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Potential of Soil Conditioners to Mitigate Deficit Irrigation Impacts on Agricultural Crops: A Review

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Abstract
In light of the current water scarcity, one strategy for reducing water consumption in irrigated agriculture is to reduce the amount of irrigation water compared to full crop irrigation or in other words deficit irrigation. Deficit irrigation management may be a critical issue due to climate change. Incorporation of different soil conditioners can improve soil hydro-physical properties and mitigate negative effects in water-stressed conditions. Recent review articles either addressed specific crop behavior under water deficit or covered a single type of soil conditioners. This manuscript represents an inclusive review providing insight into deficit irrigation methods incorporated with different soil conditioners. Crop response to deficit irrigation is discussed in the light of some mathematical models. Three main types of soil conditioners are covered: bentonite, biochar, and super-absorbent polymers. Mechanisms associated with effects of each conditioner to enhance soil water retention is highlighted as well. Previous study findings were discussed comparatively and future prospective, recommendations and challenges were addressed.

Keywords Water use efficiency · Deficit irrigation · Partial root zone drying · Soil conditioners · Biochar · Hydrogel · Bentonite

1 Introduction

The agricultural sector is being challenged to meet the ever-increasing population's nutritional demands. The increasing demand for food represents a burden on natural resources such as water. Despite water is the most abundant substance on the planet with about 70% of the earth's surface covered by water, only about 2.5% is freshwater. Generally, irrigated

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agriculture is the largest freshwater consumer and accounts for approximately 70–85% of the total freshwater use (Dalezios et al. 2018; Shu et al. 2021).

Egypt is facing severe water shortages; the country has an average freshwater availability of less than 600 m^3 per capita per year, which is 40% below the internationally accepted threshold for water scarcity. Further, the annual available per capita of freshwater in Egypt is anticipated to decrease to about 350 m^3 by 2050 (El-Agroudy et al. 2016; Geriesh et al. 2023). Egypt is also characterized by arid climate with annual precipitation of 5-200 mm. This amount of precipitation is characterized by high spatial and temporal variability and as a result, cannot be counted as a reliable source of water (Gado and El-Agha 2020).

While the total available water in Egypt is 58.8 billion cubic meters per year (BCM/year), the water required for different sectors accounts for 78.5 BCM/year. This means a shortage of 20 BCM/year between the available and required water, this shortage will reach 26 BCM in 2050. The current shortage is compensated by desalination of agricultural drainage water and unauthorized withdrawal of groundwater, which consequently decreases the ground water quality and represents a hazard to the ecosystem. Since the main consumer of fresh water in Egypt is irrigated agriculture with about 62.3 BCM/year, increasing water use efficiency in agriculture is crucial (Eltarabily 2022; Ouda et al. 2022).

Water use efficiency (WUE) also termed as water productivity is defined as the ratio between dry matter production and the amount of water consumed by plants in Evapotranspiration (ETc), or in other words WUE is the biomass or grain produced per unit of water used by the crop. It is a measure of how efficiently a plant uses water.

$$WUE = \frac{Y}{ET_c} \tag{1}$$

Where Y is the yield (kg) and ETc is the seasonal crop water use or evapotranspiration (m^3).

Although irrigation is particularly effective in overcoming drought, irrigation itself may not achieve the highest WUE. Maximizing crop productivity was the primary goal of agricultural research in the twentieth century; but recently the emphasis has turned to optimizing use of limited water resources. When the area under irrigation is constrained by limited water availability, the economic returns of water will be maximized by reducing the depth of water applied and increasing the area of land under irrigation (Alotaibi et al. 2023).

Several water conservation practices have significantly contributed to the improvement in WUE by reducing the amount of water used in evapotranspiration (ETc), deep percolation and runoff. Deficit irrigation (DI), applying less water than crop evapotranspiration, can improve WUE by maximizing crop yields per amount of water consumed. Incorporation of soil conditioners with DI practices to maintain soil moisture and increase soil water holding capacity is one of the promising solutions for water conservation.

Crop growth, yield and WUE of subtropical mango under DI was reviewed by Zuazo et al. (2021). The effect of DI on open-field and greenhouse tomato was discussed by Chand et al. (2021) and Mukherjee et al. (2023). Management of maize production under water-limited conditions has been investigated by Rudnick et al. (2019). Adaptation of ornamental plants under DI conditions was reviewed by Sánchez-Blanco et al. (2019) and Giordano et al. (2021). Effects of DI on alfalfa production was analyzed by Li et al. (2023).

With respect to latest review articles on soil conditioners, Kaur et al. (2023) discussed the application of hydrogels in agriculture. Hydrogel characteristics, water absorption, release mechanisms, and current and future use have been discussed. Liu et al. (2022) focused on the preparation methods of hydrogels, and their application in agriculture. Borah et al. (2022) studied Physical and chemical properties of bentonite and its application in different sectors. Premalatha et al. (2023) summarized the effect of biochar on soil properties, crop growth and its remediation potential in heavy metal contaminated soils. Zhao et al. (2022) reviewed recent advances of biochar as soil amendment focusing on soil properties and nutrients use efficiency. The potential ecological risks of biochar were also reviewed.

Recent review articles either considered specific crop behavior under DI conditions or covered single type of soil conditioners. However, an inclusive review covering different categories of DI and integrating different soil conditioners with DI is lacking. This review aims at clarifying the interactive effects of soil conditioners and DI on crop yields, water use efficiency and soil hydro-physical properties. The objectives of this review are: (1) to provide insight into different DI practices, (2) to report the latest research results on DI strategies, and (3) to investigate different types of soil conditioners integrated with DI to mitigate crop water stress and enhance soil hydro-physical properties.

2 Crop Water Production Function

The relationship of crop yield (Y) response to varying levels of irrigation water is described by crop water production functions. With increasing the amount of irrigation water, revenue (crop productivity) increases gradually as linear function until it reaches a certain point, and the curve takes the form of quadratic function. This means that the increase in irrigation water is not necessarily matched by an increase in production. Rather, excessive irrigation may lead to poor soil properties as waterlogging, poor aeration and consequently, a decrease in production (Cao et al. 2021).

Profit per unit of land is represented by the difference between the cost and revenue curves (Fig. 1). Total production costs are represented by linear function and begins at an intercept with the vertical axis. The intercept is associated with all fixed costs of production. The slope represents variable costs of production (energy, labor, and costs associated with irrigation) and rises when increasing the amount of applied water. The upper limit of the cost function is the design capacity point W_o, which represents the maximum water delivery capacity of the system.

W_m represents the applied water level at which yields are maximized. If more water is used, profit will be reduced as the cost and revenue curves converge. In conventional irrigation, water is always applied to W_m as full irrigation requirements. Reducing irrigation water below W_m will initially result in greater profit as variable costs decline faster than revenues. Maximum economic efficiency occurs at the point where the slope of the cost function equals the slope of the revenue curve (shown as point W_1 in Fig. 1). That point will always be to the left of the maximum yield.

As water use is reduced further, a point will be reached (W_e) where the net income will just equal the net income at maximum yield (W_m). In the range between W_m and W_e, deficit irrigation will be more profitable than full irrigation (Sapino et al. 2022). When water is limited, deficit irrigation might be applied to save water for irrigation of additional land. It is also possible to irrigate in smaller quantities to reduce costs and increase WUE.

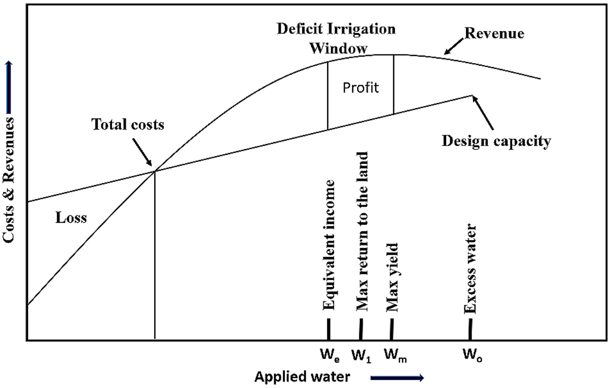

Fig. 1 The revenue and cost curves in proportion to irrigation water

3 Deficit Irrigation

Deficit irrigation (DI) is defined as an irrigation practice in which crops are irrigated with an amount of water below the optimal irrigation depth for plant growth and productivity or evapotranspiration (ETc). In DI plants are intentionally exposed to a certain level of water stress, which may cause a decrease in crop production, but in the long term, considerable water saving may be achieved (Kamali et al. 2022; El-Nashar and Elyamany 2023). Water saved by deficit irrigation may be used to irrigate additional land where water is the limiting factor. DI aims at enhancing WUE either by reducing the amount of irrigation water in each irrigation event or by eliminating irrigation events in periods when irrigation is less productive (Mehrazar et al. 2020; Li et al. 2022).

3.1 Crop Response to Deficit Irrigation

The water stress to which the crop is exposed is expressed by the decrease in evapotranspiration compared to optimal evapotranspiration conditions and can be expressed as follows:

$$CWSI = \left(1 - \frac{ET_a}{ET_m}\right) \tag{2}$$

Where CWSI is crop water stress index, ET_a and ET_m are the actual and maximum evapotranspiration.

To quantify the crop yield response to water deficit, Eq. 3 is used. This approach proposes that relative reduction in evapotranspiration (water stress) will result in a corresponding reduction in crop yield. Moreover, production factors other than water such as sunlight, nutrients, etc. are assumed to be at the optimum level. Water production function can be applied to all agricultural crops, i.e., trees, vines and herbal plants and has shown a remarkable validity (Smith and Steduto 2012).

The yield response to ET rates is expressed as:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_m}\right) \tag{3}$$

Where Y_a and Y_m are the actual and maximum crop yields and K_y is the yield response factor. Substituting in Eq. 3, (K_y) is ratio of relative yield reduction to relative evapotranspiration deficit and represents the crop yield reduction resulting from reduced evapotranspiration. Values for ky > 1 means that crop is very sensitive to water deficit, it is subjected to significant yield reduction under water stress conditions. Values for ky < 1 indicates crop tolerance to water stress, exhibiting lower yield reduction with reduced water. When K_y =1, yield reduction is directly proportional to reduced water application.

K_y values are crop specific and vary with the growth stage throughout the growing season. The same water deficit levels throughout the growing season affected crops differently. Under the same levels of ET deficit groundnut, cotton, and soybean (where $K_y < 1$) will result in smaller yield reduction compared to banana, maize, and sugarcane ($K_y > 1$). K_y of maize crop varied greatly depending on the growth stage. Flowering and fruit development stages were sensitive to stress with ky = 1.5 and 2.3 respectively. K_y in the vegetative stage was 0.4 which indicates crop tolerance to water stress and ability to recover from stress in successive stages. The least vulnerable stage to water stress is the ripening phases with ky = 0.2 (Doorenbos and Kassam 1979). DI of maize grown in arid environment was evaluated by Attia et al. (2021). They reported that full irrigation (100% ETc) during the ripening growth stage is more important than during the vegetative growth stage. Acceptable yield and increased WUE can be achieved under DI of 40% ETc during the vegetative stage and 80% ETc during the ripening stage.

DI has been classified into three main categories: (1) conventional or sustained deficit irrigation, (2) regulated deficit irrigation (RDI), and (3) partial rootzone drying (PRD).

3.2 Conventional or Sustained Deficit Irrigation

In conventional DI, water is supplied at uniform levels below full crop ETc across all the growth stages. Water deficit is applied steadily throughout the growing season as the rootzone is not completely refilled with water in irrigation events (Li et al. 2022).

DI is considered a sustainable practice, and has been adopted to improve water use efficiency, minimize yield losses, and improve product quality. Several advantages of DI have been reported and may include: (1) maximizing water use efficiency, (2) reducing the risk of spreading plant disease due to lower humidity and (3) reduction of nutrient loss and leaching out of the root zone, resulting in better groundwater quality and less fertilizer requirements compared to full irrigation (Zahraei et al. 2017). The application of DI has increased the percentage of protein in grains and the percentage of sugar in grapes and sugar beets, as water deficit in late growth stages limits vegetative growth and increases metabolism in the economic parts. Additionally, some crops have been found to exhibit increased tolerance to water stress and can adapt well to deficit irrigation practices (Ma et al. 2022).

While DI can offer several advantages, it is important to consider the potential constraints as well. These constraints may include: (1) decreased crop yields: one of the main disadvantages of DI is the potential for decreased crop yields compared to full irrigation. By intentionally providing less water than ETc, there is a risk of limiting growth and development, leading to lower crop production. Despite the increase in protein content and WUE, DI (by applying 50% of ETc) resulted in 43% decrease in grain yield of wheat (Ahmadian et al. 2021). (2) leaching of salts: in salt affected soil, leaching efficiency of salts from the root zone may be lower under DI compared to full irrigation. According to Leite et al. (2015), rainfall between irrigation events was able to leach the salts induced by irrigation water. (3) weak defense mechanisms: water-stressed plants often have weakened defense mechanisms, making them more susceptible to various pathogens and pests (Nguyen et al. 2021). In addition, different crops have different sensitivities to water stress at various development stages, DI program must be planned to manage water stress so that yield reduction is minimized. Information considering crop response to DI is crucial to achieve such objectives in water-limited areas. It is important to note that DI requires careful monitoring and management of soil/plant water status to avoid excessive stress that could lead to irreversible crop damage. Crop type, growth stage, soil type, local climate conditions, and available water must be considered when implementing deficit irrigation techniques (Moldero et al. 2021) (Fig. 2).

Ullah et al. (2021) studied the effect of DI and reduced N fertilization on tomatoes grown in soilless greenhouse culture. Three irrigation water levels (100%, 80%, and 60% of (ETc) and three nitrogen application rates (N: 100%, 75%, and 50%) were evaluated. The results revealed that the highest irrigation and N application resulted in the highest tomato yield. Reducing either irrigation level or N fertilizer rate did not result in significant difference in yield, but a concurrent deficit of irrigation and nitrogen significantly reduces yield. The results also revealed that treatment of 80% of ETc and 100% N requirements was optimal as water saving strategy. Despite the yield decrease of this treatment by 2.90% and 8.75%, there was an increase in WUE by 21.40% and 14.06% in spring–summer and fall–winter seasons, respectively. Under moderate water stress (80% ETc), root length and volume of tomato increased resulting in improved biomass, yield, WUE, and better utilization of nitrogen.

3.3 Regulated Deficit Irrigation (RDI)

RDI is a water saving strategy in which full irrigation is applied during drought-sensitive stages of crop growth. Beyond these periods, irrigation is reduced or even dispensable if rainfall supplies a minimum amount of water. Water deficit is applied only to drought-tolerant phenological stages, often the vegetative stages and the late ripening period. Unlike DI in which continuous and moderate water deficit is maintained throughout the growing season, RDI involves intentionally applying water deficits to plants during specific growth stages. RDI assumes that field crops under water stress at specific growth stages may not undergo significant yield reduction and irrigation in these stages can be ignored, leading to substantial saving of irrigation water.

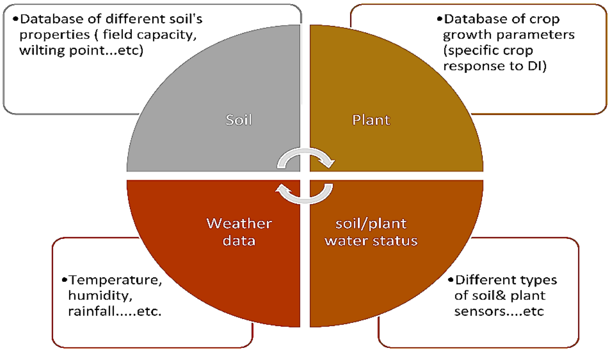

Fig. 2 Diagram of main factors taken into consideration when applying DI

According to McCarthy et al. (2002), RDI was originally developed for stone fruit orchards to reduce vegetative growth and promote fruit growth and quality. Vegetative growth is more sensitive to water stress than fruit growth, therefore reducing irrigation during predefined periods of fruit growth will ensure minimal competition between fruit ripening and vegetative growth.

Osuna-Amador et al. (2023) compared the effect of RDI and DI on chickpea growth and productivity. RDI (at 50 and 75% ETc) was applied during vegetative, flowering and pod-filling stages. Their results revealed that RDI at 75% ETc in the vegetative growth stage had the highest WUE. RDI in the flowering and grain filling stages negatively affected grain yield and WUE, especially at 50% ETc.

3.4 Partial Rootzone Drying (PRD)

PRD is a DI technique that involves irrigation of only one side of the plant root zone at each irrigation event, while the remainder is kept dry. The practices of PRD include two types: fixed and alternate PRD. If water is applied only to one side of the root without alternating the application throughout the growing season, then it is called fixed PRD. On the other hand, it is called alternate PRD if the wetted and dried sides of the root system are alternated in the subsequent irrigation events. In alternate PRD, irrigation of both sides of the plant is done alternately or sequentially allow the wetted side of the root to dry and the dry side to be fully irrigated. While DI supplies less water to the entire root zone than the amount lost by evapotranspiration, PRD involves irrigating half of the root zone at each irrigation event, while the remainder is kept dry to a specified soil moisture content (Slamini et al. 2022) Figs. (3 and 4).

PRD can conserve water, increase WUE and enhance crop quality. Irrigating one side of the root system keeps crops in favorable water conditions, while the drought of the other side stimulates root response to drought. The root system in drying soil side sends signals to the shoots and upper part of the plants to induce reduction of stomatal conductance and vegetative shoot growth. Stomata closure can reduce substantial water loss via transpiration. Stomatal closure is considered the first response to drought stress in most plants and avoids

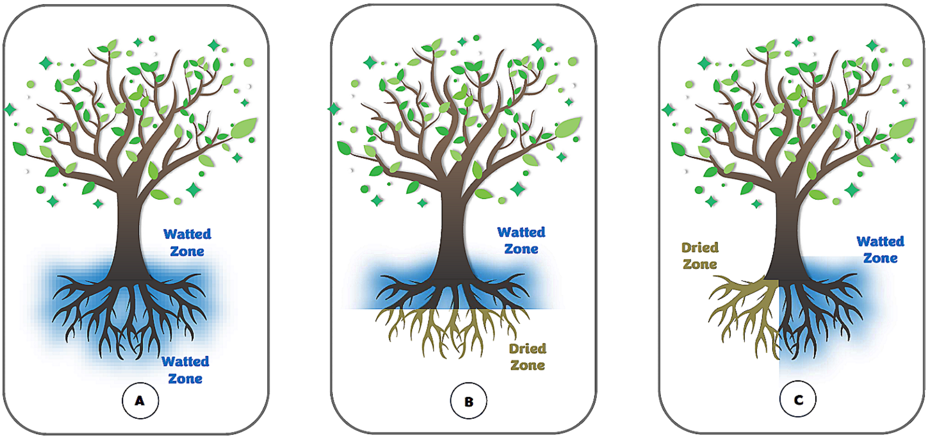

Fig. 3 Scheme of soil moisture with respect to different irrigation regimes: **a**) full irrigation, **b**) DI and (**c**) PRD

Fig. 4 Alternate wetting and drying in furrow irrigation

water loss from transpiration pathways. Stomatal closure is more directly related to soil moisture content than leaf water status, and it is controlled by chemical signals produced in dehydrating roots (Fernandes-Silva et al. 2020).

Crop growth depends on taking up water from the soil and CO_2 from the atmosphere and using it in photosynthesis. This is done by CO_2 uptake through the stomatal pores, where water is concurrently transpired. Water transpiration drives the water uptake and transport by the roots. In fully irrigated plants the stomata are widely open, CO_2 is taken up while water is transpired. A controlled water stress may lead to slight reduction of the stomatal opening, which in turn may reduce water loss significantly with little effect on photosynthesis. In PRD, the part of the root system in dry soil side responds to drought through sending a root-sourced signal to the shoots where stomata may be closed to decrease water loss or transpiration rate (Duan et al. 2024).

Wu et al. (2020) compared the impacts of RDI, PRD and DI on growth and productivity of pear trees under arid conditions. RDI and PRD treatments were irrigated with 50 and 80% ETc during the slow and rapid fruit growths stages, respectively. DI treatments were irrigated with 80% ETc during the whole growing season. The results revealed that vegetative growth and yield of pear trees did not vary significantly in PRD and RDI trees. Higher values of total soluble solids and sugar content were obtained in PRD and RDI treatments compared with DI. They concluded that variation in growth and productivity of pear trees were mainly due to the DI level rather than the DI method. RDI technique was more suitable than PRD due to lower labor cost. To ensure the success of implementation of DI practices (DI, RDI or PRD), several factors must be considered. These factors may include soil type, water deficit level and duration as well as crop type. In addition, better management of in-field irrigation water so that it remains available in the plant root zone is imperative (Fig. 2). Within this context, the incorporation of soil conditioners with DI is considered an effective tool for conserving water in agriculture.

4 Soil Amendments or Conditioners

Soil amendments or conditioners are materials added to soil to improve physical, chemical and biological properties. The improved soil properties will eventually result in improved crop growth. The potential of soil conditioners whether organic, such as biochar or inorganic, such as hydrogel and bentonite to increase soil water and nutrient holding capacity has become an important issue over time, especially in regions of limited water resources. Recent research results affirmed that soil conditioners application could improve growth and minimize yield losses due to water deficits. The degree of response varied according to soil, crop and soil conditioner (Table 1).

4.1 Hydrogels or Super Absorbent Polymers (SAPs)

Superabsorbent polymers (SAPs) are substances that can absorb and retain large amounts of water. They are used in agriculture as soil amendments to improve water management and increase crop yields. The ability of SAPs to retain water and release it slowly over time helps plants survive drought conditions. Hydrogels can also reduce water usage by increasing irrigation efficiency and reducing runoff. In addition to water management, hydrogels can also improve soil structure and nutrient availability. They can help loosen compacted

Table 1 Effect of DI strategies incorporated with different soil conditioners

Crop	Soil type	Irrigation treatments	Soil conditioner type	Conditioner application rate	Benefits	literature
tomato	Loamy sand	• DI with 40, 60 and 80% ETc • PRD at different growth stages with 100% ETc	Biochar	4% (w/w)	The highest WUE was recorded under 40% ETc with biochar, while the highest yield was obtained under PRD and biochar.	(Alghamdi et al. 2023)
Sweet corn	sandy loam	• DI: 40%, 70% of ETc and control100% ETc	Biochar	13 Mg/ha	The 70% ETc increased WUE by 21% compared to 100% ETc while maintaining similar yield. Biochar increased the root length density.	(Singh et al. 2023)
Apple	Clay loam	• RDI 50 and 75% of ETc as compared to control	SAP	0, 100, 200 and 300 g/tree	The addition of 200 g/tree SAP increased fruit weight by 15%. It also achieved the highest soluble solid content with RDI 50% ETc.	(Keivanfar et al. 2019)
grapevine	sandy	• DI with 60, 80% ETc as compared to 100% ETc.	SAP	0, 300, 600 and 900 g/tree	Using 900 g SAP/tree and 80% ETc achieved highest vegetative growth parameters, yield, fruit quality as well as WUE.	(Mohamed et al. 2023)
Plum	sandy	• DI with 60, 80% ETc as compared to 100% ETc	SAP	75, 100, and 125 g/tree	Using 125 g SAP/tree and 80% ETc achieved the highest WUE	(Khalil et al. 2022)

soil, increase aeration, and improve the soil's ability to hold nutrients. This can lead to healthier plants with better root development and increased yields.

Kathi et al. (2021) evaluated the effect cornstarch-based SAPs on growth and productivity of tomatoes as well as nitrogen and water retention in sandy clay loam soil. Different application rates of SAPs were evaluated, ranging from 0 to 0.2% (from 0 to 2 kg/1000kg soil). The leachate volume was recorded and subsequently analyzed for nitrate concentration. These results revealed that cornstarch-based SAPs enhanced water and nutrient holding capacity of the soil as compared to control. The highest application rate of SAPs significantly reduced the leachate volume and nitrate concentrations in leachate from soil by 79.34% and 93.11% at 3 days after fertilization (DAF) and 78.84% and 81.58% at 9 DAF as compared to control, respectively. Significant improvements in plant growth and yield parameters under SAP treatments were also reported. By enhancing soil water retention and reducing nitrogen leaching, SAPs has the potential to enhance crop growth in drought stress conditions, while conserving the ecosystem.

Abrisham et al. (2018) studied the Effects of SAPs on soil properties and plant growth in sandy loam soil under arid conditions. Three different application rates of SAP were evaluated: 0, 0.1 and 0.3%. The study proved that SAP's water retention properties resulted in increased soil water storage capacity in arid regions. The application rate of 0.1% SAP increased available water content to 68.5% and decreased soil infiltration rate by 21.5% and soil bulk density by 25.5% as compared to the control. No significant difference between SAP 0.1 and 0.3% application rates was recorded in most of the evaluated parameters. Therefore, considering both technical and financial issues, the 0.1% application rate is recommended.

One of the barriers hindering the spread of SAPs in agriculture is that they are easily oxidized and decomposed by the air and sunlight. To considerably obstruct SAP oxidation, sand mulching as soil insulator from decomposition factors is recommended (Yang et al. 2022; Malka and Margel 2023).

Zhao et al. (2019) evaluated hydro-physical properties of sandy loam soil columns mulched with sand and treated with various concentrations of SAP (0, 0.1, 0.2, 0.5 and 1.0%). The results revealed that SAPs slowed the downward movement of water and the soil infiltration rate. The decrease in soil infiltration was proportional to SAP's application rate. The optimum application rate of SAP was 0.2%, which achieved a reasonable infiltration rate and enhanced soil water retention.

Al-Jabari et al. (2019) utilized waste baby diapers as a source of recovered SAP. The performance of this recovered hydrogel for enhancing irrigation management was investigated. Three SAP application rates were evaluated; 1, 2 and 3% as compared to the control. The results revealed that water infiltration was reduced significantly when adding the recovered SAP to the soil. Soil treated with SAP application rate of 2% and 3%, did not infiltrate water. These results indicate that the irrigation water requirements can be reduced by 15–50% when soil is treated with the recovered SAP, depending on the application rates.

4.2 Bentonite

Bentonite is natural clay consisting mainly of montmorillonite and used as nontoxic soil amendment. It is a superabsorbent swelling clay having the ability to absorb and retain water and nutrients within the bentonite crystal structure. It also has high cation exchange capacity, which positively affects crop yield. Bentonite can alleviate crop water stress by retention and regulation of soil moisture and improving soil structure (Garbowski et al. 2023).

High water-holding capacity of bentonite prevents water loss through evaporation and deep percolation and increases plant available water. Stable soil aggregates are formed when bentonite is mixed with soil leading to improved soil structure and better soil moisture distribution. The enhanced soil structure also increases root penetration and improves water and nutrient uptake by plants. According to Zhang et al. (2020), the addition of bentonite to maize grown in sandy soil altered pore size distribution and led to enhancing soil aggregation which increases soil porosity, soil water-holding capacity, and grain yield.

In their study, Mi et al. (2020) demonstrated that the application of bentonite significantly ($P < 0.05$) increased soil water-holding capacity and plant available water up to 40 cm depth by 12 and 10% respectively. It also significantly increased millet growth parameters and WUE. Mohammadifard et al. (2022) evaluated the response of fenugreek to bentonite application in sandy loam soil under water deficit. Three application rates of bentonite (0, 5, and 10%) at three irrigation levels (30%, 60%, and 90% of field capacity (FC) were evaluated. The results showed that water stress negatively affected growth, pigments, proline and sugar contents of fenugreek. Bentonite application enhanced recovery of fenugreek from both severe and moderate water stress. The application rate of bentonite of 5% was better for alleviating water stress.

Ma et al. (2022) evaluated a mixture of bentonite and humic acid applied at six rates (0, 6, 12, 18, 24, and 30 Mg ha^{-1}) on oat crop in degraded dry land ecosystem. The results indicated a positive linear relationship between the mixture additions and water holding capacity in soil profile up to 60 cm depth. In the same profile depth, a significant decrease in soil electrical conductivity, pH, and bulk density was recorded. An increase of 40% in plant available phosphorus in soil profile was also recorded. This amelioration in soil profile environment has led to enhanced use of water and nutrients by oat crop and the consequent increases in grain yield by 20%, grain protein by 62%, and water use efficiency by 41%, with the optimum bentonite-humic acid application rate of 24 Mg ha^{-1}.

In surface irrigation, water loss in deep percolation below the plant root zone reduces irrigation application efficiency. Deep percolation depends on soil infiltration characteristics and takes place when infiltrated water exceeds soil infiltration rate. A soil column laboratory experiment was carried out by Tibebe et al. (2013) to investigate the ability of bentonite to reduce the infiltration rate of loamy sand soil. Three bentonite-water mixtures were evaluated; 2, 4, and 6 g L^{-1} as compared to control. The results revealed that infiltration rate and deep percolation significantly decreased with the addition of 2 g L^{-1} of bentonite as compared to the control. Bentonite application rates of 4 and 6 g L^{-1} did not significantly reduce soil infiltration rate. With the addition of 2 g L^{-1}, furrow length can be doubled to facilitate the operation of the farm machinery. Furrow length is one of the parameters in furrow irrigation systems design, it is determined taking into consideration the infiltration opportunity time.

4.3 Biochar

Biochar is soil conditioner rich in carbon, produced by pyrolysis of organic biomass and agricultural residues under limited oxygen conditions. Pyrolysis process is defined as the decomposition or thermal breakdown of organic substances by heat (350 and 700 °C temperature) in the absence of oxygen (Varma et al. 2018; Nadda 2023). Disposal of agricultural residues through burning results in emissions of large amounts of greenhouse gas, carbon monoxide, and other contaminants. This hazard may be overcome by producing biochar through the pyrolysis of agricultural residues (Lefebvre et al. 2023).

Biochar has negative surface charges and high cation exchange capacity, large surface area, superior porous structure, and high adsorptive capacity of water and nutrients. Therefore, biochar addition may improve soil physiochemical properties. Biochar has high porous network with various dimensions: micropores (<2 nm), mesopores (2–50 nm) and macropores (>50 nm). This high porosity enhances soil's water and nutrient holding capacity and decrease soil bulk density. Improving soil absorption capacity of nutrients reduces the risk of leaching nutrients and immobilize toxic elements (Feng et al. 2023; Park et al. 2023). The effect of biochar on soil varies greatly according to raw biomass materials, pyrolysis temperature, and soil texture.

Alghamdi et al. (2021) studied the effect of biochar produced from olive wastes on hydrophysical properties of sandy soil. Biochar was produced at three different pyrolysis temperatures 300 °C, 400 °C, and 500 °C. Biochar was mixed with soil into the top 10 cm at rates of 0%, 1%, 3%, and 5%. The results revealed that cumulative infiltration and infiltration rate of soil significantly decreased due to biochar addition. In addition, cumulative evaporation was reduced for all biochar treatments. Soil treated with 5% biochar and prepared at 500 °C showed the highest performance.

Haider et al. (2020) evaluated the effect of biochar in alleviating the adverse effects of water stress at sensitive growth stages of wheat. The biochar used in the experiment was produced from wheat straw at 500 °C. Biochar application rates of 2.7% and 3.7% were compared to no biochar addition as control treatments. Their results indicated that biochar application significantly improved WUE, yield and growth parameters of wheat under drought conditions. They also reported that higher rate of biochar application (3.7%) had the potential to alleviate the negative impacts of drought and maintain yield and growth of wheat, especially in the most sensitive growth stage to water deficit (grain filling stage).

Lebrun et al. (2022) conducted an experiment to determine the most beneficial soil amendment from biochar and manure that could reduce negative impacts of crop drought stress. Biochar was manufactured using wooden chips at 500 : 600 °C. The effect of manure, biochar and a mixture of 90% manure and 10% biochar (w/w) on soil moisture and nutrients were evaluated. The application rate of each amendment was 2 and 5%. Sugar beet crop was subjected to water stress by reducing irrigation water by 75%. The results showed superiority to treatment with biochar alone in terms of soil moisture retention and reduction of nutrient leaching. The biochar-manure amendment also mitigated negative impacts of water stress on sugar beet yield and increased sugar content.

Obadi et al. (2023) investigated the effect of biochar on mitigating salinity and drought stress of tomato crops in sandy soil. Two irrigation water qualities fresh and saline (0.9 and 2.3 dS m^{-1}) and four irrigation levels 40, 60, 80 and 100% ETc were evaluated. Biochar produced from date palm feedstock with an application rate of 5% was compared to untreated soil. The results revealed that interaction between biochar and saline water negatively affected tomato growth and productivity, especially under severe water deficit (40 and 60% ETc). On the other hand, biochar addition with freshwater led to a significant increase in tomato yields by 4.60%, 16.74%, 8.67%, and 2.97%, for 100%, 80%, 60%, and 40% ETc, respectively.

5 Conclusion and Future Prospective

Climate change and global water scarcity are forcing farmers to adopt effective water saving strategies. Deficit irrigation strategies are highly advantageous in terms of water saving and can enhance WUE. Published research have demonstrated that the incorporation of soil conditioners with DI can improve soil water retention, minimize the impacts of plant water stress as well as sustaining yield and improving yield quality parameters. The positive effects of soil conditioners and DI strategies could be further improved by focusing on the following areas:

- Existing crop water production functions were developed under specific geographical locations, therefore continuous modification for different regions is required, especially in light of climate changes in recent decades.
- Crop response factor (K_y) to DI supported by soil conditioners in different growth stages should also be evaluated.
- Studies on the effect of combining DI and soil conditioners on crops that are more sensitive to water stress should be subjected to further investigations.
- With respect to SAPs, the majority of the analyzed publications used commercial/synthetic polymers. More research should be devoted to the utilization of agricultural residues as a source of biodegradable and ecofriendly superabsorbent polymers. The analysis of the published reports also revealed that SAPs are easily decomposed by air and sunlight. Different soil mulches and covers combined with SAPs has to be evaluated.
- Future research should address the interaction between DI, saline irrigation water, saline soil and different soil conditioners. SAPs are characterized by their lower salt tolerance. Biochar may have negative impact on yield and WUE when using saline water for irrigation or adopting DI, especially if the salinity of the biochar itself is high, which may sometimes reach 8 $dS.m^{-1}$.
- Despite the fact that Soil conditioner interactions with soil may vary over time, published results on soil conditioners were basically based on short-term studies (≤2 years). Long-term investigations are required to clarify the time required for complete decomposition of soil conditioners and the final effect on soil hydro-physical properties in the long-term.
- The integration of soil conditioners with growth promoting microorganisms (biofertilizers) and antitranspirants under DI needs to be investigated.

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Declarations

Ethical Approval Compliance with Ethical Standards.

Consent to Participate The research non involve other human participants.

Consent to Publish Authors are agreeing to publish this article in Water resources Management.

Competing Interests 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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