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Soil Water Relations and Hydraulic Properties in Agricultural Systems: Processes, Influencing Factors, and Implications for Irrigation Efficiency and Crop Productivity: A Review

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Abstract: The most significant components of soil physics are the soil water relations and hydrostatic properties which determine the entry, flow and storage of water in agricultural soils. These processes directly impact the irrigation efficiency, plant-available water, root development and crop productivity. This was a review to provide a scientific review of the soil water relations and hydraulic properties in agricultural systems with particular focus on soil moisture, water retention, infiltration, permeability and hydraulic conductivity. The review also looked at the key considerations on soil water movement such as soil texture, soil structure and organic matters and the implication of these on irrigation efficiency and crop productivity. The results show that the hydraulic behavior of the soil is greatly affected by the nature of the soil and the management of soil. The positive hydraulic characteristics of soils increase water retention, water movement and crop growth whereas, negative hydraulic characteristics reduce the efficiency of irrigation systems and increase chances of water stress and loss of crops. Overall, water-use efficiency should be enhanced, by enhancing understanding of hydraulic properties and sustainable agricultural practice, to enhance the health of the soil, and to maintain the crop productivity in the long-term.

Key words: Soil water relations; Hydraulic properties; Soil moisture; Water retention; Infiltration; Hydraulic conductivity; Irrigation efficiency; Agricultural systems.

Introduction

Some of the most significant aspects of soil physics are soil water relations and hydraulic properties since they dictate the entry of water into the soil, its flow through the profile, and its retention in the root zone to be used by plants. Such processes have direct impacts on the efficiency of irrigation, supply of crop-water, nutrient transportation and end productivity in agricultural systems. Hydraulic properties like water retention and hydro-conductivity in soil are thus fundamental in comprehending the soil behaviour in cases of irrigation and rainfall and in enhancing the agro-hydrological management in crop production systems (Bonfim-Silva et al., 2025; Pinheiro et al., 2019).

The significance of the topic has been growing over the past years due to the exposure of agricultural soils to irregular rainfall, shortage of water, intensive fieldwork, and structural erosion. Hydraulic functioning of the soil in this instance is a critical factor of the water retained in the root zone or lost in water runoff, evaporation, and the deep percolation. It has been shown that soil hydraulic properties play an important role in the aspect of water-balance and crop productivity, and this means that the low hydraulic performance may reduce the irrigation efficiency and crop response in the context of water stresses in the soil (Pinheiro et al., 2019; Tucker et al., 2025).

The soil water retention and the hydraulic conductivity of soil are among the most crucial hydraulic properties of soil. The retention of water in the soil shows that the soil is capable of holding water at the different tension whereas the hydraulic conductivity shows that the water can flow easily through the soil pores in saturated or unsaturated soils. Infiltration, redistribution, drainage and water available to plant life is defined as a combination of these properties. Recent works on Agronomy emphasized that the water retention and hydraulic conductivity are to be estimated properly to handle irrigation and

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agro-hydrological modeling as the two characteristics are induced when simulating crop yield under different water-stress and soil-management regimes (Bonfim-Silva et al., 2025).

Soil hydraulic behavior is also very sensitive to agricultural management. The field evidence of long-term field behavior demonstrates that the contrasting management systems can change significantly the field-saturated and near-saturated hydraulic conductivity, and aggregate stability, pore-size distribution, and macroporosity. As an example, a recent study found that the soil-health-oriented systems were more likely to increase water-stable aggregates, macroporosity, and unsaturated hydraulic behaviour in comparison to the conventional systems, and that the management of differences also impacted the ability of the soil to transmit water through the profile (Garg et al., 2025; Tangen et al., 2025).

The result of these relationships is that it is the dynamics of soil water that sustainable agriculture is concerned about. Effective infiltration, good retention and continuity of pores in soils together allow soils to facilitate root development, increase water-use efficiency, and stabilize crop production during climatic stress periods. On the other hand, soils that have poor hydraulic characteristics are less effective in storing and providing water, thus lowering the utility of irrigation and leading to yield loss. That is why the examination of the interactions between soil and water has recently acquired an important position not only in the science of soil physics, but also in the science of irrigation, the science of environmental management, and climate change resilient agriculture (Xing et al., 2025; Singh et al., 2025). Recent systematic reviews highlighted the need to understand modern trends and future challenges in heterogeneous developmental sectors in a holistic analytical approach, by focusing on the interplay between structural conditions and economic determinants and long-term planning (Palani, 2025a; Palani, 2025b).

In this way, this review aims to provide a scientific summary of soil water relations and hydraulic properties in agricultural systems in the context of soil moisture behavior, water retention, infiltration, permeability and hydraulic conductivity and which factors are significant in influencing these processes. The implications of soil hydraulic behavior on the efficiency of irrigation and crop productivity are also considered in the review and the current challenges and future directions in sustainable soil-water management in agriculture are identified (Bonfim-Silva et al., 2025; Garg et al., 2025; Pinheiro et al., 2019).

Methodology

The review article was written in a systematic narrative-review format to find, arrange, and summarize the most pertinent scientific data on soil water relations and hydraulic characteristics of agricultural systems. Although the current paper is not a meta-analysis, the review process was carried out based on the transparent principles of identifying and screening evidence and synthesizing it according to the PRISMA 2020 guidelines that are typically used to increase the degree of clarity and reproducibility of the review studies (Page et al., 2021a, 2021b).

Peer-reviewed journal articles located in extensive academic databases were used to perform the literature search; specifically, articles that discussed soil water retention, infiltration, permeability, hydraulic conductivity and the behavior of soil-water in relation to irrigation. Special consideration was made to the recent research on soil-physics and agricultural-water studies since the soil hydraulic properties are directly applied to the irrigation management and agro-hydrological practices (Bonfim-Silva et al., 2025; Garg et al., 2025; Pinheiro et al., 2019).

The combinations of the key words such as soil water relations, soil hydraulic properties, soil water retention, hydraulic conductivity, infiltration, permeability, soil moisture, irrigation efficiency, crop productivity and agricultural systems were the basis of this search strategy. To narrow the search, it was narrowed down by using Boolean operators such as AND and OR to narrow the search. The reference lists of the selected studies were also inspected manually to identify additional sources that are relevant in the study, especially those that focus on the issue of soil hydraulic behavior and crop response to different management systems (Pinheiro et al., 2019; Garg et al., 2025).

Peer-reviewed articles and authoritative review papers that had a direct relationship with soil hydraulic behavior in agricultural soils were used as inclusion criteria. Included in the studies that were considered in the research were those ones that had one or more of the following themes: properties of soil water retention, saturated or unsaturated hydraulic conductivity, infiltration, and permeability, management effects on soil-water behavior, and implications on irrigation efficiency or crop productivity. Old foundational studies were not excluded when they also directly pertained to the conceptual basis of the review, but the most recent ones were placed first (Bonfim-Silva et al., 2025; Pinheiro et al., 2019).

Duplication records, poorly documented materials, and the studies, which were not directly related to the soil-water processes within the agricultural setting, were used as the exclusion criteria. Articles that only dealt with irrelevant chemical or biological issues were not accepted unless they made a definite addition to hydraulic behavior knowledge in soil. After the primary screen of titles and abstracts, the potentially relevant studies were accessed in a full text and sorted into the types of key themes of the review. Among them were the soil moisture and water retention, infiltration and hydraulic conductivity, effect on soil-water movement, irrigation efficiency and crop productivity consequences (Page et al., 2021a, 2021b).

The conclusion that was reached was both descriptive and critical but not statistical. The chosen works were compared to see the general findings, significant contributing factors, and implications on managing water in agriculture. This method was deemed suitable since it was the aim of the article to give a synthesized scientific knowledge of the soil water relations and hydraulic properties and not a pooled quantitative effect size. In this respect, it was anticipated that the review would possess a high-quality reference base in all spheres, and each of the main topics of the discussion would be supported by credible and relevant sources (Bonfim-Silva et al., 2025; Garg et al., 2025; Pinheiro et al., 2019).

Soil Water Relations and Hydraulic Properties Concept.

The relationship between soil water storage, storage, release and transmission within the soil profile and quantitative characteristics which serve as controls, respectively, are specified using the terms soil water relations and soil hydraulic properties. These properties are important in agricultural systems since they dictate the amount of water that gets into the soil, the rate at which it moves, the length of time it can stay in the root zone as well as the efficiency of crops to use it. This is why the relations between soil water are one of the key components of soil physics and one of the main foundation of irrigation planning and crop-water management (Bonfim-Silva et al., 2025; Pinheiro et al., 2019).

Soil water retention is one of the most important notions in the given field, as it explains the correlation between soil water content and soil water potential. This correlation explains how deeply the water is bound to the soil and the quantity of water that will be available to be taken up by the plants freely. Bonfim-Silva et al. (2025) highlighted that one of the primary hydraulic properties needed in irrigation and agro-hydrological uses is soil water retention as it assists in determining the scope of water conditions that are pertinent to crop growth. Similarly, Jabro et al. (2025) explained that the soil water retention curve demonstrates how soil may be in a position to absorb as well as discharge water as suction changes and that the curve is often employed to estimate numerous physical as well as hydraulic parameters in the unsaturated state.

The other principle concept is that of hydraulic conductivity which is a value of the ability of soil to conduct water in the form of water pore. The saturated condition primarily affects conductivity due to larger pores and pore continuity, whereas the water-filled pore networks and soil-water tension primarily affect conductivity in the unsaturated condition. It is stated that the field-saturated and near-saturated hydro of the soil is a significant indicator of the behavior of hydraulic conductivity of the soil to the agricultural management and da Silva and Kay (2007) found that hydraulic conductivity is a central operation to determine the flow of water in the field, especially due to the fact that the conductivity varies drastically as.

The concept of the soil water relations also includes infiltration, permeability and redistribution of water in the profile. The penetration of water into the soil surface is referred to as infiltration and permeability and conductivity are related to the water penetration in the soil body. The processes are not only determined by the texture but also they are most reliant on the aggregation, the pore continuity, the compaction state and the management history. The agricultural literature has shown that field-saturated hydraulic conductivity and infiltration behavior can be significantly changed by the tillage system, crop rotation, and soil-health practices and that hydraulic properties are dynamic and can be manipulated by management rather than a fixed characteristic (Garg et al., 2025; Patra et al., 2023).

A similar concept is the plant-available water, i.e. the portion of the soil water which is accessible to plants within upper and lower moisture limits. This notion is particularly significant in irrigation agriculture since the overall water content does not imply the availability of water to roots. Hydraulic properties of soil analyzed by Pinheiro et al. (2019), showed that elements of water-balances and crop water-use efficiency strongly depend on the difference between the retention and conductivity, and, therefore, the difference in productivity can be directly converted to the difference between the retention and conductivity. It is in this respect that the relationship between soil physics and crop performance becomes very practical due to the hydraulic properties.

Water relations and hydraulic soil properties may therefore be viewed in a larger agronomic context as the set of concepts that elucidate the manner in which water is received, retained, transported and allocated to crops by soil. They are extremely important in deciphering the efficiency of irrigation, drought behavior, drainage behavior and the management influences on the soil-water functioning. Thus, the concepts are vital to the sustainable agricultural systems, especially in the regions with limited water resources or increased climate variability and strain soil-water systems (Bonfim-Silva et al., 2025; Garg et al., 2025; Pinheiro et al., 2019).

Characteristics of Soil Moisture and Water Retention.

One of the most significant indicators of soil-water conditions in an agricultural system is soil moisture as it indicates the level of water available in the soil at a certain point, and this has a direct effect on germination, root growth, movement of nutrients, and the growth of crops. Nevertheless, soil moisture has a greater agricultural value than just the quantity of water present, and the ability of water to be held by the soil, and its ability to be released and utilized by plants. This is why soil moisture and water retention properties are considered collectively as an important aspect of soil hydraulic behavior (Bonfim-Silva et al., 2025; Eishoeei et al., 2026).

The retention properties of water are usually expressed as the water retention curve that is the relationship between water content and water potential in soil. This curve is important because it illustrates the quantity of water lost to soil at a given level of suction and it is usually used to estimate the quantity of water available to plants and the way water drains and irrigation requirements. The recent literature emphasizes that the soil water retention curve is a natural physical characteristic as it indicates the distribution of pore-size and overall physical quality of the soil (Bonfim-Silva et al., 2025; Sandram et al., 2025).

The texture, structure, bulk density, and organic matter are the factors that have power over retention of water in agricultural soils. The fine-textured soils can hold more water because of the high percentage of small pores as compared to the coarse-textured ones which drain quicker and hold less water to be utilized by the plant in the future. In the meantime, the capacity to store and release that water in the root zone is changed by structure and aggregation. Studies on irrigation and soil type have shown that the light-textured soils have a higher tendency to require more irrigation because they have a low water-holding capacity, and those soils with a better structure and organic status have a better storage behavior (Deveci et al., 2025; Bonfim-Silva et al., 2025).

The dynamics of soil moisture in the field is also highly dynamic owing to the change of rainfall, irrigation, evaporation, crop uptake and redistribution in the soil profile. It means that two soils with the same average water content may well act in very different ways as far as the speed of water loss or other methods of water storage between irrigation intervals are concerned. According to a recent survey of soil-moisture measurement, it has been noted that the availability of soil-water plays a central role in crop yield and farm management because of its effects on the hydrological process and physical behavior of the soil such as shrinkage, swelling and density (Eishoeei et al., 2026).

The practical importance of water retention in agronomics is that it is directly proportional to water at the disposal of plants. Soils that have too little water retention may expose the crops to recurrent drought stress and soils that have too much water retention may reduce the ratio of water that roots can extract. Therefore, it is necessary to have good irrigation management where the awareness of soil moisture in the root zone is not only known, but also the nature of soil retention which controls the supply of water in the root zone. That is why the soil water retention properties are still considered as key inputs in the agro-hydrological study to design irrigation and crop models, as well as assess the soil-quality (Bonfim-Silva et al., 2025; Tucker et al., 2025).

Finally, soil moisture and water retention properties are paramount in the description of the process of water receipt, storage and supply of crops on agricultural soils. They form a basis of knowledge of water available in plants, the need of irrigation, and they also affect the physical state of the soil on the performance of crops. Therefore, soil physics and sustainable water management in the agricultural sphere pay attention to these properties (Bonfim-Silva et al., 2025; Eishoeei et al., 2026).

Infiltration, Permeability and Hydraulic Conductivity.

The basic hydraulic features include infiltration, permeability and hydraulic conductivity which determine the entry of water into the soil, the movement within the profile, and availability of water to the use of plants. The immediate beneficiaries of the processes are the agricultural systems in the sense of the efficiency in irrigation, the runoff generation, the drainage and the storage of soil-water. These terms are not the same though they are connected. The process of water penetrating into the soil surface is referred to as infiltration, the degree to which water can pass through the soil in the saturated or unsaturated state is termed as permeability and the degree to which the water may pass through the soil is termed as hydraulic conductivity (Garg et al., 2025; Xu et al., 20).

Of these properties, the infiltration is of particular relevance to the field conditions as it determines whether the rainfall or irrigation water will get into the soil or become surface run-offs. In their recent field study, the Mollisols region of northeast China found that tillage treatments increased the initial, stable, and average infiltration rates by about 8.4 to 52.94 percent, and the authors found that Horton model was more effective in explaining the infiltration process than both Kostiakov and Philip models (Xu et al., 2024). This observation shows that infiltration is very sensitive to the management of soils since management controls surface structure, aggregation and pore continuity.

Permeability and hydraulic conductivity are closely connected with the internal pore system of soil. When the networks of pores have been well connected, water flows freely through the profile, compressions, blockages and poor connections among pores inhibit water flow. Garg et al. (2025) found that field-saturated and near saturated hydraulic conductivity differ in opposite agricultural management systems, which confirms the fact that management practices could be highly effective in shifts the capacity of soil to transfer water. They also highlighted in their work that hydraulic conductivity is an important measure of soil hydrological functioning due to its sensitivity to soil structure and pore organization behaviors of soils under wet conditions.

Aggregate stability and quality of structure also have a strong influence on the hydraulic performance of soil. Xu et al. (2024) showed that improved aggregate stability and porosity was related to improved infiltration behaviour during crop growth, suggesting that infiltration was not dictated by the texture but the physical integrity of the soil structure. On the same note, the recent information of the soil-health management systems indicates that systems that have higher stable aggregates and larger pores are more likely to exhibit dynamic hydraulic behaviour, compared to traditional systems, especially when exposed to rainfall conditions (Tangen et al., 2025).

The second important aspect is that the hydraulic conductivity may vary in accordance with the level of saturation. In saturated conditions, the water flow is regulated by the larger pores, in near-saturated and unsaturated conditions by smaller connected pores. This makes near-saturated conductivity particularly valuable to agricultural studies: it can be applied to simulate real field behavior when it rains or is being irrigated, when soil is often moist, although not saturated. Field-saturated and near-saturated conductivity have especially been used by Garg et al. (2025) to determine the role of management, and they have proved to be excellent in determining practical differences in soil-water transmission in agricultural practice.

Favourable infiltration and hydraulic conductivity will increase the efficiency of irrigation because it will get more water entering and moving through the root zone instead of going to waste as a runoff. Poor permeability and low conductivity on the other hand lower the efficacy of irrigation and can likewise augment the danger of erosion, surface sealing or short-term waterlogging. In this manner, besides playing a crucial role in the description of soil physics, they contribute to better water-use efficiency and crop productivity in sustainable agricultural practices (Xu et al., 2024; Garg et al., 2025).

In conclusion, the key concepts that should be learned in the movement of soil-water in agricultural systems are infiltration, permeability, and hydraulic conductivity. They elaborate on the entry of water in the soil, how easily the water moves along the pore networks and the control that management has over the hydraulic activities. The uniform soil structure, the excellent continuity of the pore, and the desirable conductivity of the soil are better positioned to support the efficiency of the irrigation, the available root-zone water, and the sustainable yield of the crop (Xu et al., 2024; Tangen et al., 2025; Garg et al., 2025).

Driving Forces (Affect Soil Water Movement) Texture, Structure, Organic Matter.

Soil water movement depends on a combination of the natural soil characteristics and management factors, and some of the most important include the soil texture, soil structure and organic matter. These features characterize the pore-size distribution, pore continuity, and interaction between water and soil particles that in combination define infiltration, hydraulic conductivity, and water retention of agricultural soils (Pinheiro et al., 2019; Garg et al., 2025).

The importance of soil texture is basic as it defines the basic distribution of the particles in the soil. Sandy soils are coarse-textured soils, which have large pores that enable rapid infiltration and drainage but their water-holding capacity is low. On the other hand, fine-textured soils and particularly clay soils contain more small pores that are more effective to hold water, but may hinder movement of water and aeration when compacted. Pinheiro et al. (2019) confirmed that soil texture is a potent parameter that defines the water balance, and efficiency of crop water-use, i.e. changes in soil texture may lead to the essential change in the quantity of water and crop performance under equal conditions.

However, this is not what makes soil-water behave, it is just texture. The prevailing aspect is in most cases the soil structure as it influences actual water movements through the soil profile. The concept of structure can be used to explain how soil particles are arranged to form aggregates and pore networks which determine the degree to which flow pathways are connected and continuous. Properly organized soils are made up of stable aggregates and interconnecting macropores that enable fast infiltration and efficient redistribution of water. On the other hand, poorly compacted or unstructured soils possess less pore continuity according to which the infiltration rates and water movement are reduced. Garg et al. (2025) have shown that the variations in soil management greatly transformed the field-saturated and near-saturated hydraulic conductivity, and structural changes directly influence the water transmission in agricultural soils.

Another component of importance is soil organic matter because it aids in the formation of aggregates, stabilizes pores and the overall structure of the soil. The importance of organic matter as a binding agent is that it enhances the stability of aggregates and resistance of soil to compaction and structural degradation. It also increases the water-holding capacity because it improves the distribution of the micropores and the increase in the aggregation of soil. Research has indicated that soils that have high organic matter are more likely to have better infiltration capacity, higher hydraulic conductivity as well as more desirable water retention properties. The soil-health management systems which are more likely to improve the organic matter improved the aggregate stability and hydraulic behavior compared to the conventional systems as indicated by Tangen et al. (2025).

These factors are particularly important in agroecosystems. An example of this is that soils that are low in organic matter, have low structure and high in clay may have low infiltration and waterlogging, but similar soils that are more highly aggregated and high in organic matter may have far superior hydraulic properties. Similarly, sandy soils can also benefit of receiving additional organic matter which enhances water holding and makes soils more accessible to water by crops. Xu et al. (2024) found the positive correlation between better aggregate stability and porosity with infiltration rate, which showed the combined impact of the structure and organic matter on the water movement.

These factors are also affected by management practices which alter the soil structure and content of organic matter. Aggregation, pore connectivity, and organic carbon content can be influenced by tillage and crop rotation, residue management, and cover cropping, all of which can influence water movement. Research has continuously shown that conservation-based practices improve soil structure and organic matter that in turn improve hydraulic properties and water-use efficiency of agricultural systems (Tangen et al., 2025; Xu et al., 2024).

To conclude, the interaction of the three factors (texture, structure, and organic matter), and not any one of them alone controls soil water movement. The nature of the soil is the texture that provides the natural structure to the soil but the structure and the organic matter determine the extent to which the water can move and be retained in the structure. Such interactions can be learned and applied to achieve the efficacy of irrigation, regulate the availability of soil water and make sure that agricultural production will be sustainable (Pinheiro et al., 2019; Garg et al., 2025).

The Soil Water Dynamics and the Productivity of Crop.

The crop productivity is directly and essentially influenced by the dynamics of the soil water because it determines how water is stored, transported and availed to the growing season to the plant roots. The amount of water in the root zone does not solely define crop performance of the agricultural systems, but also how, when and where the water travels. When the soil water dynamics is favourable, the plants can maintain a better root activity, nutrient uptake, photosynthesis and biomass growth. On the other hand, the low soil-water performance reduces the crop growth and increases the risk of yield variability in reality not only in irrigation but also in rainfed environments (Pinheiro et al., 2019; Tucker et al., 2025).

The influence of the soil water on the crop productivity is one of the primary ways, in which the dynamics of the soil water influences the availability of water to the plants. Good infiltration and adequate moisture content of soils in the root zone provides a more reliable source of water during rains or irrigation. This enhances the use of crop-water and minimizes stress of plants during dry seasons. Pinheiro et al. (2019) have shown that the soil hydraulic properties strongly influence crop water-use efficiency as well as that variations in water retention and conductivity may result in large variations in crop performance despite similar climatic conditions. This shows that the physical-hydraulic behavior of soil is a major factor of agricultural productivity and not just a background soil property.

The nature of the soil water also affects productivity in that it affects the growth of roots. When water gets into the soil in an appropriate way and distributed throughout the soil profile, root penetration to a deeper depth and volume of soil results. This enhances access to water and nutrients and increases the resilience of crops to short-term droughts. On the other hand, when infiltration is weak or the water mobility is restricted by the weak structure or compaction, the roots are shallow and inefficient. These situations reduce the ability of plants to proceed with growth, especially in the case of a shortage of water (Garg et al., 2025; Xu et al., 2024).

The other factor is the impact of soil water dynamics on the efficiency of irrigation. When the soil is not able to absorb and redistribute the irrigation water, then a large percentage of the applied water will be lost through runoff, deep percolation or evaporation. This reduces efficiency of irrigation and profitability of water inputs to crop production. The study by Tucker et al. (2025) indicated that soil-water movement is an important knowledge that can be used to maximize the timing of irrigation and ensure that the crops use more water. Thus, hydraulic characteristics of soil have a direct impact on the response of crops as well as the economic and practical effectiveness of water management in agriculture.

Moreover, soil water dynamics will contribute to nutrient transport and uptake which are highly related to crop productivity. Water is the most important in the process of transportation of dissolved nutrients to plant roots. The low moisture content or the unequal distribution of soil moisture leads to slower transport of nutrients and plants may be unable to absorb nutrients that are present in the soil. Conversely, adequate amounts of moisture on the soil enable better nutrient availability and physiological performance, which leads to higher yield and better quality of crops (Pinheiro et al., 2019).

Such adverse impacts of unhealthy soil water dynamics are more evident during stressful situations. Soils that have low retention and poor conductivity are weakly infiltrating soils that expose crops to both water shortage and flooding. These changes can slow down germination, slow down growth, inhibit reproductive development and lower yield. In comparison, the better structured soils with more favorable hydraulic behavior buffer crops against the variability of climate better, and allow more stable production with time (Tangen et al., 2025; Xu et al., 2024).

To conclude, the dynamics of soil water influence the productivity of crops by regulating the amount of water available to the plants, growth of roots, efficiency of irrigation, and uptake of nutrients. It is not then merely soils that are covered with water that are productive agricultural soils but soils that are covered with water that allow water to enter, move and remain available to the plants in a balanced and efficient way. This is why enhancing soil hydraulic performance is needed to boost crop productivity and ensure a sustainable agricultural production (Palani et al.,2019: Pinheiro et al., 2019; Tucker et al., 2025; Garg et al., 2025).

Optimization of irrigation and Soil Water Management.

The importance of irrigation efficiency and soil water management in agricultural systems is that the yield of crops is not only determined by the quantity of water applied to the soil, but by the effectiveness with which this water gets into the soil, into root zone stores and to the plant. The positive soil hydraulic properties lead to the increased efficacy of irrigation water distribution, decreased run off and deep percolation, and water use efficiency of crops. Recent studies provide information to prove that good management of irrigation is a requirement, particularly in a situation where water is limited and climate is uncertain.

The most important part of soil water management is the scheduling of irrigation that determines the timing and amount of water to be used. Adequate scheduling helps to maintain the soil wet at a level that helps in the growth of crops without waterlogging, drainage of nutrients or wasteful use of water. According to recent publications in Frontiers in Agronomy, efficient scheduling helps to increase the efficiency of water use and allows aligning irrigation with crop demand and the state of the soil-water.

Monitoring soil moisture is also of great importance in soil water management. Application of soil-moisture based irrigation systems allows application of water according to the actual root-zone conditions, compared to the calendar-based water application. A 2025 sensor-based study on comparisons of soil based irrigation management and weather based irrigation management showed that soil-moisture-guided irrigation could be used to improve irrigation management and facilitate water productivity in the field. Similarly, recent surveys on soil-moisture sensing and smart irrigation point out that real-time monitoring has the potential to enhance the accuracy and timeliness of irrigation decisions.

The second area of concern is that efficacy of irrigation is directly connected with the physical and hydraulic characteristics of soil. When infiltration is low or the hydraulic conductivity is low, some of the water being applied may be lost before being consumed by crops. On the other hand, improved soil structure and water conduction will enable the soils to retain greater water of irrigation in the rooting zone. The recent research on comparing the agricultural management systems indicates that management practices can considerably change the hydraulic conductivity and hence irrigation performance and crop response.

Precision irrigation is an area of the modern management of soil water, including soil moisture sensors, automated controllers, and data-based scheduling, becoming an important component. The term precision irrigation was coined in a 2024 review to describe this water-saving technology as valuable due to its ability to maximize the efficiency of water management by more effectively applying water to crops based on their needs. These findings are also supported by recent surveys of smart irrigation systems which report that sensor-based and automated irrigation systems can help to improve water saving and maximize irrigation choices in agricultural fields.

Simply put, the management of soil water and efficiency of irrigation necessitates an integration of soil hydraulic knowledge, proper timing, moisture monitoring and proper irrigation equipment. Efficient systems are systems in which the soil moisture is kept within the productive level, losses of water are minimized and water application is linked to the demand and soil properties. It is not so much about the entry of water to the soil, but about the proper management of soil-water relations in a correct and sustainable way.

Challenges and Future Forecast.

Some of the important problems of studying soil water include the fact that the hydraulic behaviour of soil is extremely sensitive to soil texture, structure, organic matter and management history and it is difficult to predict in the field. Recent studies show that agricultural activities may have a powerful effect on the field-saturated and the near-saturated hydrostatic conductivity, i.e. the soil-water behavior is not known to be fixed but dynamic (Garg et al., 2025).

Climate variability and increasing pressure to irrigation water is another significant challenge. As the frequency of rainfall decreases and there is shortage of water, weakly infiltrating soils, low retaining, or low hydraulic continuity soils lose their crop supporting properties. According to the recent literature review of irrigation and soil health, a more efficient use of water has become an important aspect of sustainable agricultural production under changed environmental conditions (Lakhiar et al., 2024; Kelley et al., 2025).

The other problem is that it needs better tools of monitoring and management. The older irrigation practices are likely to waste the water whereas the new sensor-based and precision irrigation techniques could assist them to conserve on water and time. Recent research has suggested that soil-moisture sensing and hydraulic knowledge are going to be more extensively relied on in the future to control soil-water in addition to information-driven irrigation timing (Lakhiar et al., 2024; Kelley et al., 2025).

An improved soil structure, improved hydraulic evaluation, and improved precision irrigation technologies are likely to be a key to sustainable management of soil water in the future. Systems of long-term soil-health also seem to be promising since they have the potential to enhance aggregate stability and macroporosity, which enhance hydraulic performance during rainfall and irrigation (Tangen et al., 2025).

In conclusion, the future of soil water management in agriculture is the improvement of the hydraulic functioning, efficiency in irrigation, and responsive to the soil condition and climate stress monitoring and management systems (Garg et al., 2025; Lakhiar et al., 2024).

Conclusion

To conclude, soil water relations, and hydraulic properties are fundamental in comprehending the manner in which water is stored, transmitted and used in agricultural soils. These characteristics directly influence the amount of water that is available to plants, the growth of roots, irrigation efficiency and crop yields in general. The review has shown that it is not one of the factors that defines the soil hydraulic behavior but rather the combination of the texture, structure and the organic matter.

It is also clear that ineffective soil hydraulic properties like low infiltration, low conductivity or low water retention may decrease crop performance due to the inability to supply adequate water and high losses. On the other hand, the equal water flow and retention of soils provide more stable and effective conditions in which the plants are grown.

In sum, the enhancement of soil water management by enhancing the knowledge of hydraulic properties, proper use of irrigation methods, and management of soil and human health is a key to sustainable agriculture. In the future, the need to maintain good soil-water conditions will be even more critical to making crops more productive and making the utilization of water resources more efficient in future under environmental pressure.

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