2021). SAPs also promote stable crop growth by enhancing plant height, leaf area index, and increasing dry matter production (Yang et al., 2020).

Research on DI and SAP have been growing in pursuit of adaptation strategies to reduce water use and maximize crop WP. Given the extensive information available in the literature, this review paper aims to provide a comprehensive analysis of the effects of DI and SAP on crop yield and WP, focusing on different DI categories, SAP application levels, and their uses across various crops and soil types.

2 Methods and data

2.1 Selection of papers for analysis

Articles were retrieved in Scopus® using the keyword string "super-absorbent polymer" AND "deficit irrigation" with no search restrictions applied to maximize the inclusion of relevant studies. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol was followed to screen the articles (Hansen et al., 2022; Page et al., 2021; Hunter et al., 1982). The first level of screening was done by reading the title and abstract. The articles were selected based on the following inclusion criteria: (a) focus: studies must focus on the effects of DI and SAP on crop yield and WP; (b) study design and objectives: well-defined objectives, methodology and studies that reported experimental results; (c) outcomes measures: empirical data of pairwise comparison of the control versus treatment groups i.e. SAP levels vs. no SAP and DI levels vs. FI; and (d) language and accessibility: studies should be peer-reviewed and published in English. An automation tool (Mendeley) was used to store the selected papers and to screen for duplicate papers. Finally, a total of 306 articles were retrieved, but only 59 articles were considered for the review after rigorous screening (Figure 1; Supplementary Material).

The selected papers were analyzed by considering: (a) soil characteristics such as the soil type and soil moisture content at field capacity ($cm^3\ cm^{-3}$) or permanent wilting point ($cm^3\ cm^{-3}$); (b) study geographical location categorized into regions such as Asia, Europe, Middle East and North Africa, and South America; (3) SAP levels ($kg\ ha^{-1}$) and number of replications; (4) crop category such as cereals, fruits, legumes and oil seeds, roots and tubers, vegetables, and others (industrial crops); (5) crop performance data such as yield ($ton\ ha^{-1}$) and WP ($kg\ m^{-3}$); (6) irrigation methods, irrigation strategies, and replications; and (7) growing environment either field or greenhouse conditions.

2.2 Data extraction

From the final papers selected for review, the quantitative data were collected and organized in a spreadsheet database. Data were treated as individual data points for studies that reported multiple locations, years, or seasonal variations.

In our systematic review, some studies did not report all the quantitative data necessary to analyze the combined effects of SAP and irrigation, which leads to differences in sample sizes depending on the variables analyzed. To manage missing data, we ensured that we only included studies that reported the required variables for each specific analysis. We clearly documented which datasets were used in each case in Supplementary Material.

2.3 Characteristics of the selected papers

Approximately 21% of the articles selected had no rainfall nor irrigation data but had values of yield and WP. Treatment under rainfed was classified as no irrigation while those under irrigated were categorized depending on the percentage of water applied relative to full irrigation (FI) (100% ET_c). The DI categories were as follows: 71–85% of FI, 56–70% of FI, 41–55% of FI; 26–40% of FI, and 10–25% of FI. Some studies did not report WP but the total amount of crop water use throughout the growing period including rainfall (mm) and irrigation (mm) in various SAP and DI treatments was reported. Thus, WP was estimated by dividing crop yield by the total water use (rainfall + irrigation) if irrigated, otherwise only by rainfall if no irrigation was documented (Equation 1). We acknowledge that this estimation assumes uniform water use across the growing period and may not capture variability in crop response or temporal water availability.

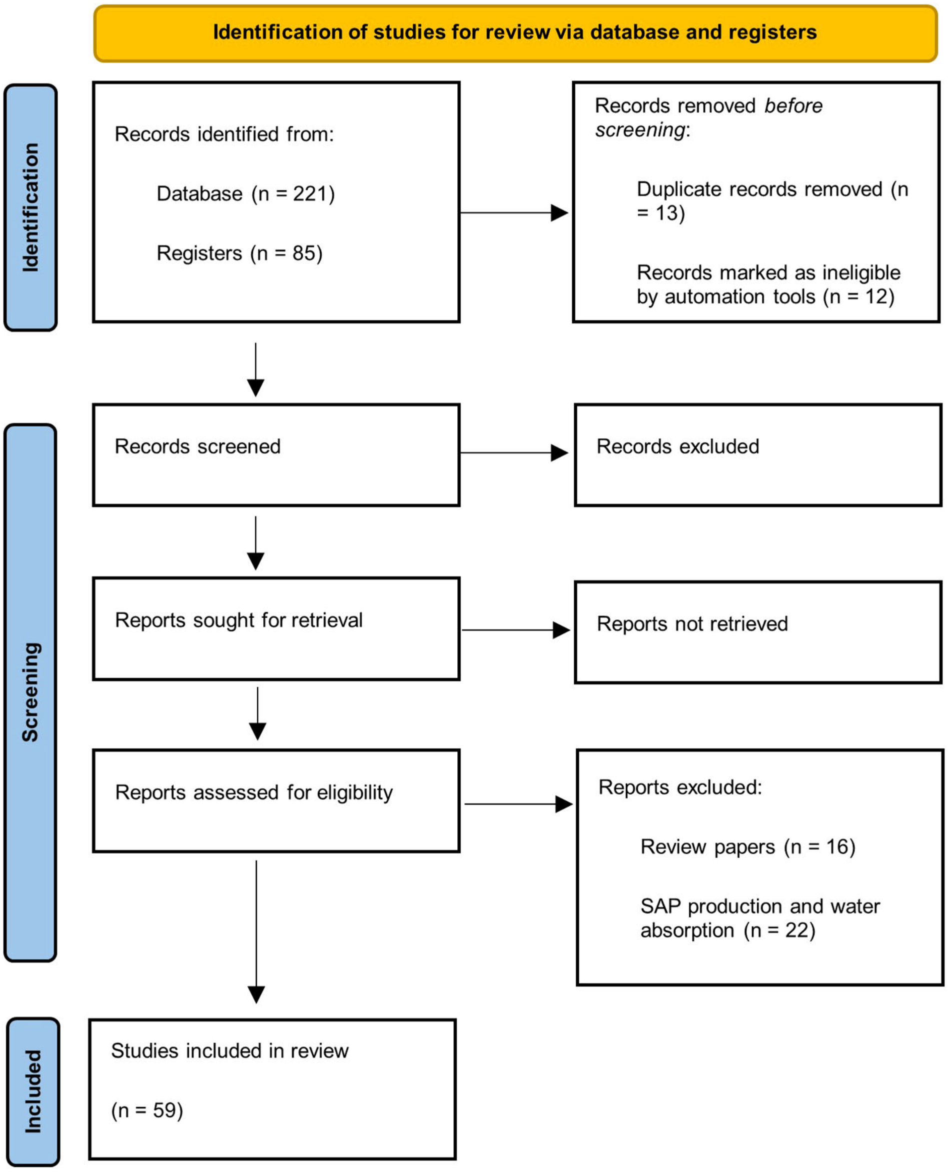

FIGURE 1
Screening process used in selecting papers for review following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol (Page et al., 2021).

$$WP\ (kg\ m^{-3}) = \frac{Yield\ (kg\ ha^{-1})}{Total\ water\ applied\ (mm)x\ 10} \tag{1}$$

The selected papers for review reported six irrigation methods. About half of the papers had no defined methods of irrigation (48%), while some studies used surface drip (35%) and the least being sub-surface drip and flood irrigation (2%). Other irrigation methods include furrow (5%), sprinkler (5%), and check basin (3%). Standard deficit irrigation (SDI) was the most frequently reported DI strategy in the reviewed papers (76%) followed by regulated deficit irrigation (RDI) (18%), and partial root-zone drying (PRD) (5%). For each DI method, crop yield and WP were reported against the levels of SAP used in the study. Otherwise, they were reported separately for some studies that did not report combined DI and SAP application.

A total of 11 soil types were identified from the selected studies with only 5% of the papers that did not specify soil types based on the USDA soil textural triangle. Sandy loam soil was the most frequently reported soil type (36%) while and sandy clay loam (2%) was the least common. Other soil types include loam (14%), sandy (11%), clay loam (10%), silty clay loam (5%), silty loam (5%), clay (3%), sandy clay (3%), silty loam (3%), and silty clay (3%).

On the other hand, SAP treatment in different crop types across various soil textural classes was recorded according to the weight proportions they were amended in the soil per hectare (kg ha^{-1}). About 10% of the papers had no quantification of SAP but still reported yield and WP. These papers were included in the review because they provided relevant data other than SAP. However, they were not used in the quantitative analysis of SAP categories and were broadly classified as "without SAP". For papers where SAP application was quantified, the highest and lowest amounts applied were recorded and categorized into the following ranges: without SAP (control), <50 kg ha^{-1}, 51–100 kg ha^{-1}, 101–200 kg ha^{-1}, 201–

400 kg ha^{-1}, 401–800 kg ha^{-1} and >800 kg ha^{-1}. The frequency of these SAP categories in the selected papers for review were 55%, 16%, 13%, 6%, 6%, and 3%, respectively. The categorization was done to determine the best range for SAP application for a specific crop type across irrigation strategies.

2.4 Data analysis

The data was analyzed using descriptive statistics. A two-way analysis of variance (ANOVA) was used to statistically determine the effect of SAP and DI on yield and WP under different irrigation regimes, soil types, and crop types followed by *post hoc* analysis at $\alpha = 0.05$ using Tukey's Honest Significant Difference (HSD). Before analysis, all observations were standardized to common units and response variables. The primary aim of the analysis was to evaluate differences among predefined categorical factors, e.g., deficit irrigation categories, SAP application levels, and experimental conditions, rather than to estimate an overall pooled effect size across studies. However, we acknowledged that variability among studies may introduce heterogeneity. The results are interpreted as comparative patterns rather than absolute global estimates, e.g. effect size. Statistical tests were performed using open-source R software. Further, the library(ggplot2) in R was used for data visualizations (R Core Team, 2021).

3 Results and discussion

3.1 Global distribution of selected papers for review

The global distribution of papers selected for the review is presented in Figure 2. About 51% of the papers were from the Middle East and North Africa, comprising Iran (n=14), Egypt (n=8), Iraq (n=2), Pakistan (n=2), Lebanon (n=1), Morocco (n=1), Saudi Arabia (n=1), and Turkey (n=1). The papers from Asia comprised about 37% which include India (n=9), China (n=8), and Mongolia (n=5). A small percentage were from Europe (8%), comprising Italy (n=2), Czech Republic (n=1), Russia (n=1), and Slovakia (n=1). Similarly, papers from South America were the least represented (3%) with only entry from Brazil (n=2). In these regions, different crops were grown in various soil types and environments with varying levels of SAP amendments. Therefore, a general comparison on yield and WP due to SAP and irrigation regimes in various crop types was done. Our findings align with Starovoitova et al. (2019), who investigated the effects of SAP on potato yield and reported widespread SAP use in crop production across countries such as Russia, China, USA, Canada, India, Italy, Iran, Poland, and Turkey among others. The results of our review highlight the growing interest and recognition within the global scientific community regarding the study of DI and SAP as soil amendment. Therefore, DI and SAP are increasingly being considered as effective strategies to enhance soil moisture, improve water efficiency, and sustain crop productivity, offering promising solutions for resilient agroecosystems (Rajanna et al., 2022; Zheng et al., 2023).

3.2 Main effect of DI and SAP on yield and WP

The main effect of SAP and DI on yield and WP is presented in Figure 3, generated using 336 data entries from 29 studies. Yield and WP varied across different irrigation strategies. Super-absorbent polymer application significantly improved WP under DI condition, surpassing the performance of FI in without SAP treatment. In addition, SAP increased yield under all irrigation strategies with FI consistently showing higher yields than DI

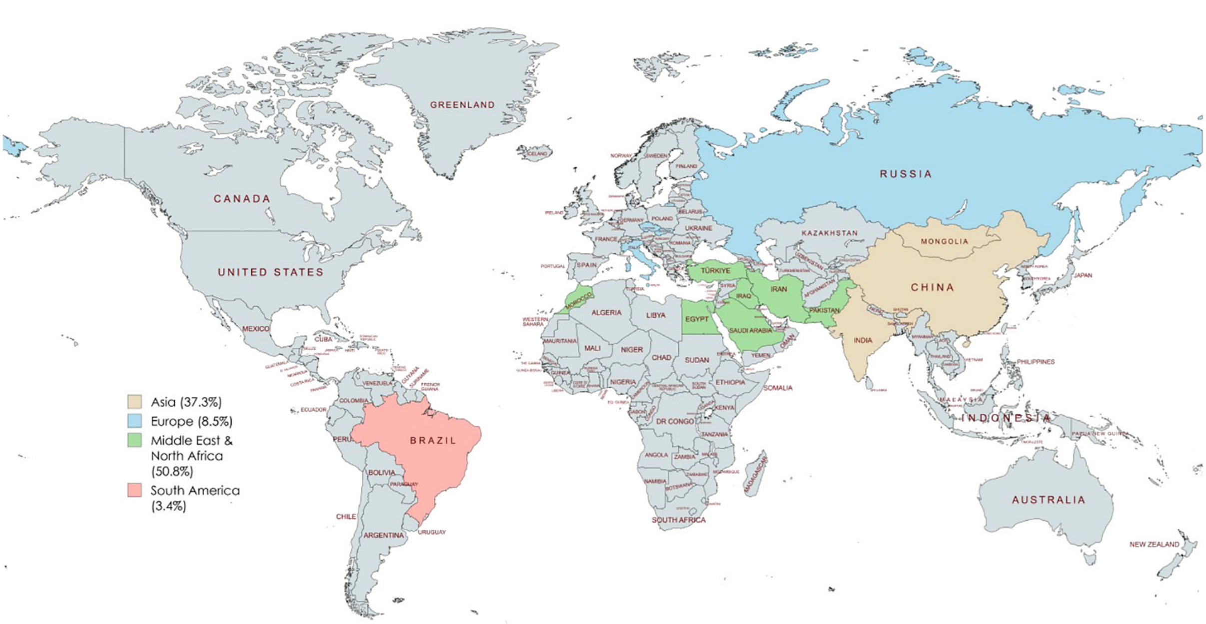

FIGURE 2
Global distribution of research papers used for review. Generated using MapChart (https://www.mapchart.net/).

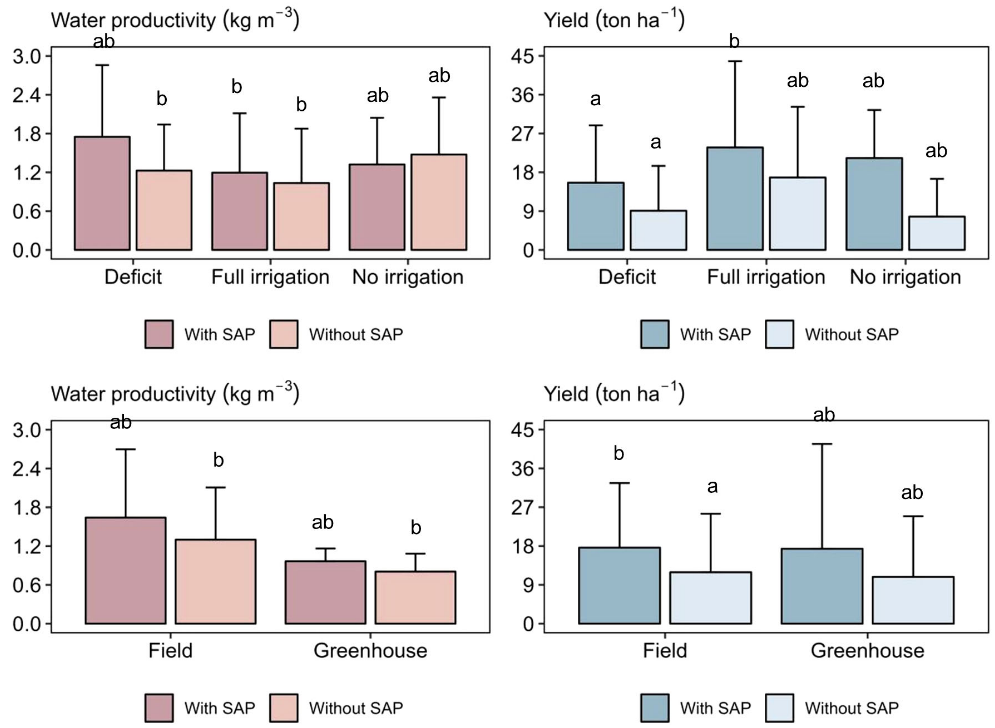

FIGURE 3
Main effect of super absorbent polymer (SAP) on the water productivity (WP) (kg m^{-3}) and yield (ton ha^{-1}) of crops under various irrigation strategies and in field and greenhouse conditions. The error bars represent standard deviation. Categories with different letters are statistically significant.

regardless of SAP application. This suggests that SAP is particularly effective when water is limited. These findings align with previous studies demonstrating positive impact of SAP on yield (Rajanna et al., 2022; Starovoitova et al., 2019; Zinivand et al., 2020). Similarly, Zheng et al. (2023) reported that SAP application increased yield and WP by an average of 12.8% and 17.2%, respectively with the rate of increase dependent on crop type.

Water productivity was higher under field conditions compared to greenhouse farming regardless of SAP application (Figure 3). This finding corresponds to Zheng et al. (2023) who reported higher WP in the field with no irrigation than under irrigated conditions in the greenhouse at 18.3% and 14.8% respectively. The WP was 1.64 kg m^{-3} and 1.3 kg m^{-3} under field conditions in with and without SAP treatments, respectively. Under greenhouse conditions, WP was 0.90 kg m^{-3} in with SAP treatment and 0.81 kg m^{-3} in without SAP. These results highlight the positive effect of SAP on WP in both environments, with a more pronounced positive effect under field conditions. The difference in magnitude could be attributed to the larger sample size in the field where 81% of the experiments were conducted compared to 19% in the greenhouse. There was no significant difference in yield between field and greenhouse conditions within each SAP treatment. The SAP application under field and greenhouse conditions both resulted in higher yield. The yield under field conditions was 17.7 ton ha^{-1}- and 11.9 ton ha^{-1} in with and without SAP treatments, respectively. Similarly, under greenhouse conditions, the yield was 17.4 ton ha^{-1} in with SAP treatment and 10.6 ton ha^{-1} in without SAP. Overall, our results suggest that SAP is more effective in increasing yield under field conditions as also observed by Zheng et al. (2023).

3.3 SAP effect on yield and WP under various irrigation regimes

The effect of SAP on yield and WP under various levels of DI is presented in Figure 4, generated using 247 data entries from 26 studies. The highest WP in with SAP treatment was at 26–40% DI (2.0 kg m^{-3}) and the lowest at FI (1.2 kg m^{-3}). In without SAP treatment, the highest WP was under no irrigation and 71–85% DI (1.5 kg m^{-3}) and the lowest under FI and 56–70% DI (1.0 kg m^{-3}). Overall, SAP had a significant impact on WP across all irrigation regimes except in no irrigation where WP was higher without SAP compared to with SAP. Similar results were obtained by Fallahi (2015) where cotton under deficit and SAP increased water use efficiency by 14% compared to zero SAP.

A general trend of decreasing yield was observed as DI levels decreased, with higher yields observed in with SAP treatment than without SAP. The highest yield in with SAP treatment was 21.0 ton ha^{-1} under FI and no irrigation while the lowest at 10–25% DI (2.5 ton ha^{-1}). In without SAP treatment, the yield was decreased compared to with SAP with the highest reduction under FI (15.1 ton ha^{-1}) and the lowest at 26–40% DI (2.6 ton ha^{-1}). These results highlight the higher effectiveness of SAP under water-limiting conditions compared to conditions where water is available to fully satisfy crop water requirements. Therefore, yield under no irrigation could be maximized with the addition of SAP. When SAP is applied, the yield at DI levels (41–85%) was not significantly different from that of FI without SAP. This was highly supported by Shweta et al. (2022) in the study of wheat crop response to irrigation scheduling and superabsorbent polymer. The results clearly

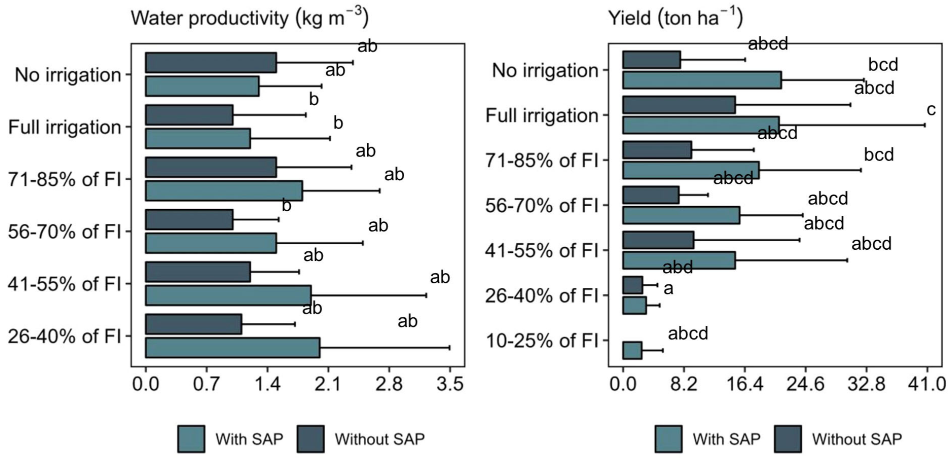

FIGURE 4
Effect of super absorbent polymer (SAP) on crop water productivity (WP) (kg m^{-3}) and yield (ton ha^{-1}) under various irrigation regimes. The error bars represent standard deviation. Categories with different letters are statistically significant.

demonstrate that DI improves WP across irrigation regimes, with only slight yield reductions due to reduced irrigation. However, SAP mitigates the absence of irrigation under rainfed and reduced irrigation under DI conditions due to its water retention capacity thus, offsetting yield losses.

3.4 Crop-specific effect of SAP on yield and WP

The effect of SAP on yield and WP across crop types is presented in Figure 5, generated using 292 data entries from 32 studies. In general, higher WP was observed with SAP application though the mean difference was only significant in cereals, which exhibited higher WP with SAP treatment than without SAP. In addition, cereals with SAP showed significantly higher WP than vegetables (both with and without SAP), as well as legumes and oil seeds without SAP. This suggests that SAP has a more pronounced effect on WP in cereals or cereals are more responsive to SAP treatment compared to other crop types. The WP in with SAP treatment was highest (2.0 kg m^{-3}) in cereals while the lowest was in roots and tubers (1.1 kg m^{-3}). In the absence of SAP, fruits exhibited the highest WP (1.5 kg m^{-3}) while roots and tubers remained the lowest (0.8 kg m^{-3}). This suggests a crop-specific response of SAP in terms of WP. Overall, our findings align with general results indicating that SAP increases WP (Zeineldin and Al-Molhim, 2021).

The yield varied significantly across different crop types, showing a general trend of higher yields in with SAP treatment compared to without SAP. Regardless of SAP application, the fresh yield categories such as fruits, vegetables, roots and tubers, and sugarcane had the highest yields compared to dry yield categories such as cereals and legumes and oils seeds. In with SAP treatment, the fresh yield was highest in sugarcane (36 ton ha^{-1}) followed by vegetables (28.6 ton ha^{-1}), roots and tubers (23.1 ton ha^{-1}), and fruits (19.1 ton ha^{-1}). Likewise, dry yield in cereals was 10.4 ton ha^{-1}- and 5.4 ton ha^{-1} in legumes and oil seeds. The fresh yield of

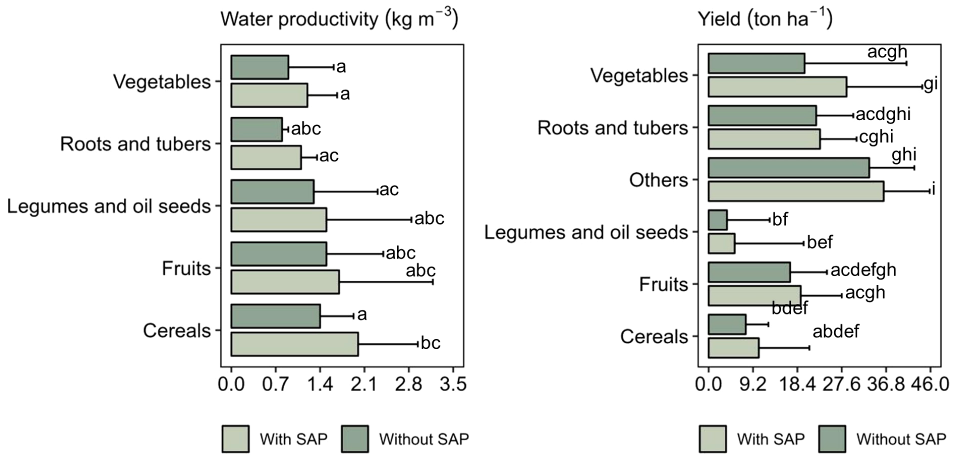

FIGURE 5
Effect of super absorbent polymer (SAP) on the water productivity (WP) (kg m^{-3}) and yield (ton ha^{-1}) of various crop types. The error bars represent standard deviation. Categories with different letters are statistically significant.

sugarcane remained the highest in without SAP (33.3 ton ha^{-1}) treatment followed by roots and tubers (22.3 ton ha^{-1}), vegetables (19.9 ton ha^{-1}), and fruits (16.9 ton ha^{-1}). In addition, the yield was the lowest in cereals (7.7 ton ha^{-1}) and legumes and oil seeds (3.8 ton ha^{-1}).

The interaction between SAP and crop types highlighted variations in yield. However, the mean difference observed between with and without SAP treatments was not significant considering each crop type. Nonetheless, when SAP is applied, cereals showed a significantly lower yield with all crop types except legumes and oil seeds. Similarly, in the absence of SAP, cereals yield remained significantly lower with all the crop types except fruits and legumes and oil seeds. Fruits yields in with and without SAP were significantly lower compared to sugarcane and vegetables with SAP, as well as legumes and oil seeds both in with and without SAP treatments. Legumes and oil seeds yield, regardless of SAP application, differed significantly from all other crop types both in with and without SAP treatments except cereals. Finally, the sugarcane yield with SAP treatment showed significant difference with roots and tubers in with SAP and vegetables in without SAP.

3.5 SAP effect on yield and WP across various soil types

The effect of SAP on yield and WP across various soil types is presented in Figure 6, generated using 280 data entries from 30 studies. There was a significant difference in WP between with and without SAP treatments across various soil types. However, *post-hoc* analysis revealed no significant differences in WP within each soil type when comparing with and without SAP. Nonetheless, sandy soil in with SAP treatment (2.5 kg m^{-3}) exhibited significantly higher WP than clay soil (0.60–1.2 kg m^{-3}), regardless of SAP application. In addition, sandy soil in with SAP showed significantly higher WP than sandy clay soil both in with (1.1 kg m^{-3}) and without (0.55 kg m^{-3}) SAP treatments, as well as sandy loam (1.2 kg m^{-3}) and silty loam (0.9 kg m^{-3}) without SAP. The results highlight the positive effect of SAP on enhancing soil water-holding capacity, with greater benefits observed in soils with lower water-holding capacity (e.g. sandy) than soils with higher water-holding capacity (e.g. clay).

There was a significant yield difference in with SAP treatment and soil types (Figure 6). However, *post-hoc* analysis revealed no

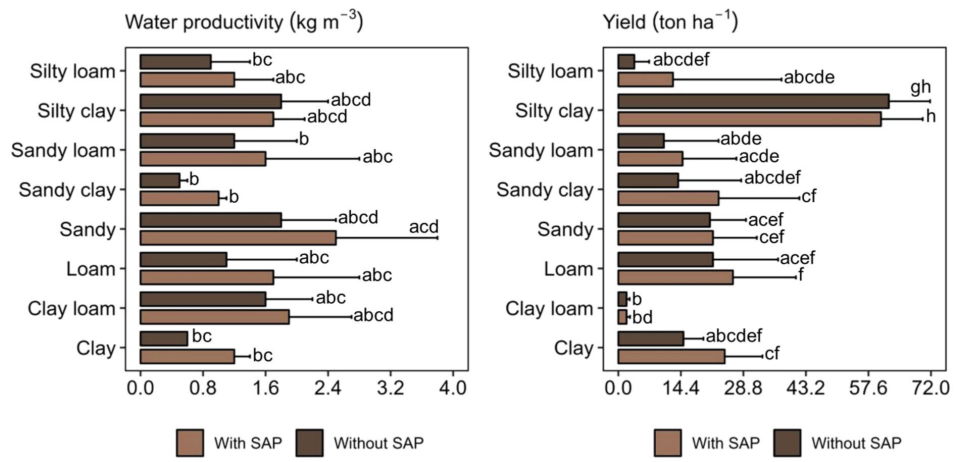

FIGURE 6
Effect of super absorbent polymer (SAP) on water productivity (WP) (kg m^{-3}) and yield (ton ha^{-1}) of crops under various soil types. The error bars represent standard deviation. Categories with different letters are statistically significant.

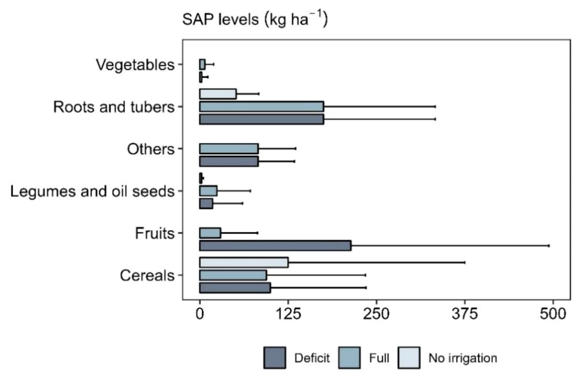

FIGURE 7
Super-absorbent polymer (SAP) levels (kg ha^{-1}) of various crops under different irrigation strategies. The error bars represent standard deviation. Categories with different letters are statistically significant.

significant differences in yield within each soil type when comparing SAP application. Nonetheless, significant variations were observed when comparing yield in various soil types across SAP treatments. The highest yield was observed in silty clay both in with (60.5 ton ha^{-1}) and without (62.5 ton ha^{-1}) SAP while the lowest was in clay loam (1.9 ton ha^{-1}). The yield in silty clay both in with and without SAP was significantly higher than all other soil types, while the opposite was true for clay loam. In literature, it was reported that SAP increases yield and WP across all the soil types. The parameters only differs dependent on the water holding capacity of the soil where soil with high water holding capacity has high yield and high WP vis-a -vis those with low water holding capacity (Dehkordi, 2016; Zheng et al., 2023).

3.6 SAP level of crops across irrigation strategies

The SAP level of crops across irrigation strategies is presented in Figure 7, generated using 336 data entries from 29 studies. There was a significant difference on SAP levels across crop types. However, considering each crop type, the variations observed in SAP levels across irrigation strategies were not significant. Nonetheless, under DI, cereals had significantly higher SAP levels than legumes and oil seeds. On the other hand, legumes and oil seeds had lower SAP levels than roots and tubers both in DI and FI. In general, the results show that SAP levels differ among crop types but exhibit less variation across irrigation strategies, suggesting that crop characteristics are prioritized more over irrigation strategies when applying SAP.

4 Conclusions

This systematic review analyzed the combined effects of DI and SAP on crop yield and WP. Deficit irrigation increased WP compared to FI and no irrigation. Crop yield was slightly reduced under DI but the yield losses can be mitigated by the application of SAP. There was no significant difference in yield and WP regardless of growing environment (greenhouse and field) and SAP application. Considering various levels of DI, high variability in WP and yield was observed in with SAP treatment compared to without SAP. At lower DI levels, a significant increase in yield was achieved when SAP is applied. Super-absorbent polymer also induced crop- and soil type-specific response on yield and WP such that cereals and soil with low water holding capacity were more responsive to SAP application than other crop types and soil classifications. Therefore, yield and WP are affected by different proportions of SAP and different DI levels on various soil classifications and crop types.

This review paper also demonstrated that SAP are effective in enhancing soil water retention and release. However, it is worth noting that SAP when use in large scale is quite expensive and so it is not economical to use in areas with high amount of rainfall that could satisfy crop water requirements. The findings also indicated that the amount of SAP applied was dependent on the area of land under cultivation. Therefore, it is recommended that SAP application be targeted directly to the plant rooting depth and tailored to the specific crop type being planted. Lastly, systematic irrigation scheduling criteria and appropriate irrigation regimes should be adopted in future investigations if SAP is to be applied in conjunction with DI.

Finally, it is important to note that the results presented in this review paper are highly dependent on the data from the selected studies. We directly reported data without extensive statistical assessment which may overemphasize findings from studies with larger sample sizes or those with extreme results, leading to potential bias in interpretation. Therefore, caution should be exercised when interpreting these findings and further studies like meta-analyses could be done to address these gaps and inconsistencies. In addition, the results may vary if updated data are incorporated in future investigations. Moreover, the quantity of SAP used in some studies was not clearly defined or quantified, making it challenging to determine its specific effects on certain crop parameters. Nonetheless, our findings provide valuable insights into the combined effects of DI and SAP on crop yield and WP. These insights serve as important decision-support tools for farmers, policymakers, and other stakeholders emphasizing the role of DI and SAP in reducing water consumption without compromising yield.

Author contributions

VN: Conceptualization, Data curation, Formal analysis, Writing – original draft. WB: Data curation, Formal analysis, Validation, Writing – original draft. CT: Writing – review & editing. DM: Conceptualization, Writing – review & editing. JO: Writing – review & editing. AD: Conceptualization, Formal analysis, Supervision, Validation, Writing – review & editing. LV: Conceptualization, Formal Analysis, Validation, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The authors declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2026.1785544/full#supplementary-material

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