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A REVIEW ON SOIL-WATER-PLANT INTERACTIONS AS IMPLICATIONS FOR IRRIGATION EFFICIENCY AND CROP PRODUCTIVITY

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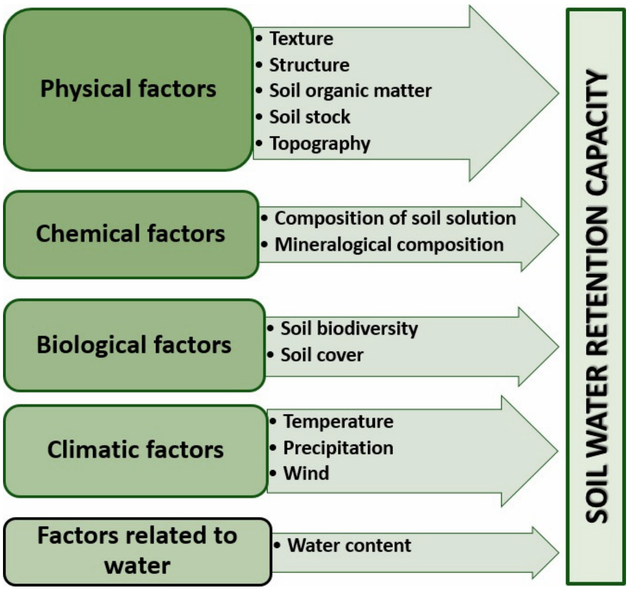
ABSTRACT

Soil-plant-water relationships are at the center of formulating the basis of sustainable agriculture because they have a direct bearing on irrigation efficiency, crop yields, and conservation of resources. A thorough understanding of the intricate and dynamic interplay between soil characteristics, water status, and plant physiological responses is essential for improving water use efficiency and soil health, particularly in the context of an escalating impact of climate variability and resource limitation. This review integrates and summarises up-to-date scientific information on important topics including soil physical and hydraulic characteristics, water infiltration and percolation processes, and plant water uptake and transport mechanisms. Special focus is given to the role of the root-soil interface in water intake and its interaction with soil texture, structure, and water status. The publication also examines new irrigation technologies like drip and sprinkler systems, soil moisture sensors, and precision irrigation equipment that are transforming on-farm water management. Furthermore, the review discusses the essential factors that influence soil water retention capacity, evapotranspiration rates, and spatial-temporal variability of water availability in the root zone. The role of agro-climatic conditions, cropping systems, and land management practices in affecting such interactions is examined to give region-based recommendations. Integrating research results and field-level innovations, this paper provides pragmatic insights into best management practices (BMPs) to enhance water productivity, optimize plant growth, and develop stable agricultural systems. In total, this review emphasizes the necessity of a systems approach to soil-water-plant relationships, providing a scientific basis for strategies that enable sustainable and climate-resilient agriculture.
***Keywords*:** soil plant interaction, Physical and hydraulic, Crop productivity with water deficit.

Introduction

Crop productivity and sustainability are integrally linked to the optimal use of natural resources, including water (Shah, and Wu, 2019). Water is not just an essential input for plant growth but also a bottleneck in several agro-ecosystems, especially in arid and semi-arid environments (Russo, *et al.*, 2014). As world agriculture continues to grapple with escalating population pressures, shifting climatic regimes, and declining freshwater resources, maximizing water use has emerged as a key element of sustainable crop production systems (Mehta, 2024).

The soil-plant-water interaction is the fundamental foundation of agricultural water management (Horel, 2024). This three-way interaction regulates the storage of water in the soil, uptake by plant roots, and use for physiological processes like transpiration, nutrient transport, and photosynthesis (Kirkham, 2023). The soil properties of texture, structure, porosity, and organic matter content affect water infiltration, retention, and movement within the profile (Franzluebbers, 2002). These factors regulate the soil's water-holding capacity and its capacity to deliver moisture to plants during critical development phases (Bhattacharya, and Bhattacharya, 2021).



Source, Gavrilescu, 2021).

Fig. 1 : Image of soil water capacity

Plant characteristics, including root structure, density, depth, and hydraulic conductivity, determine the ability of the plant to obtain water from the soil (Kato,and Okami, 2011). Similarly, root growth patterns are determined by the availability and distribution of soil moisture, and thus a plantation feedback process affects the general health and productivity of the plant (Nambiar, 1990). Additionally, environmental factors such as temperature, humidity, wind velocity, and solar radiation add to evapotranspiration, which influences the soil-water balance and the water demand of the plant (Evett *et al.*, 2012).

In such a scenario, an integrated knowledge of soil-water-plant interactions is critically necessary to create more accurate and responsive irrigation practices (Sankari *et al.*, 2024). These practices have the objective of synchronizing water application with crop needs, reducing losses to evaporation and deep percolation, and maximizing yields. Improvements in soil moisture sensing, remote sensing technology, and precision irrigation equipment provide new means of monitoring and optimizing water use (Bwambale *et al.*, 2022).

Knowledge of the soil–plant–water continuum and the complex interrelationships between its constituents is essential for evaluating its wider influence on ecosystems (Gavrilescu, 2021). A thorough understanding of these relationships is necessary for formulating effective mitigation measures towards sustainable land management (Wang, *et al.*, 2019). These include the effective management of water and nutrients, optimization of crop yields, enhancement of biodiversity, and assessment of environmental footprints (Penuelas, and Sardans, 2021).

Soil ecosystems are very intricate and dynamic networks that are controlled by multi-faceted interactions, especially the interchanges of carbon, nutrients, and water between soils, plants, and the atmosphere (Hillel, 2007). They are controlled by both natural and human-induced factors and are very important for maintaining soil health and facilitating plant growth.

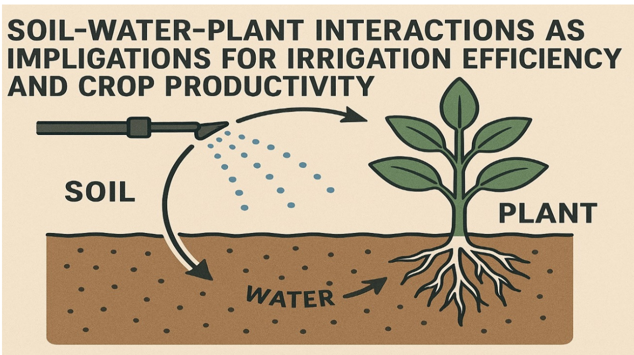


Fig. 2 : Soil water plant interaction

Availability of water in soil is one of the key factors that determine plant physiological processes (Williams *et al.*, 2007). It has a direct influence on nutrient and water uptake by plant roots, as well as the activity and richness of microbial communities in the soil (Van Der Heijden *et al.*, 2008). Microorganisms, in return, are involved in cycling nutrients and decomposing organic matter, further impacting soil fertility and plant health (Hawkes, *et al.*, 2007).

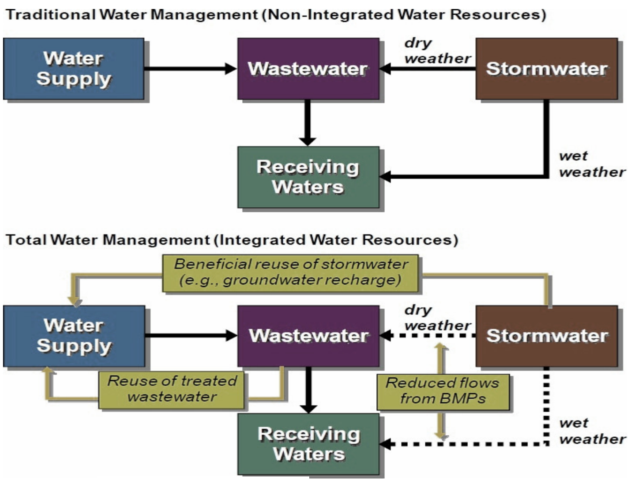
Plants are not passive recipients in this system - they actively modify soil water dynamics by a number of mechanisms (Dumais, and Forterre, 2012). These include the root architecture and density, specific water extraction needs, and transpiration rate. Plants modify the distribution, storage, and use of water in the soil profile by influencing all these processes (Gavrilescu, 2021).

In addition, plant presence and soil structure together affect the water balance. For instance, aggregated and porous soils allow for more infiltration and retention of water, while plant canopies minimize evaporation by shading the soil surface and blocking rainfall (Connolly, 1998). On the other hand, dense vegetation can enhance transpiration loss, subject to vegetation species and environmental conditions (Shaxson and Barber, 2003).

The entire balance and productivity of the soil–plant–water system are also regulated by external environmental components, viz., climatic parameters (e.g., temperature, rain, and humidity), management practices on the land (e.g., tillage, mulching, and irrigation), and land use/land cover changes. They may augment or derogate the functional harmony of the system (Sharma and Kumar, 2023).

With this complexity, there is a need to conduct integrated assessments and comprehensive evaluations of soil–plant–water interactions (Wang, *et al*., 2025). This knowledge supports the establishment of adaptive strategies that maintain ecosystem services, enhance agricultural resilience, and reduce negative effects from climate variability and unsustainable land use (Fatichi *et al*., 2016).

This review examines the intrinsic principles and recent advances in the concept of soil physical properties, plant water uptake processes, and water transport mechanisms (Altieri *et al*., 2008). It also assesses the effect of current irrigation technologies and management regimes on crop performance across different agro-climatic conditions. By explaining the complex interactions between soil, water, and plants, this research will contribute to the promotion of resilient and resource-conserving agricultural systems (Kumar *et al*., 2019).



Source, Gavrilescu, 2021).

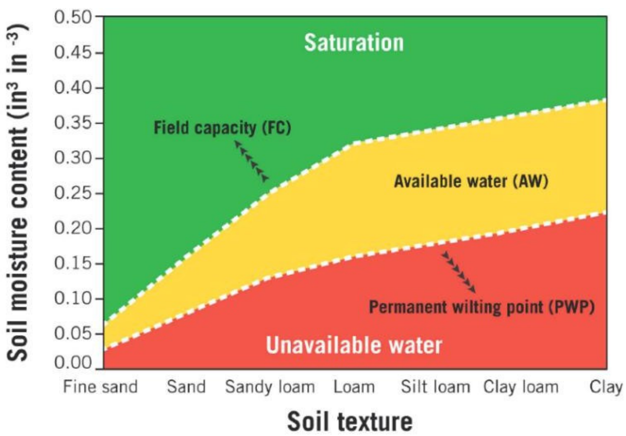
Fig. 3 : Tradition water management

Soil-Water Relationships

A clear understanding of soil-water relationships is a key component of effective water management and crop production. The relationships referred to are primarily based on the soil's physical properties (texture, structure, porosity, and bulk density) as they relate to water retention and movement, and the availability of water for plants (Osman *et al*., 2013).

Structure and Texture of Soil

Soil texture is the relative amounts of sand, silt and clay particles that affects how water will infiltrate, retain and move through the soil (Dexter, 2004). Sandy soils have larger particles and wider pore spaces, so water infiltrates quickly into sandy soils but Sand retains relatively small amounts of moisture, this tends to lead to drought stress (Phogat *et al*., 2015). Sandy soils are not very good at retaining moisture. Clay soils have very small particles with smaller pore size. Therefore, clay soils have slower infiltration rates, but they do hold more water (but they also can tend to hold water in a location leading to poor drainage and aeration and possibly waterlogged or root suffocated plants) (Reeve *et al*., 1973).



(Source, Gavrilescu, 2021).

Fig. 4 : Image of Soil texture

Soil structure pertains to how those particles aggregate to produce a structure (Ghezzehei, 2012). Well-structured soils with stable aggregates equal greater water holding capacity, greater infiltration and greater root penetration. Structures that are granular or crumb are characteristic of surface horizons of soils with good organic matter ratios (Kay, 2018). These soils will help meet the plants' water holding capacity while providing adequate aeration.

Table 1 : Soil-Water-Plant Interactions and Their Implications for Irrigation Efficiency and Crop Productivity

Component	Description	Implications for Irrigation Efficiency	Implications for Crop Productivity
Soil Properties	Includes texture, structure, porosity, infiltration rate, and water-holding capacity	Affects water retention, drainage, and availability to plants; determines irrigation frequency and amount	Influences root development, nutrient uptake, and resilience to drought
Water Availability	Refers to soil moisture content and distribution in the root zone	Determines timing and quantity of irrigation needed to maintain optimal moisture levels	Impacts cell expansion, photosynthesis, and overall crop growth and yield
Plant Root Characteristics	Root depth, density, and distribution pattern	Deep-rooted crops access moisture from deeper profiles, allowing longer intervals between irrigation	Improves water use efficiency and tolerance to moisture stress
Soil-Water Retention Curve	Relationship between soil water content and matric potential	Helps in determining field capacity and permanent wilting point for optimal irrigation scheduling	Maintains sufficient water for physiological processes without causing waterlogging
Transpiration and Evapotranspiration (ET)	Water loss through plant transpiration and soil evaporation	Guides irrigation needs based on ET rates; minimizes losses through mulching and canopy management	Directly linked to biomass production and yield when water is not limiting
Stomatal Conductance	Regulation of gas exchange and water vapor loss through stomata	Affects transpiration rates and water conservation strategies under stress	Controls photosynthesis and carbon fixation, impacting crop yield
Water Stress Response	Includes stomatal closure, ABA accumulation, osmotic adjustment	Indicates the need for timely irrigation to avoid irreversible stress	Prolonged stress reduces growth rate, flowering, fruit set, and ultimately yield
Irrigation Methods	Surface, sprinkler, drip, subsurface systems	Drip and subsurface systems increase water use efficiency by targeting the root zone	Efficient water delivery reduces plant stress and enhances productivity
Soil Management Practices	Tillage, mulching, organic matter addition, compaction control	Improves infiltration, reduces evaporation, and enhances water retention	Promotes healthy root growth and better nutrient and water uptake
Climate Factors	Temperature, humidity, wind, and solar radiation	Influence evapotranspiration rates and irrigation planning	Affect crop water demand and stress levels, influencing final yield
Crop Type and Growth Stage	Different crops and stages (vegetative, flowering, fruiting) have varying water needs	Critical for scheduling irrigation during peak demand periods (e.g., flowering and grain filling)	Timely water availability during critical stages maximizes yield potential
Water Quality	Salinity, pH, presence of toxic elements	Poor water quality may affect infiltration, soil structure, and plant health	Affects plant metabolism and nutrient uptake, potentially reducing yield
Soil-Water-Plant Feedback Loop	Interdependent dynamics where plant water uptake alters soil moisture, and soil conditions influence plant growth	Understanding feedback helps refine irrigation strategies for sustainable water use	Enhances long-term productivity by maintaining soil health and plant resilience

Water Holding Capacity

Water holding capacity is an important attribute that determines how much water is available for plant uptake between field capacity and permanent wilting point (Irmak, *et al*., 2018). Field capacity is defined as the water content of the soil when excess water has drained from the soil and downward water movement is decreasing (Ahuja *et al*., 2008). The permanent wilting point is defined as the moisture content of soils at which water cannot be taken up by the plant, leading to wilting and/or inability to carry out physiological processes (Tolk, 2003).

The difference between field capacity and permanent wilting point is called available water capacity (AWC) (Patil *et al.*, 2012). AWC can vary considerably according to soil texture. Sandy soils have a limited AWC because of rapid drainage, and clayey soils can have more water content overall, but the water cannot be easily extracted, or there is less available water due to the strong retention forces (in micropores) (Sun and Lu, 2014). Loam soils generally have adequate amounts of water holding capacity to achieve reasonable levels of AWC to it can be used in crops.

Soil Porosity and Bulk Density

Soil porosity is the volume of pore spaces between soil particles and is an important factor in the retention and movement of water in soils (Robinson *et al.*, 2022). Porosity is affected by soil texture and structure, and is usually expressed as a percentage of total volume. There are two types of pore spaces; macropores and micropores (Hao *et al.*, 2008). Macropores are larger pores and allow for rapid rate of nonrestricted water movement and air movement. Micropores are smaller pores and retain water against the force of gravity as well as provide moisture for plant roots (Tonkha and Dzyazko *et al.*, 2014).

Bulk density is the oven dry mass of soil per unit volume, and has an inverse relationship with porosity (Chaudhari *et al.*, 2013). High bulk densities indicate compacted soils which can have limited pore spaces, resulting in hindrance of root growth, limited access of infiltration of water, and less capacity of the soil to store and transmit moisture. For soils with optimal bulk density and soil structure adequate pore spaces will lead to more rapid and greater movement for root system development, and eventual crop development (Keller and Håkansson, 2010).

Yield Response to Water Deficit

Crop yield is very sensitive to water supply, and the plant response in the moisture stress condition is closely related to the degree, duration, and time of the water deficit (Navari-Izzo and Rascio, 1999). When experiencing drought or water-limited conditions, plants activate different physiological, biochemical, and morphological responses to reduce water loss and maximize water uptake (Tardieu *et al.*, 2013).

Physiologically, when soil water content lowers and the leaf water potential falls below a certain critical value, stomata the minute pores present on the leaf surface start closing (Buckley, 2019). Stomatal closure is one of the first visible signs of water stress and serves as a defense strategy to curtail transpiration and save water but at the cost of reduced CO_2 entry, which restricts the substrate for photosynthesis (Pirasteh-Anosheh *et al.*, 2016). As a result, the rate of photosynthesis falls, affecting carbohydrate formation and eventually cutting back growth and yield. Further, the decrease in transpiration increases leaf temperatures as a result of diminished evaporative cooling. Water stress also modifies solute transport and nutrient assimilation, impacting a number of key metabolic processes and overall plant health (Gahir *et al.*, 2021).

Biochemically, water deficit triggers the deposition of stress-responsive compounds that are critical for tolerance to stress. One such molecule is abscisic acid (ABA), an important hormone that controls stomatal closure as well as other drought adaptive processes (Muhammad Aslam *et al.*, 2022). Osmoprotectants such as proline, sorbitol, and glycine betaine are also accumulated by plants, which help in osmotic adjustment and stabilize cellular components during stress (Dikilitas *et al.*, 2020). In addition, drought stress also elevates the yield of reactive oxygen species (ROS) including superoxide radicals and hydrogen peroxide, which may inflict oxidative damage (Singh *et al.*, 2015). To overcome this, plants trigger antioxidant defense mechanisms through the synthesis of enzymes like superoxide dismutase (SOD), catalase (CAT), and peroxidases. Stress proteins like dehydrins and heat shock proteins are also synthesized to help preserve cellular structure and function under water stress conditions (Fahad *et al.*, 2017).

Morphologically and developmentally, plants show some adaptive modifications under water stress. Root systems become elongated and more dense to provide the plant access to deeper soil water. Leaf area can be minimized by restricting leaf growth or through the loss of older leaves, which reduces the transpirational surface area (Collins *et al.*, 2007). Drought can also affect developmental processes; in some crops, it causes delayed flowering and fruiting, whereas in others, it can induce premature senescence (Schenk *et al.*, 2002).

From the standpoint of yield, the period when water stress occurs in the crop cycle determines the degree of yield loss (Hsiao *et al.*, 1976). Drought early in the season can hamper seedling establishment and vegetative development (Anjum *et al.*, 2007). Stress in the middle of the season during the periods of flowering and grain filling tends to have the most critical effect on ultimate yield (Farooq *et al.*, 2014). Late-season water stress has the effect of accelerating plant maturity and decreasing grain filling, weight, and quality.

From the management point of view, it is crucial to know how crops react under water deficit in order to formulate efficient mitigating measures. This encompasses choosing drought-resistant varieties, embracing soil moisture conservation techniques like mulching and conservation tillage, and irrigating according to critical growth stages (Xing, and Wang, 2024). The use of anti-transpirants and growth regulators can also help plants to deal with water-stress conditions.

Interactions Between Plants and Water

Interactions between plants and water are central to crop development, growth, and productivity. These interactions decide the ability of plants to uptake, transport, and use water for physiological functions. Root structure, transpiration behavior, and water use efficiency are among the factors that influence how crops react to different moisture levels (Aung *et al.*, 2018).

Water Uptake and Transpiration

Plants take up water mainly by root hairs in the zone of elongation, where the root is in close contact with the soil (Aston and Lawlor, 1979). This water enters the soil and then enters the root xylem by a mixture of apoplastic, symplastic, and transmembrane routes (Bhatla *et al.*, 2023). Water, once within the xylem vessels, is moved up to the above-ground parts of the plant through capillary action and transpirational pull a mechanism initiated by evaporation of water from the leaf stomata (Mohr *et al.*, 1995).

Transpiration plays a number of important roles in plant physiology. It aids temperature regulation in leaves, allows the absorption and transport of minerals and nutrients from the ground, and sustains the turgor pressure required for stomatal operation and cell growth (Khalil *et al.*, 2018). Yet it also means large water losses, particularly on hot, windy, or dry days. Management of water intake and loss is thus essential for sustaining plant water status and preventing stress (Khan *et al.*, 2020).

Root Architecture

Root architecture has a major impact on a plant's efficiency in accessing water, particularly in conditions of limited moisture (Lynch, 1995). Deep and spreading root systems enable plants to tap water from deeper layers of soil, and thus maintain resilience during drought or unpredictable rainfall incidences (Li *et al.*, 2022). Root characteristics such as length density, depth, surface area, branching pattern, and root hair development regulate the water absorption efficiency (Huang, 2000).

In addition, the size of the contact area between roots and soil is critical to water absorption. Increased contact area maximizes the capacity of the root to draw water from soil micropores (Carminati *et al.*, 2009). Water absorption effectiveness can be restricted by compaction, poor aeration, or low levels of organic matter in the soil, preventing root growth and ensuing plant access to soil water (Kozlowski, 1999). Thus, healthy root development should be enhanced through appropriate soil management to increase plant access to soil water.

Plant Water Use Efficiency (WUE)

Water Use Efficiency (WUE) is an important measure of the efficacy of a plant in converting water absorbed into biomass or economic yield (Blum, 2009). It has been generally defined as the dry matter produced divided by the amount of water transpired or evaporated through evapotranspiration. Increased WUE suggests that water resources are being utilized more efficiently, which is of utmost importance in areas experiencing water scarcity (Zhao *et al.*, 2020).

Enhancing WUE requires a number of measures, for example, breeding more drought-resistant crop varieties, deeper roots, and improved photosynthesis (Blum, 2005). Agronomic methods like mulching, irrigation at the right time, conserving soil moisture, and antitranspirant application can also minimize water losses and increase efficiency. Precision irrigation methods, including drip and deficit irrigation, are becoming more popular to deliver water directly to the root zone, reducing losses to a minimum while improving crop performance per unit of water consumed (Raine *et al.*, 2007).

Water use efficiency (WUE) reflects the energy conversion efficiency in plant production and serves as a critical metric for assessing the relationship between crop yield and water utilization (Sun *et al.*, 2018). Previous studies have demonstrated that non-pressure irrigation (NPI) treatments reduced water consumption by 53.4–67.8% while enhancing WUE by 12.7–124.7% in *Capsicum annuum* L., compared to conventional watering methods (Li *et al.*, 2017).

In our study, when compared to conventional irrigation (CI), NPI treatments improved yield-based WUE (WUEY) by 45.9–74.2% and biomass-based WUE (WUEB) by 46.7–53.8% in cherry radish under similar soil water content (SWC) conditions. However, these WUEY and WUEB values were calculated based on evapotranspiration, as described by Sun *et al.* (2018), Wang (2020), and Liao *et al.* (2022), which primarily aligns with irrigation efficiency in the field. Since the soil evaporation component of evapotranspiration does not directly contribute to plant physiological development, WUEY and WUEB may not fully capture the influence of soil water stability on actual plant water use efficiency.

Despite this limitation, our experimental data revealed that a stable water supply (SW) significantly increased radish yield by 34.6–94.1%, biomass by 42.2–63.5%, and leaf transpiration rate (Trmmol) by 11.3–31.9% when compared to fluctuating water (FW) treatments. Notably, the increments in yield and biomass outpaced those of evapotranspiration, as further supported by Partial Least Squares Path Modeling (PLS-PM) results (Figure 5). This indicates that improved soil water stability enhances cherry radish WUE by directly promoting biomass accumulation and yield formation.

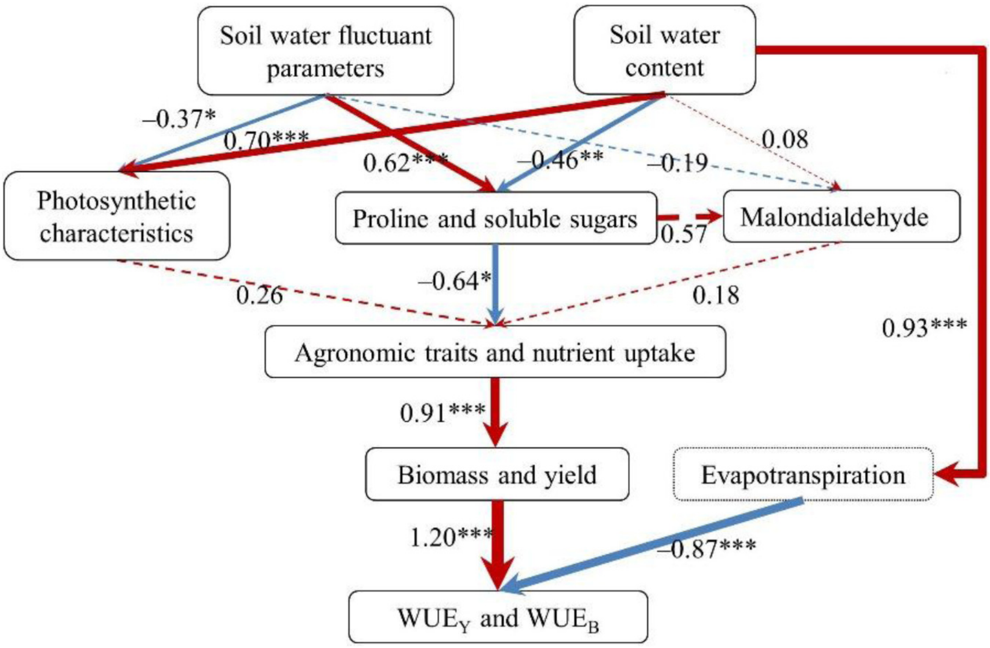


Fig. 5 : The partial least squares path analysis model (PLS-PM) was used to analyze how soil water affected the yield and water use efficiency of cherry radish. The path coefficients were represented by the width of the arrows. The red color indicated a positive effect, and the blue color indicated a negative effect. The solid arrows indicated significant effects (*P < 0.05; **P < 0.01; ***P < 0.001), and the dotted line indicated no significant effect (P > 0.05). WUE$_Y$, yield water use efficiency; WUE$_B$, biomass water use efficiency. The quality of the PLS-PM was evaluated by examining the goodness-of-fit index (GOF), and the GOF of this model was 0.79. The data used in the model were the data from the harvest periods.

Movement of Water in Soil

Movement of water within the soil profile is a vital process controlling the availability of water to plants, nutrient leaching, and the general health of the soil (Huntley, 2023). Water movement is controlled by a number of physical processes that involve infiltration, percolation, capillary rise, and hydraulic conductivity. These processes are controlled by soil properties and environmental factors, and their identification is important for effective irrigation and nutrient management (Selim, 2020).

Infiltration and Percolation

Infiltration is the mechanism by which water is entering into the soil surface and then moves downward toward the soil profile. Soil texture, surface cover, organic content, and level of compaction all significantly affect infiltration rates (Seiler and Gat, 2007). Sandy soils of coarse texture tend to have high infiltration rates because of huge pore spaces, while clay soils with finer texture have lower infiltration rates because of tiny pores and greater water holding capacity (Haghnazari *et al.*, 2015).

Surface cover, such as mulch or plants, can enhance infiltration by covering the soil against crusting and erosion and by encouraging improved soil structure (Prosdocimi *et al.*, 2016). The opposite effect is achieved by soil compaction due to heavy vehicles or overgrazing, which minimizes pore space and hinders the ingress of water.

After infiltration, water will move deeper into the soil as percolation. Percolation is the downward water movement in the soil profile due to gravity. When percolation extends below the root zone, it may result in the leaching away of vital nutrients like nitrogen, phosphorus, and potassium, thus decreasing the fertility of the soil and even contaminating groundwater resources (Rashmi *et al.*, 2017). Infiltration and percolation management is hence a necessity for agronomic as well as environmental sustainability (Stagnari *et al.*, 2010).

Capillary Action

Capillarity, or capillary action, is the movement of water upward or sideways in unsaturated soils through minute pores against gravity (Heidar Barghi, 2019). The movement happens because of cohesion and adhesion between soil particles and water molecules. Capillary rise plays a vital role in arid and semi-arid conditions where the water from lower layers may be sucked up to the root zone during the dry season (Hendrickx *et al.*, 2003).

The magnitude of capillary rise varies with the texture of the soil. Fine-textured soils like clay have tiny pores and therefore have a greater capillary rise, albeit at a reduced rate. Fine soils like sands exhibit rapid but restricted capillary movement as a result of larger pores (Lawrence *et al.*, 1977). Capillarity can be utilized in dryland agriculture and subsurface irrigation systems to provide water to plants below the root zone, thus enhancing moisture supply in water-limited environments (Wang *et al.*, 2023).

Hydraulic Conductivity

Hydraulic conductivity is an indication of the ease with which water can flow through soil pores in saturated or unsaturated conditions. It is an important parameter for determining the direction and rate of water movement in the soil profile (Chapuis, 2012). High hydraulic conductive soils permit free movement of water, which can be advantageous in drainage but can also result in insufficient water holding capacity. Conversely, low-conductivity soils will hold water longer but are susceptible to waterlogging (Jarvis *et al.*, 2013).

Soil hydraulic conductivity is affected by several factors such as soil texture, structure, organic content, and the level of compaction. Sandy soils, with their high-interconnected pores, usually have higher hydraulic conductivity, while clayey soils, though with higher total porosity, will tend to have lower conductivity because of dominance by micropores (Ben-Hur *et al.*, 2009). The presence of organic matter enhances porosity and conductivity by structuring the soil and making the aggregates more stable. Compaction of the soil, on the other hand, discourages pore continuity and limits water flow (Boyle 1989).

Hydraulic conductivity is important to understand in designing efficient irrigation and drainage systems, as well as in forecasting water movement on the field and preventing soil degradation caused by excess water build-up (Varman, 2025).

Implications for Irrigation Efficiency

Effective irrigation management is crucial for optimizing crop production while conserving water loss, particularly in the face of rising water shortage and climate uncertainty (De Pascale *et al.*, 2011). Comprehending soil-water-plant relationships enables one to apply irrigation management techniques which provide crops with water when they require it most, in amounts that optimize growth without loss. Scheduling, method choice, and tactical water application such as deficit irrigation are critical factors that affect irrigation efficiency (Somefun *et al.*, 2024).

Irrigation Scheduling

Scheduling irrigation means the decision of when and how much water to apply to synchronize with crop water use. Good scheduling depends on various data sources such as crop evapotranspiration (ETc), which is the sum of water loss by evaporation and plant transpiration. Estimating ETc in terms of growth stage of the crop, climatic factors, and reference evapotranspiration (ETo) aids in establishing the amount of water to be supplied (Somefun *et al.*, 2024).

Soil water sensors, including tensiometers, gypsum blocks, and capacitance probes, give real-time information on soil water content so that irrigation can be decided in a precise manner (Evett, 2007). Weather-based irrigation scheduling programs and models also include temperature, humidity, solar radiation, and wind speed to better predict crop water requirements (Thompson and Gallardo, 2003).

Applying timely irrigation as per real plant requirement eliminates unnecessary water application, reduces leaching and runoff, and averts both drought stress and waterlogging (Sabir *et al.*, 2024). Consequently, it improves water use efficiency (WUE) and facilitates sustainable agriculture.

Irrigation Methods

Irrigation method selection is a critical factor in the overall water efficiency and effectiveness. Each irrigation method has its strengths and weaknesses based on crop type, soil status, topography, and water supply (Attri *et al.*, 2022)

Surface irrigation, which consists of furrow, border, and basin irrigation, is extensively practiced in conventional agriculture because it is simple and inexpensive in the short run. It tends to produce high water losses via evaporation, deep percolation outside the root zone, and surface runoff, especially on uneven or compacted soils (Pereira and Gonçalves, 2018).

Sprinkler irrigation systems apply water under pressure in a pattern that is much like rainfall (Sheikhesmaeili *et al.*, 2016). Sprinkler systems allow for more even water application and are versatile to soil types and crops. Sprinkler systems minimize surface runoff, but they can also cause evaporation losses, particularly in windy and hot conditions (Zapata *et al.*, 2018).

Drip irrigation is rated as one of the most effective irrigation technologies. Drip irrigation refers to the slow and direct application of water to the plant root zone in a system of emitters. Drip irrigation conserves water from evaporation and runoff, suppresses weeds, and increases nutrient uptake efficiency. It is especially useful in horticulture and high-value crops and in areas with a water shortage (Dasberg and Or *et al.*, 2013).

Implementing the proper irrigation technique, accompanied by precision scheduling, has a substantial impact on irrigation efficiency and preserving precious water resources.

Different type soil water and their plant interaction

Soil water is a vital natural resource that plays a pivotal part in maintaining both vegetation and the entire ecosystem. It is vital for plant growth and physiological processes since it is involved in nutrient transport, photosynthesis, maintenance of cellular turgor, and temperature regulation. Besides, the extent of soil water availability controls the biological functioning of soil organisms and affects major processes of the soil like aeration, nutrient cycling, and root respiration. It is therefore imperative to comprehend soil water dynamics to ensure maximum optimization of crop yields, sustainable land use, and ecological equilibrium (Bhattacharyya *et al.*, 2015).

Soil water is present in different forms based on the degree of its retention by the soil particles. These types are commonly grouped into gravitational water, capillary water, and hygroscopic water, each having different physical characteristics and varying degrees of access to plants (Bittelli, 2011). Gravitational water fills the macropores large pore spaces in soil and is the first to drain after rainfall or irrigation. It is very mobile and temporary, supplying only short-term water to the root zone. Because it drains rapidly under the influence of gravity before plant roots may take it up, gravitational water is generally not accessible to plants. This kind of water is most evident when soil becomes saturated and pore spaces are completely filled with water, at which time soil water potential approaches 0 kPa and means that the water exists in a state of free flow, similar to pure water (Gardner *et al.*, 2000).

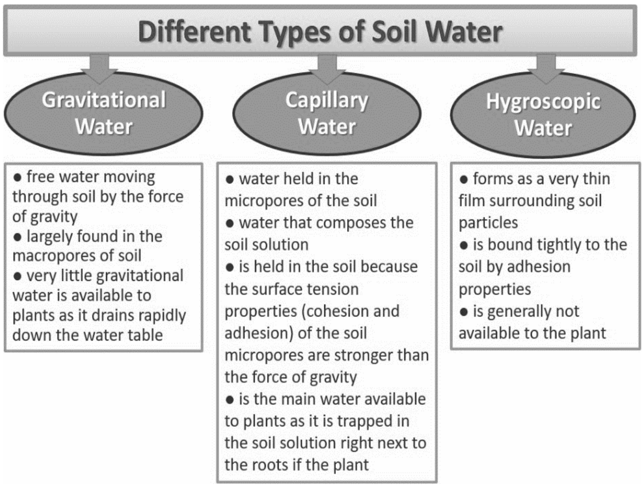
Capillary water, in contrast, is stored within the micropores and mesopores of the soil by surface tension and cohesive forces. It develops thin films around soil particles and is the most crucial type of water for plant absorption (Bachmann *et al.*, 2002). Since it is held with a medium amount of force, capillary water is available to plant roots and is within the soil between field capacity and the permanent wilting point. The capillary action enables this water to move laterally and even upwards through the soil so that the plants can obtain water from different depths (Yudina *et al.*, 2022).

By contrast, hygroscopic water exists in very thin films, which are strongly bound to soil particle surfaces through adhesive forces. This water is held at very low water potentials (below-1500 kPa) and is unavailable to plants because roots cannot generate enough suction to remove it. Hygroscopic water is typically encountered in dry soils and makes no contribution to plant water or nutrient transport (Ghezzehei, 2012).

The ability of the soil to hold and provide water is primarily determined by its texture the ratio of sand, silt, and clay and structure, which describes how particles of the soil are organized into clumps. Clay soils, with their tiny particles and tiny pores, can hold a lot of water. But a great deal of water in clay is held too strongly to be easily accessible to plants (Phogat *et al.*, 2015). Sandy soils, having larger pores, drain quickly and retain less water, thus having a low water-holding capacity and needing to be watered frequently. Loamy soils, having an equal proportion of sand, silt, and clay, provide the most ideal conditions for water supply, courtesy of an optimal ratio between macropores and micropores (Balasubramanian, 2017).

After a saturation event like rain or irrigation, water starts draining from the macropores of soil in response to gravity, and the water content declines to field capacity. Field capacity is where the remaining water is held by matric forces, mainly adhesion and cohesion, and is typically accessible to plants. As more and more water is lost through evaporation and transpiration, the moisture in the soil moves toward the permanent wilting point. When all remaining water is held so tightly that plants cannot recover it, plants wilt and undergo physiological stress (Balasubramanian, 2017).

The distribution and availability of water in the soil are regulated by soil water potential gradients differences in energy that result in the redistribution of water within the soil. In conditions of saturation, water migrates downward through gravitational potential, while in dry soils, capillary forces prevail, enabling water to migrate towards the root zone of the plant (Novák *et al*., 2019). Knowledge of such processes is important for the establishment of suitable irrigation timings, the choice of drought-resistant crop varieties, and suitable soil moisture conservation management practices. Methods like mulching, incorporation of organic matter, and minimal tillage can improve the structure and water-retention capacity of soil, ultimately leading to greater availability of water to plants as well as sustainable agricultural productivity (Knappett *et al*., 2012).



(Source, Gavrilescu, 2021).

Fig. 6 : Different type of soil moisture

Deficit Irrigation

Deficit irrigation is a sophisticated water-conserving strategy where less water is applied than the crop's maximum evapotranspiration requirement during certain development stages that happen to be less responsive to water stress. The idea is to maximize yield per unit of water instead of yield per se (Fereres and Soriano, 2007).

This method needs to be planned with precision and by gaining good knowledge on crop phenology to determine critical and non-critical growth phases. For instance, several crops can suffer from less severe water stress at the vegetative stage or terminal senescence but are extremely vulnerable at flowering and fruit set phases (Chai *et al*., 2016).

By selectively under-irrigating during off-peak seasons, farmers can save water without meaningfully reducing yield or quality. Deficit irrigation is particularly beneficial in dry and semi-dry regions, where water supply is scarce, and it enhances sustainable management of water while sustaining agricultural production (Ouda *et al*., 2020).

Increasing Crop Productivity by Soil-Water-Plant Management

Maximizing the interaction between soil, water, and plants is crucial for increasing crop productivity, especially under resource-constrained and climate-stressed agricultural production environments (Acharya, 2008). An integrated strategy that uses the improvement of soil health, efficient water use management, and good agronomic practices is critical to improve both yield and resource use efficiency. Various strategies have been outlined for enhancing the management of soil-water-plant systems (Horel, 2024).

Utilization of Organic Amendments for Enhancing Soil Water Retention

Organic amendments like compost, farmyard manure, green manure, and biochar improve the soil structure, porosity, and ability of the soil to hold water (Singh, 2022). These amendments help build soil organic matter, and it has a fundamental function of aggregating soil particles together. Better aggregation improves infiltration with water, lessens surface runoff, and provides a higher availability of water in the root zone (Zhou *et al.*, 2020).

In addition, organic matter enhances the cation exchange capacity (CEC) of the soil, which contributes to retaining and also making essential nutrients available. Organic amendments enhance the physical, chemical, and biological properties of the soil by improving the structure, enabling a conducive environment for root development and water absorption, hence increased crop productivity (Usharani *et al*., 2019).

Conservation Tillage and Mulching to Minimize Evaporation

Conservation tillage methods, such as reduced tillage and no-till systems, preserve soil moisture by reducing soil disturbance (Gill *et al*., 1977). These methods keep the crop residues on the surface, which form a protective covering, preventing direct exposure of the soil to sunlight and wind. This leads to reduced soil temperature and lower evaporation losses.

Mulching with organic (like straw, leaves, or grass clippings) or synthetic (like plastic films) materials has the same function (Prem *et al*., 2020). Mulching not only inhibits evaporative loss but also curbs weed growth, regulates soil temperature, and maintains soil microbial activity. Conservation tillage and mulching in combination aid in water conservation and develop a more stable microclimate in the root zone, allowing for continuous plant growth (Ahmad *et al.*, 2022).

Application of Crop Models to Estimate Water Requirements and Plan Irrigation

Crop simulation models like DSSAT, AquaCrop, and SWAT are excellent predictors of crop water requirements and planners of irrigation schedules (NK, and Ga, 2024). The models combine climatic information (e.g., precipitation, temperature, radiation), soil properties, crop development stages, and management practices to predict water requirements under changing scenarios.

Through the modeling of plant reaction to varying irrigation patterns, crop models support decision-making that enhances water use efficiency, avoids over- or under-irrigation, and maximizes overall productivity. Their use is particularly valuable in precision agriculture and for creating site-specific water management strategies (Pereira *et al.*, 2020).

Synergism of Nutrient and Water Management

Water and nutrients are complementary resources, and their combined management results in synergistic impacts on crop yields (Anderson, 2011). Effective water management makes nutrients available in the root zone and are used with high efficiency by the plants. Similarly, optimum nutrient availability supports healthy root growth and effective water uptake (Li *et al.*, 2009).

Techniques like fertigation (use of fertilizers by irrigation water), nutrient application according to soil analysis, and matching supply with crop requirement increase nutrient and water use efficiency. INWM not only increases yield but also reduces environmental hazards like nutrient leaching and water pollution (Wu and Ma, 2015).

Challenges and Future Directions

Although remarkable progress has been made in soil-water-plant interaction understanding and irrigation efficiency enhancement, there are a number of challenges that still limit the sustainable management of agricultural water resources. Global challenges such as climate change, resource exhaustion, and socio-economic limitations require new and innovative solutions as well as visionary approaches. The subsequent subsections describe the most important challenges and present future research directions for sustainable soil-water-plant management.

Climate Change and Falling Water Tables Pose Challenges to Irrigation Sustainability

Climate change represents a serious threat to agricultural water management through the transformation of precipitation, enhancement of the occurrence of extreme weather events, and rise in temperature. These factors can contribute to extended droughts, heightened evapotranspiration, and lower surface and groundwater resources availability. Over-extraction of groundwater to irrigate lands has resulted in dramatic drops in water tables in most areas, compromising the long-term sustainability of irrigated agriculture.

While water supply becomes more uncertain, traditional irrigation practices might no longer be adequate. There is a pressing necessity to shift toward adaptive irrigation practices that take cognizance of climate variability and optimize the use of available water resources. This calls for region-specific technology outreach and research in areas of drought management, water harvesting, and sustainable groundwater utilization.

Requirement of Precision Agriculture Tools for Real-Time Monitoring

In order to improve the use of irrigation under varying environmental conditions, precision agriculture technologies must be embraced. Internet of Things (IoT) devices, remote sensing, geographic information systems (GIS), global positioning systems (GPS), and artificial intelligence (AI) can facilitate real-time data monitoring as well as data-based decision-making.

For example, IoT-linked soil moisture sensors can give real-time feedback about the water status of the soil to enable automated and accurate irrigation scheduling. Remote sensing devices based on satellites or drones can measure crop health, water stress, and canopy temperature over large fields. The use of these technologies reduces water loss, cuts input costs, and increases the yield.

Nonetheless, issues of cost, availability, technical expertise, and infrastructure must be overcome to make these technologies scalable and relevant for a wide range of agricultural systems, particularly for smallholder farmers.

Breeding Resilient Crop Varieties with Enhanced WUE and Root Systems

The creation of crop varieties that are water stress tolerant and can make better use of water is essential for future agricultural sustainability. Crop improvement programs are also accentuating traits like increased water use efficiency (WUE), deep and effective root growth, osmotic adjustment, and delayed senescence to enhance plant performance under drought and water-deficit conditions.

Improved molecular breeding, genomics, and biotechnology have spurred the identification and deployment of drought-tolerance genes and root architectural traits into high-yielding crop varieties. These genetic traits, together with effective irrigation systems, have the potential to dramatically elevate productivity in water-scarce conditions. Research should also target the diversification of crops and the introduction of underutilized species, which naturally occur on dry and marginal soils.

Farmer Education and Policy Support to Adopt Water-Efficient Practices

Successful adoption of water-saving technologies and sustainable soil-water-plant management hinges significantly on farmers' knowledge, attitudes, and practices. Hence, capacity building and farmer education are critical in overcoming the gap between research and practice. Extension services should emphasize farmer training in the utilization of irrigation scheduling tools, mulching practices, soil moisture conservation, and water-efficient cropping systems.

Apart from education, there is a critical role for policy support. Government policies like subsidies for drip and sprinkler systems, financial rewards for climate-resilient practice adoption, water price reforms, and investment in water infrastructure can promote the use of efficient irrigation technologies at large scale. In addition, policies ought to support IWRM, community water governance, and institutional arrangements that guarantee equitable and sustainable access to water by all farming communities.

Table 2 : Challenges and Future Directions in Soil-Water-Plant Interactions for Irrigation Efficiency and Crop Productivity

S. No.	Challenge	Description	Future Directions / Solutions
1	**Climate Change and Falling Water Tables**	Climate variability alters precipitation, increases temperature, and causes extreme weather events, leading to prolonged droughts and groundwater depletion due to over-extraction.	Develop adaptive irrigation practices Promote region-specific research on drought management, rainwater harvesting, and sustainable groundwater use Encourage integrated water resource management (IWRM)
2	**Need for Precision Agriculture Tools**	Limited adoption of modern technologies like IoT, GIS, remote sensing, and AI for real-time monitoring hampers efficient irrigation, especially under varying environmental conditions.	Deploy soil moisture sensors, drone-based monitoring, and automated irrigation systems Invest in R&D and capacity building for digital agriculture Address affordability and accessibility for smallholder farmers
3	**Breeding Resilient Crop Varieties with High WUE**	Many current crop varieties are vulnerable to drought and inefficient in water usage. There is a need to improve traits like root architecture, osmotic adjustment, and stress tolerance.	Focus on breeding programs targeting drought-resilient and water-efficient crops Use biotechnology and genomics to introduce stress-tolerance genes Promote crop diversification with underutilized, climate-resilient species
4	**Farmer Education and Supportive Policy Frameworks**	Lack of awareness and technical knowledge among farmers restricts the adoption of water-saving practices. Policy incentives are often inadequate or poorly implemented.	Strengthen extension services and farmer training in efficient irrigation techniques Provide subsidies and incentives for micro-irrigation and sustainable practices Implement water pricing reforms and strengthen community-based water governance systems

Conclusion

An integrated concept of the soil-water-plant continuum underlies improving sustainable agriculture against increasing global challenges like climate change, water deficit, and food insecurity. This complex interrelationship regulates the supply and effective utilization of water by crops, determining all facets of plant growth, development, and yields.

It needs an integrated strategy that involves soil health management, understanding the mechanisms of plant water uptake, and adoption of innovative irrigation technologies. By increasing soil physical properties via organic amendments, adopting conservation strategies such as mulching and reduced tillage, and applying smart irrigation systems, it is possible to considerably lower water losses and maximize plant water use.

In addition, precision agriculture technologies like IoT-based soil moisture sensors, remote sensing, and decision support systems are poised to revolutionize real-time, site-specific water management. These technologies, when linked with enhanced crop genetics and education among farmers, provide an avenue toward sustainable and resource-efficient agricultural systems.

Going forward, there should be a focus on developing location-specific best management practices, water and nutrient management integration, and scaling digital technology for small and big farms. It will be essential to have interdisciplinary collaborations among policymakers, scientists, extension agents, and farmers to make this knowledge translate into action, such that agriculture continues to be productive, sustainable, and climate resilient.

References

Acharya, C.L. (2008). Soil-water-plant relationships and input use efficiency. *Journal of the Indian Society of Soil Science*, **56**(4), 404-413.

Ahmad, S., Tariq, H., Abbas, S., Arshad, M., Mumtaz, A., & Ahmed, I. (2022). Organic and synthetic mulching: Effects on soil-plant productivity and environment. In *Mulching in agroecosystems: Plants, soil & environment* (pp. 329-351). Singapore: Springer Nature Singapore.

Ahuja, L. R., Nachabe, M. H., & Rockiki, R. (2008). Soils: field capacity. *Encyclopedia of Water Science*, **2**, 1128-1131.

Altieri, M. A., & Koohafkan, P. (2008). *Enduring farms: climate change, smallholders and traditional farming communities* (Vol. 6, p. 63). Penang: Third World Network (TWN).

Anderson, R.L. (2011). Synergism: a rotation effect of improved growth efficiency. *Advances in agronomy*, **112**, 205-226.

Anjum, S. A., Ashraf, U., Zohaib, A., Tanveer, M., Naeem, M., Ali, I., ... & Nazir, U. (2017). Growth and development responses of crop plants under drought stress: a review.

Aston, M. J., & Lawlor, D. W. (1979). The relationship between transpiration, root water uptake, and leaf water potential. *Journal of Experimental Botany*, **30**(1), 169-181.

Attri, M., Bharti, V., Ahmad Nesar, N., Mehta, S., Bochalya, R. S., Kumar Bansal, K., & Sandhu, R. (2022). Improved irrigation practices for higher agricultural productivity: A review. *Int. J. Environ. Clim. Chang*, **12**, 51-61.

Aung, K., Jiang, Y., & He, S.Y. (2018). The role of water in plant–microbe interactions. *The Plant Journal*, **93**(4), 771-780.

Bachmann, J., & van der Ploeg, R. R. (2002). A review on recent developments in soil water retention theory: interfacial tension and temperature effects. *Journal of plant nutrition and soil science*, **165**(4), 468-478.

Balasubramanian, A. (2017). Physical Properties of Soils. *Volume*, **6**, 1-8.

Ben-Hur, M., Yolcu, G., Uysal, H., Lado, M., & Paz, A. (2009). Soil structure changes: aggregate size and soil texture effects on hydraulic conductivity under different saline and sodic conditions. *Soil Research*, **47**(7), 688-696.

Bhatla, S. C., & Lal, M. A. (2023). Mechanisms of water and solute transport. In *plant physiology, development and metabolism* (pp. 51-73). Singapore: Springer Nature Singapore.

Bhattacharya, A., & Bhattacharya, A. (2021). Effect of soil water deficit on growth and development of plants: a review. *Soil water deficit and physiological issues in plants*, 393-488.

Bhattacharyya, T. A. P. A. S., & Pal, D.K. (2015). The soil: A natural resource. *Soil Science: An Introduction; Rattan, RK, Katyal, JC, Dwivedi, BS, Sarkar, AK, Tapas Bhattacharyya, JC, Tarafdar, SK, Eds*, 1-19.

Bittelli, M. (2011). Measuring soil water content: A review. *HortTechnology*, **21**(3), 293-300.

Blum, A. (2005). Drought resistance, water-use efficiency, and yield potential are they compatible, dissonant, or mutually exclusive?. *Australian journal of agricultural research*, **56**(11), 1159-1168.

Blum, A. (2009). Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field crops research*, **112**(2-3), 119-123.

Boyle, M., Frankenberger Jr, W. T., & Stolzy, L. H. (1989). The influence of organic matter on soil aggregation and water infiltration. *Journal of production agriculture*, **2**(4), 290-299.

Buckley, T.N. (2019). How do stomata respond to water status?. *New Phytologist*, **224**(1), 21-36.

Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, **260**, 107324.

Carminati, A., Vetterlein, D., Weller, U., Vogel, H. J., & Oswald, S. E. (2009). When roots lose contact. *Vadose Zone Journal*, **8**(3), 805-809.

Chai, Q., Gan, Y., Zhao, C., Xu, H. L., Waskom, R. M., Niu, Y., & Siddique, K. H. (2016). Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for sustainable development*, **36**, 1-21.

Chapuis, R. P. (2012). Predicting the saturated hydraulic conductivity of soils: a review. *Bulletin of engineering geology and the environment*, **71**, 401-434.

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M., & Maity, S. (2013). Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. *International Journal of Scientific and Research Publications*, **3**(2), 1-8.

Collins, D. B. G., & Bras, R. L. (2007). Plant rooting strategies in water‐limited ecosystems. *Water Resources Research*, **43**(6).

Connolly, R. D. (1998). Modelling effects of soil structure on the water balance of soil–crop systems: a review. *Soil and Tillage Research*, **48**(1-2), 1-19.

Dasberg, S., & Or, D. (2013). *Drip irrigation*. Springer Science & Business Media.

De Pascale, S., Dalla Costa, L., Vallone, S., Barbieri, G., & Maggio, A. (2011). Increasing water use efficiency in vegetable crop production: from plant to irrigation systems efficiency. *HortTechnology*, **21**(3), 301-308.

Dexter, A. R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma*, **120**(3-4), 201-214.

Dikilitas, M., Simsek, E., & Roychoudhury, A. (2020). Role of proline and glycine betaine in overcoming abiotic stresses. *Protective chemical agents in the amelioration of plant abiotic stress: biochemical and molecular perspectives*, 1-23.

Dumais, J., & Forterre, Y. (2012). "Vegetable dynamicks": the role of water in plant movements. *Annual Review of Fluid Mechanics*, **44**(1), 453-478.

Evett, S. R. (2007). Soil water and monitoring technology. *Irrigation of agricultural crops*, **30**, 23-84.

Evett, S. R., Prueger, J. H., Tolk, J. A., & Huang, P. (2012). *Water and energy balances in the soil-plant-atmosphere continuum*. CRC Press: Boca Raton, FL, USA.

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., ... & Huang, J. (2017). Crop production under drought and heat stress: plant responses and management options. *Frontiers in plant science*, **8**, 1147.

Farooq, M., Hussain, M., & Siddique, K. H. (2014). Drought stress in wheat during flowering and grain-filling periods. *Critical reviews in plant sciences*, **33**(4), 331-349.

Fatichi, S., Pappas, C., & Ivanov, V. Y. (2016). Modeling plant–water interactions: an ecohydrological overview from the cell to the global scale. *Wiley Interdisciplinary Reviews: Water*, **3**(3), 327-368.

Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of experimental botany*, **58**(2), 147-159.

Franzluebbers, A. J. (2002). Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage research*, **66**(2), 197-205.

Gahir, S., Bharath, P., & Raghavendra, A. S. (2021). Stomatal closure sets in motion long-term strategies of plant defense against microbial pathogens. *Frontiers in Plant Science*, **12**, 761952.

Gardner, C. M., Robinson, D., Blyth, K., & Cooper, J. D. (2000). Soil water content. In *Soil and environmental analysis* (pp. 13-76). CRC Press.

Gavrilescu, M. (2021). Water, soil, and plants interactions in a threatened environment. *Water*, **13**(19), 2746.

Ghezzehei, T. A. (2012). Soil structure. *Handbook of soil science*, **2**, 1-17.

Gill, K. S., Jalota, S. K., Prihar, S. S., & Chaudhary, T. N. (1977). Water conservation by soil mulch in relation to soil type, time of tillage, tilth and evaporativity. *Journal of the Indian Society of Soil Science*, **25**(4), 360-366.

Haghnazari, F., Shahgholi, H., & Feizi, M. (2015). Factors affecting the infiltration of agricultural soils. *International Journal of Agronomy and Agricultural Research*, **6**(5), 21-35.

Hao, X., Ball, B. C., Culley, J. L. B., Carter, M. R., & Parkin, G. W. (2008). Soil density and porosity. *Soil sampling and methods of analysis*, **2**, 743-759.

Hawkes, C. V., DeAngelis, K. M., & Firestone, M. K. (2007). Root interactions with soil microbial communities and processes. In *The rhizosphere* (pp. 1-29). Academic press.

Heidar Barghi, M. (2019). *Use of capillary action to control soil moisture* (Doctoral dissertation, University of Birmingham).

Hendrickx, J. M., Phillips, F. M., & Harrison, J. B. J. (2003). Water flow processes in arid and semi-arid vadose zones. In *Understanding water in a dry environment* (pp. 167-226). CRC Press.

Hillel, D. (2007). *Soil in the environment: crucible of terrestrial life*. Elsevier.

Horel, Á. (2024). Soil–plant–water systems and interactions. *Plants*, **13**(3), 358.

Hsiao, T. C., Fereres, E., Acevedo, E., & Henderson, D. W. (1976). Water stress and dynamics of growth and yield of crop plants. In *Water and Plant life: Problems and modern approaches* (pp. 281-305). Berlin, Heidelberg: Springer Berlin Heidelberg.

Huang, B. (2000). Role of root morphological and physiological characteristics in drought resistance of plants. In *Plant-environment interactions* (pp. 39-64). CRC Press.

Huntley, B. J. (2023). Soil, water and nutrients. In *Ecology of Angola: Terrestrial biomes and ecoregions* (pp. 127-147). Cham: Springer International Publishing.

Irmak, S., Sharma, V., Mohammed, A. T., & Djaman, K. (2018). Impacts of cover crops on soil physical properties: Field capacity, permanent wilting point, soil-water holding capacity, bulk density, hydraulic conductivity, and infiltration. *Transactions of the ASABE*, **61**(4), 1307-1321.

Jarvis, N., Koestel, J., Messing, I., Moeys, J., & Lindahl, A. (2013). Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrology and Earth System Sciences*, **17**(12), 5185-5195.

Kato, Y., & Okami, M. (2011). Root morphology, hydraulic conductivity and plant water relations of high-yielding rice grown under aerobic conditions. *Annals of Botany*, **108**(3), 575-583.

Kay, B. D. (2018). Soil structure and organic carbon: a review. *Soil processes and the carbon cycle*, 169-197.

Keller, T., & Håkansson, I. (2010). Estimation of reference bulk density from soil particle size distribution and soil organic matter content. *Geoderma*, **154**(3-4), 398-406.

Khalil, U., Ali, S., Rizwan, M., Rahman, K. U., Ata-Ul-Karim, S. T., Najeeb, U., ... & Hussain, S.M. (2018). Role of mineral nutrients in plant growth under extreme temperatures. *Plant nutrients and abiotic stress tolerance*, 499-524.

Khan, Naeem, Shahid Ali, Haleema Tariq, Sadia Latif, Humaira Yasmin, Asif Mehmood, and Muhammad Adnan Shahid. "Water conservation and plant survival strategies of rhizobacteria under drought stress." *Agronomy* 10, no. 11 (2020): 1683.

Kirkham, M. B. (2023). *Principles of soil and plant water relations*. Elsevier.

Knappett, J. (2012). *Craig's soil mechanics* (Vol. 8). London: Spon Press.

Kozlowski, T. T. (1999). Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*, **14**(6), 596-619.

Kumar, S., Meena, R. S., Jakhar, S. R., Jangir, C. K., Gupta, A., & Meena, B. L. (2019). Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. *Sustainable agriculture. Scientific Publisher, Jodhpur*, 226-274.

Lawrence, G. P. (1977). Measurement of pore sizes in fine‐textured soils: a review of existing techniques. *Journal of Soil Science*, **28**(4), 527-540.

Li, B., Zhang, X., Morita, S., Sekiya, N., Araki, H., Gu, H., ... & Liu, X. (2022). Are crop deep roots always beneficial for combating drought: A review of root structure and function, regulation and phenotyping. *Agricultural Water Management*, **271**, 107781.

Li, D., Long, H., Zhang, S., Wu, X., Shao, H., and Wang, P. (2017). Effect of continuous negative pressure water supply on the growth, development and physiological mechanism of *Capsicum annuum* L. *J. Integr. Agric*. **16**, 1978–1989.

Li, S. X., Wang, Z. H., Malhi, S. S., Li, S. Q., Gao, Y. J., & Tian, X. H. (2009). Nutrient and water management effects on crop production, and nutrient and water use efficiency in dryland areas of China. *Advances in agronomy*, **102**, 223-265.

Liao, Q., Gu, S., Kang, S., Du, T., Tong, L., Wood, J. D. *et al.* (2022). Mild water and salt stress improve water use efficiency by decreasing stomatal conductance via osmotic adjustment in field maize. *Sci. Total Environ*. **805**, 150364.

Lynch, J. (1995). Root architecture and plant productivity. *Plant physiology*, **109**(1), 7.

Mehta, P. (2024). The Impact of Climate Change on the Environment, Water Resources, and Agriculture: A Comprehensive Review. *Climate, Environment and Agricultural Development: A Sustainable Approach Towards Society*, 189-201.

Mohr, H., Schopfer, P., Mohr, H., & Schopfer, P. (1995). Physiology of xylem transport. *Plant Physiology*, 467-486.

Muhammad Aslam, M., Waseem, M., Jakada, B. H., Okal, E. J., Lei, Z., Saqib, H. S. A., ... & Zhang, Q. (2022). Mechanisms of abscisic acid-mediated drought stress responses in plants. *International journal of molecular sciences*, **23**(3), 1084.

Nambiar, E. S. (1990). Interplay between nutrients, water, root growth and productivity in young plantations. *Forest Ecology and Management*, **30**(1-4), 213-232.

Navari-Izzo, F., & Rascio, N. (1999). Plant response to water-deficit conditions. *Handbook of plant and crop stress*, 231-270.

NK, S., & Ga, D. (2024). Coupled weather and crop simulation modeling for smart irrigation planning: a review. *Water Supply*, **24**(8), 2844-2865.

Novák, V., Hlaváčiková, H., Novák, V., & Hlaváčiková, H. (2019). Basic physical characteristics of soils. *Applied Soil Hydrology*, 15-28.

Osman, K. T., & Osman, K. T. (2013). Physical properties of soil. *Soils: Principles, properties and management*, 49-65.

Ouda, S., Noreldin, T., & Zohry, A. E. H. (2020). *Deficit Irrigation* (pp. 15-27). springer.

Patil, N. G., Pal, D. K., Mandal, C., & Mandal, D. K. (2012). Soil water retention characteristics of vertisols and pedotransfer functions based on nearest neighbor and neural networks approaches to estimate AWC. *Journal of Irrigation and Drainage Engineering*, **138**(2), 177-184.

Penuelas, J., & Sardans, J. (2021). Developing holistic models of the structure and function of the soil/plant/atmosphere continuum. *Plant and Soil*, **461**(1), 29-42.

Pereira, L. S., & Gonçalves, J. M. (2018). Surface irrigation. In *Oxford research encyclopedia of environmental science*.

Pereira, L. S., Paredes, P., & Jovanovic, N. (2020). Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. *Agricultural water management*, **241**, 106357.

Phogat, V. K., Tomar, V. S., & Dahiya, R. I. T. A. (2015). Soil physical properties. *Soil science: An introduction*, 135-171.

Pirasteh‐Anosheh, H., Saed‐Moucheshi, A., Pakniyat, H., & Pessarakli, M. (2016). Stomatal responses to drought stress. *Water stress and crop plants: A sustainable approach*, **1**, 24-40.

Prem, M., Ranjan, P., Seth, N., & Patle, G. T. (2020). Mulching techniques to conserve the soil water and advance the crop production—A Review. *Curr. World Environ*, **15**, 10-30.

Prosdocimi, M., Tarolli, P., & Cerdà, A. (2016). Mulching practices for reducing soil water erosion: A review. *Earth-Science Reviews*, **161**, 191-203.

Raine, S. R., Meyer, W. S., Rassam, D. W., Hutson, J. L., & Cook, F. J. (2007). Soil–water and solute movement under precision irrigation: knowledge gaps for managing sustainable root zones. *Irrigation Science*, **26**, 91-100.

Rashmi, I., Shirale, A., Kartikha, K. S., Shinogi, K. C., Meena, B. P., & Kala, S. (2017). Leaching of plant nutrients from agricultural lands. *Essential plant nutrients: uptake, use efficiency, and management*, 465-489.

Reeve, M. J., Smith, P. D., & Thomasson, J. (1973). The effect of density on water retention properties of field soils. *Journal of soil science*, **24**(3), 355-367.

Robinson, D. A., Thomas, A., Reinsch, S., Lebron, I., Feeney, C. J., Maskell, L. C., ... & Cosby, B. J. (2022). Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. *Scientific reports*, **12**(1), 7085.

Russo, T., Alfredo, K., & Fisher, J. (2014). Sustainable water management in urban, agricultural, and natural systems. *Water*, **6**(12), 3934-3956.

Sabir, R. M., Sarwar, A., Shoaib, M., Saleem, A., Alhousain, M. H., Wajid, S. A., ... & Raza, A. (2024). Managing Water Resources for Sustainable Agricultural Production. In *Transforming Agricultural Management for a Sustainable Future: Climate Change and Machine Learning Perspectives* (pp. 47-74). Cham: Springer Nature Switzerland.

Sankari, M., Kamatchi, K. S., KarpuraDheepan, G. M., Sridevi, N., & Hemalatha, C. (2024). Innovations in Irrigation: Water Conservation in Agriculture.

Schenk, H. J., & Jackson, R. B. (2002). Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. *Journal of Ecology*, 480-494.

Seiler, K. P., & Gat, J. R. (2007). *Groundwater recharge from run-off, infiltration and percolation* (Vol. 55). Springer Science & Business Media.

Selim, M. M. (2020). Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. *International Journal of Agronomy*, **2020**(1), 2821678.

Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, **11**(5), 1485.

Sharma, P. K., & Kumar, S. (2023). *Soil Physical Environment and Plant Growth*. Berlin/Heidelberg, Germany: Springer.

Shaxson, T. F., & Barber, R. G. (2003). *Optimizing soil moisture for plant production: The significance of soil porosity* (Vol. 79). Food & Agriculture Org..

Sheikhesmaeili, O., Montero, J., & Laserna, S. (2016). Analysis of water application with semi-portable big size sprinkler irrigation systems in semi-arid areas. *Agricultural Water Management*, **163**, 275-284.

Singh, M., Kumar, J., Singh, S., Singh, V. P., & Prasad, S. M. (2015). Roles of osmoprotectants in improving salinity and drought tolerance in plants: a review. *Reviews in environmental science and bio/technology*, **14**, 407-426.

Singh, V. K., Malhi, G. S., Kaur, M., Singh, G., & Jatav, H. S. (2022). Use of organic soil amendments for improving soil ecosystem health and crop productivity. *Ecosystem Services*.

Somefun, O. T., Masasi, B., & Adelabu, A. O. (2024). Irrigation and Water Management of Tomatoes–A Review. *Journal of Sustainable Agriculture and Environment*, **3**(4), e70020.

Stagnari, F., Ramazzotti, S., & Pisante, M. (2010). Conservation agriculture: a different approach for crop production through sustainable soil and water management: a review. *Organic Farming, Pest Control and Remediation of Soil Pollutants: Organic farming, pest control and remediation of soil pollutants*, 55-83.

Sun, F., & Lu, S. (2014). Biochars improve aggregate stability, water retention, and pore‐space properties of clayey soil. *Journal of Plant Nutrition and Soil Science*, **177**(1), 26-33.

Sun, Q., Wang, Y., Chen, G., Yang, H., and Du, T. (2018). Water use efficiency was improved at leaf and yield levels of tomato plants by continuous irrigation using semipermeable membrane. *Agric. Water Manage.* **203**, 430–437.

Tardieu, F. (2013). Plant response to environmental conditions: assessing potential production, water demand, and negative effects of water deficit. *Frontiers in physiology*, **4**, 17.

Thompson, R. B., & Gallardo, M. (2003). Use of soil sensors for irrigation scheduling. *Improvement of water use efficiency in protected crops. Advanced specialization course. Direccion General de Investigacion y Formacion Agraria de la Junta de Andalucia, HortiMed, FIAPA, Cajamar*, 375-402.

Tolk, J.A. (2003). Soils, permanent wilting points. *Encyclopedia of water science*, *120010337*, 92.

Tonkha, O. L., & Dzyazko, Y. S. (2014). Soils and plant roots. *Structural properties of porous materials and powders used in different fields of science and technology. Springer, London*, 221-249.

Usharani, K. V., Roopashree, K. M., & Naik, D. (2019). Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry*, **8**(5), 1256-1267.

Van Der Heijden, M. G., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology letters*, **11**(3), 296-310.

Varman, S. (2025). *Advanced irrigation and drainage techniques*. Educohack Press.

Wang, C., Fu, B., Zhang, L., & Xu, Z. (2019). Soil moisture–plant interactions: an ecohydrological review. *Journal of Soils and Sediments*, **19**, 1-9.

Wang, R., Yang, Q., Deng, Z., & Nian, W. (2025). The research on soil-plant-climate interactions: An integrated assessment of water management and drought resilience. *Advances in Resources Research*, **5**(1), 456-476.

Wang, T., Wu, Z., Wang, P., Wu, T., Zhang, Y., Yin, J., ... & Yan, D. (2023). Plant-groundwater interactions in drylands: A review of current research and future perspectives. *Agricultural and Forest Meteorology*, **341**, 109636.

Wang, Z. (2020). Effects of soil moisture temporal variation on growth, physiology and water use efficiency of maize and lettuces. (Beijing, China: Chinese Academy of Agricultural Sciences).

Williams, M. A., & Rice, C. W. (2007). Seven years of enhanced water availability influences the physiological, structural, and functional attributes of a soil microbial community. *Applied Soil Ecology*, **35**(3), 535-545.

Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of the Total Environment*, **512**, 415-427.

Xing, Y., & Wang, X. (2024). Precision agriculture and water conservation strategies for sustainable crop production in arid regions. *Plants*, **13**(22), 3184.

Yudina, A. V., Klyueva, V. V., Romanenko, K. A., & Fomin, D.S. (2022). Micro-within macro: How micro-aggregation shapes the soil pore space and water-stability. *Geoderma*, **415**, 115771.

Zapata, N., Robles, O., Playán, E., Paniagua, P., Romano, C., Salvador, R., & Montoya, F. (2018). Low-pressure sprinkler irrigation in maize: Differences in water distribution above and below the crop canopy. *Agricultural Water Management*, **203**, 353-365.

Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F., & Wu, J. (2020). Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. *Water*, **12**(8), 2127.

Zhou, H., Chen, C., Wang, D., Arthur, E., Zhang, Z., Guo, Z., ... & Mooney, S. J. (2020). Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. *Soil and Tillage Research*, **202**, 104663.