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Assessment of Hydraulic conductivity in Iraqi soils (Articular review)

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Abstract:

Given the importance of hydraulic conductivity in agriculture—particularly in determining soil's ability to transport water through its pores—understanding this property is essential for improving productivity, minimizing water and nutrient loss, enhancing soil aeration, selecting suitable crops, managing salinity, and optimizing fertilizer efficiency. Therefore, this article aims to assess hydraulic conductivity and highlight the key factors influencing it. The average hydraulic conductivity values in different regions of Iraq were recorded as follows: 3.36 cm•h^{-1} in the north, 2.24 cm•h^{-1} in the central and southern regions, and 2.95 cm•h^{-1} in the west. A review of previous studies indicates that gypsum and its concentration significantly affect hydraulic conductivity. When added to the soil, gypsum increases pore size, thereby enhancing hydraulic conductivity. Additionally, the dissolution of small gypsum crystals in moist soils leads to soil disintegration and an increase in pore spaces, which improves soil permeability and consequently enhances hydraulic conductivity. The presence of salts also influences hydraulic conductivity, depending on the dominant salt type. Calcium and magnesium salts promote soil particle aggregation, increasing hydraulic conductivity. In contrast, monovalent ions such as sodium cause soil swelling and particle dispersion, leading to reduced conductivity. This effect is exacerbated in soils dominated by 2:1 clay mineral, unlike 1:1 clay mineral, which are less affected by increased SAR (Sodium Adsorption Ratio) and ESP (Exchangeable Sodium Percentage). The impact of sodium begins at 5% and worsens at 15% or more, particularly in soils with higher clay content, which increases bulk density and decreases hydraulic conductivity. Tillage practices and the type of plow used also significantly influence hydraulic conductivity. Studies show that chisel plows yield the highest conductivity values compared to other plows across different soil types. Additionally, conductivity values tend to decrease with soil depth. Research further indicates that incorporating organic residues—regardless of type and source—or biochar (whether derived from plant or animal materials) enhances hydraulic conductivity. Moreover, hydraulic conductivity is not only affected by the solid phase of the soil but also by the type and properties of the infiltrating fluid, as it depends on the density and concentration of the percolating liquid.

Keywords: *Hydraulic conductivity, Factors affecting hydraulic conductivity, Hydraulic conductivity assessment.*

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تقييم الإيصالية المائية في الترب العراقية (مراجعة تحليلية)

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الخلاصه:

نظرًا لأهمية الإيصالية المائية في الزراعة، خصوصًا في تحديد قدرة التربة على نقل الماء عبر مساماتها، فإن فهم هذه الخاصية يعد أمرًا ضروريًا لتحسين الإنتاجية، تقليل فقدان المياه والعناصر الغذائية، تعزيز تهوية التربة، اختيار المحاصيل المناسبة، إدارة ملوحة التربة، وتحسين كفاءة استخدام الأسمدة. لذا، تهدف هذه المقالة إلى تقييم الإيصالية المائية وتسليط الضوء على العوامل الرئيسية المؤثرة فيها. سُجلت متوسط قيم الإيصالية المائية في مناطق العراق المختلفة كما يلي: 3.36 سم/ساعة في الشمال، 2.24 سم/ساعة في المناطق الوسطى والجنوبية، و2.95 سم/ساعة في الغرب. أظهرت مراجعة الدراسات السابقة أن للجبس وتركيزه تأثيرًا كبيرًا على الإيصالية المائية، حيث يؤدي إضافته إلى التربة إلى زيادة حجم المسام، مما يعزز من الإيصالية المائية. كما أن ذوبان بلورات الجبس الصغيرة في الترب الرطبة يؤدي إلى تفكك التربة وزيادة حجم المسام، مما يحسن نفاذية التربة وبالتالي يعزز الإيصالية المائية. كما أن وجود الأملاح يؤثر على الإيصالية المائية، وذلك اعتمادًا على نوع الملح السائد. تعمل أملاح الكالسيوم والمغنيسيوم على تعزيز تجمع دقائق التربة، مما يؤدي إلى زيادة الإيصالية المائية. في المقابل، تتسبب الأيونات الأحادية مثل الصوديوم في انتفاخ التربة وتشتت دقائقها، مما يؤدي إلى انخفاض الإيصالية المائية. تتفاقم هذه المشكلة في الترب التي تسود فيها معادن الطين من النوع 2:1، على عكس معادن الطين من النوع 1:1، التي تتأثر بشكل أقل بارتفاع نسبة الصوديوم الممتص (SAR) ونسبة الصوديوم المتبادل (ESP). يبدأ تأثير الصوديوم من 5% ويتفاقم عند 15% أو أكثر، خصوصًا في الترب ذات المحتوى الطيني العالي، حيث يؤدي ذلك إلى زيادة الكثافة الظاهرية وانخفاض الإيصالية المائية. كما أن عمليات الحراثة ونوع المحراث المستخدم تؤثران بشكل كبير على الإيصالية المائية. أظهرت الدراسات أن المحراث الحفار يعطي أعلى قيم للإيصالية المائية مقارنة بالمحاريث الأخرى في أنواع مختلفة من الترب، كما أن قيم الإيصالية المائية تنخفض مع زيادة عمق التربة. تشير الأبحاث أيضًا إلى أن إضافة المخلفات العضوية، بغض النظر عن نوعها أو مصدرها، أو الفحم الحيوي (سواء كان نباتيًا أو حيوانيًا) تعزز من الإيصالية المائية. إضافةً إلى ذلك، فإن الإيصالية المائية لا تتأثر فقط بالطور الصلب في التربة، ولكن أيضًا بنوع وخصائص السائل المتخلل فيها، حيث تعتمد على كثافة وتركيز السائل المتحرك عبر التربة.

الكلمات المفتاحية: الإيصالية المائية، العوامل المؤثرة في الإيصالية المائية، تقييم الإيصالية المائية.

Introduction

The theory of water flow in porous media has widespread applications in various fields of soil and water sciences. Soil's ability to transport water is crucial for professionals working in areas such as groundwater contamination, soil conservation, and land use management. Saturated hydraulic conductivity (Ks) is expressed as the ratio of water flow to the hydraulic gradient in saturated flow conditions. It represents the capacity of pore spaces in a porous medium to allow fluid passage under complete saturation. Saturated hydraulic conductivity is used to determine various water transport parameters such as diffusivity, Sorptivity, and unsaturated hydraulic conductivity (Hillel, 2004; Lal and Shukla, 2004; Gupta et al., 2020). The ratio of water flux (q) to the hydraulic gradient ($\Delta H/L$) in saturated flow is defined as saturated hydraulic conductivity (Kast), which serves as a proportionality constant between flow rate and the hydraulic gradient. Richards (1952) defined hydraulic conductivity as the ability of a porous medium to transmit water and quantitatively expressed it as the volume of water passing through a unit cross-sectional area of the porous medium, perpendicular to the flow direction, per unit time, under a unit hydraulic gradient at any given point (Jadczyszyn and Niedwiecki, 2005; Ati *et al*., 2025). Tayml and Ashcroft (1972) explained that saturated hydraulic conductivity reaches its maximum when all soil pores are filled with water, ensuring that interconnected pores are ready to conduct water. Hillel (1980b) described saturated hydraulic conductivity as the condition in which pore spaces in the porous medium are fully prepared to allow fluid movement. It is represented by the slope of the linear relationship between flow rate and the hydraulic gradient. Hydraulic conductivity has units of velocity, which are essential for the mathematical description of flow in saturated as well as unsaturated conditions. According to Tuli (2001), hydraulic conductivity depends upon both medium and properties of the flowing liquid and is influenced by the geometry of the soil pores. Jovette and Bruno (2007) give similar comments, with hydraulic conductivity being dependent on the characteristics of the fluid as well as the medium; the representation is expressed by Equation

$$K_{sat} = f_m f_s f_v$$

Where:

K_{sat} = Saturated hydraulic conductivity

f_m = Medium characteristics

f_s = Soil properties

f_v = Fluid properties

It is a value that is not fixed and varies due to different chemical, physical, and biological processes as well as changes in cation exchange complex composition. It is conveniently used to study soil water properties and assess water flow in soils. This is further used for degradation of soil structure and closing up of pores due to leaching and irrigation.

1- Key Factors Affecting Hydraulic Conductivity

1-1- The Effect of Gypsum on Soil Hydraulic Conductivity Rate

The saturated hydraulic conductivity is also dependent on the gypsum content of the soil. Its values increase with higher concentrations of gypsum present in the soil. For example, Smith and Robertson (1962) found it to be 3.3 $cm \cdot h^{-1}$ in gypsiferous soils from northern Iraq. According to Ghazal (1987), gypsum dissolution enhances soil permeability by creating additional pore spaces between soil particles. The salts present determines the type and concentration of salts that will influence this process in the soil. Such a study was performed by Al-Hadithi and Al-Khatib (2007). The hydraulic conductivity values significantly increased with increasing contents of gypsum and electrical conductivities in the soil with or without sodium adsorption ratio values. There was an inverse relationship between the hydraulic conductivity of the soil and the sodium adsorption ratio. But this inverse relationship was valid only up to a certain limit of gypsum content, about 460 $g \cdot kg^{-1}$, above which the hydraulic gradient began to increase with the increase in SAR. The increasing trend of gypsum content and hydraulic conductivity of soil may usually be explained by the swelling of the mean pore radius that results from the dilution of the effective cross-sectional area of the pores. The high levels of moisture cause the small gypsum crystals to be dissolved, thereby causing soil disintegration and breakdown of aggregates (Nettleton et al., 1982). In addition, the water runs where the motion is faster, therefore accelerating the dissolution of gypsum, and consequently the effect on hydraulic conductivity is such that the values are enhanced.

1-2- The Effect of Salts and Their Types on Hydraulic Conductivity

Hydraulic conductivity is influenced by salt concentration and the dominant salts in the soil solution. The increase in divalent cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) leads to a reduction in the thickness of the electrical double layer, thereby promoting particle aggregation (Bolt & Bruggenwert, 1976). Research by Durand and Rahman (1979) and Rowell (1965) demonstrated that an increase in magnesium levels on the cation exchange complex behaves similarly to sodium, causing soil structure deterioration due to clay mineral dispersion. Similarly, Ali et al. (1987) found that soil dispersion was higher in the Na-Mg system compared to the Na-Ca system, attributing this to the increase in exchangeable sodium in the presence of magnesium. However, Yousaf et al. (1987)

reported no significant effect of magnesium on montmorillonite dispersion when comparing Na-Mg and Na-Ca systems, if EC (electrical conductivity) and ESP (exchangeable sodium percentage) levels were similar. An increase in water salinity concentration resulted in higher values for all water transport parameters. However, the presence of sodium in saline water mitigated the impact of high salinity, especially in clay-rich soils (Younan, 2008). The use of saline irrigation water led to a 14.5% reduction in hydraulic conductivity compared to non-saline irrigation treatments, which maintained stable conductivity levels. This reduction was attributed to the higher sodium and magnesium concentrations relative to calcium in the irrigation water, causing soil particle dispersion and reduced water infiltration rates. Conversely, studies by Bauder et al. (2005) and Hedayati & Sadeghi (2022) indicated that saturated hydraulic conductivity increased with higher concentrations of calcium and magnesium ions in water, reinforcing the role of divalent cations in improving soil structure and permeability.

1-3- The Effect of SAR and ESP Values on Hydraulic Conductivity

Hydraulic conductivity is highly dependent on the electrolyte concentration of the soil solution. A decrease in electrolyte concentration combined with an increase in exchangeable sodium percentage (ESP) leads to swelling and dispersion of soil particles, negatively affecting water movement (Quirk & Schofield, 1955). McNeal et al. (1966) demonstrated that an increase in SAR values and a reduction in ionic concentration in percolating water significantly decrease saturated hydraulic conductivity, particularly in clay-rich soils. Similarly, Park and O’Connor (1980) studied the effects of different irrigation water types with salt concentrations ranging from 1250 to 1500 ppm and SAR values between 16% and 57% on hydraulic conductivity in four different soil textures (sandy, loamy, silty clay, and clay). Their findings showed no significant differences in hydraulic conductivity among treatments. However, alternating poor-quality irrigation water with rainwater led to a significant decline in soil permeability, especially in soils with high ESP values, due to swelling caused by sodium accumulation. The impact of ESP on hydraulic conductivity is particularly evident in sodium-affected soils, where high ESP levels cause clay particle swelling, reducing pore connectivity and lowering hydraulic conductivity, especially after rainfall infiltration. Some workers (Aodea et al., 1993; Mohammed et al., 2001; Al-Hadithi et al., 2001) found an increase in saturated hydraulic conductivity with higher salt concentrations and lower SAR values at any given soil clay content. This means the composition of the cation and salinity levels must be in an optimum balance for good maintenance of water flow within the soil profile. In summary, this relationship between SAR and ESP with hydraulic conductivity is very important for the management of soils and irrigation practices. Higher SAR causes dispersion and swelling which restrains the movement of water, while lower SAR and higher salts make the soil structure stable increasing hydraulic conductivity in different soil textures. Proper irrigation water management, specifically alternate application of saline water and fresh water, would be also required to maintain soil permeability and prevent development of structure.

1-4- The Effect of Clay Content on Hydraulic Conductivity

Clay dominates the behavior of soils due to its high development of specific surface properties, bringing together physical and chemical interactions that modify the properties of soil such as structure, porosity, water retention, and reactivity toward external stimuli. These properties have been thoroughly investigated in many different soils. However, they are far less defined in high-clay-content soils. A study of the hydraulic properties of soils gives a general picture of distribution and movement of water within them because the functions of water transport depend on the properties of soils and the composition of the solution. Saturated and unsaturated hydraulic conductivity, Sorptivity, permeability, and diffusivity are some of the basic parameters in the equations that govern water flow. Other factors which influence irrigation water use on soil moisture properties include saline water, where the effect on aggregate stability and water flow is significant. This was supported by Lagerwerif et al. Clay swelling is very significant in reducing hydraulic conductivity since it blocks the way of water movement on the soil profile as found by Weaver, Parr, and Wilson in 1969. Auerswald in 1995 concluded that the most likely primary dependency of the breakdown of soil aggregates may be on entrapped air in soil pores, and in most cases, the former condition would be fulfilled by the latter two phenomena, i.e., clay swelling and dispersion. According to Levy, M. C. et al. 2005, degradation of soil structural condition, weak aggregate stability, and the combined effects of swelling and dispersion result in reduced hydraulic conductivities. An aggregate breakdown is known to take place due to the compression of air during the process of wetting dry soils (Ruiz-Vera & Wu, 2006). It can be supported by the fact, Hanay, Y. et al 2003 that even the stability of aggregates reduces with the advancement of the levels of salinity and exchangeable sodium percentage (ESP). Levy & Torrento (1995) proved that when ESP is above 5%, aggregate stability begins to break. On the other hand, Rhoades & Ingvalson (1969) found hydraulic conductivity to decrease after aggregate breakdown for soils within an ESP range of 10 to 20%. These results highlight the significance of controlling clay swelling and dispersion as a measure to uphold the permeability of soil and hydraulic effectiveness in agricultural arrangements.

1-5- The Effect of Tillage Practices and Plow Type on Hydraulic Conductivity

To produce fruitful plant growth and increase agricultural productivity in the long term, proper tillage breaks up soil aggregates, mixes layers, and alters physical properties. Thus, tillage is the most important operation within a tillage system. The surface tool used, and the soil conditions determine how effective it will be. Proper selection of tillage depth is important for improving the physical state of the soil by enhancing root growth and distribution, indeed increasing crop yield. The studies conducted by Lal and Jasim et al. (2015), ati et al. (2014 a, b, c), and lal (1999) revealed that the hydraulic conductivity attained the peak value for the chisel plow as compared to moldboard plow or no-tillage in the silty clay loam soil, being 127% and 42% higher, respectively. Al-Qazzaz and Haider (2010) research further proved that chisel plowing had the highest hydraulic conductivity values, which were 0.793 cm•h^{-1}, as compared to moldboard plowing, which accounted for a relatively lower conductivity, 0.460 cm•h^{-1}. This was related to the better capability of chisel plow in enhancing soil porosity plus an addition to the volume of macropores contributing to water movement. Another study by Jabro et al. (2010) that compared two tillage systems, minimum tillage at a 10 cm depth and chisel plow conventional tillage at a 20 cm depth, also indicated significantly superior performance of conventional tillage to minimum tillage where hydraulic conductivity was registered at 41.5 mm•h^{-1} and 30.4 mm•h^{-1}, respectively. Improvement was associated with higher soil porosity and a lower bulk density that comes under conventional tillage. In another similar study, Khan et al. (2017) worked on different tillage systems such as hydraulic conductivity research in minimum tillage, conventional tillage, and deep tillage on sandy clay loam soil. The highest value was realized in deep tillage with 48.95 mm•h^{-1} followed by the other two, with values of 57.71 mm•h^{-1} and 57.92 mm•h^{-1} for conventional and minimum tillage, respectively. This hydraulic conductivity result is in agreement with one obtained by Al-Moussawi and Baha (2017), who found higher values in tilled soils than non-tilled soils. In this study, the S1D3 and S2D2 treatments gave comparatively high values of conductivity. The MT treatment gave the lowest value; the rest of the treatments had relatively similar mid-range values. Another observation was a general decrease in hydraulic conductivity with the depth of soil. The test was carried out towards the end of the rainy season; thus, macropores had started to close up due to the swelling of the soil with water. A well-aggregated soil has good porosity for aeration. Maintaining good aggregate stability is a very important factor in the management of soil for healthy plant growth. However, aggregate stability decreases as the intensity of land use increases, leading to lower porosity, therefore, lower bulk density, lower penetration resistance, and better hydraulic conductivity. Compaction eliminates larger pores, hence modifying the soil water retention and the soil conductivity. Particle rearrangement and closer packing due to mechanical stress contribute to this decrease, according to Harris (1971). Large- and medium-sized soil particles seem to offer significantly more hydraulic conductivity compared to fine particles, as outlined by Hassan and Al-Qahwaji (2008). Soil hydraulic properties are directly affected by soil structural degradation resulting from aggregate breakdown because changes occur in water movement pathways (Al-Hadithi, 1995; Mahmoud et al., 2024). The findings from Reicosky et al. (1981), and Kreiselmeier et al. (2020), in addition to some other studies, showed that compacted soils have their macropore volume greatly reduced, which suppresses the rate of hydraulic conductivity.

Tillage improves soil hydraulic conductivity because it makes the soil more porous and lowers bulk density. In this study, chisel plowing proved better than moldboard plowing and no-tillage systems. Deep tillage maximizes conditions for water movement but, in most cases, soil compaction and surface sealing reduce hydraulic conductivity since these two factors eliminate larger pores and limit infiltration. Proper tillage practices would therefore be used to enhance water infiltration and reduce the level of compaction as a means of maintaining soil productivity.

1-6- The Effect of Bulk Density on Hydraulic Conductivity

Hydraulic conductivity is not a constant property, but it changes due to chemical, physical, and biological processes and modifications in the cation exchange complex. A decline in hydraulic conductivity takes place over time because salt concentrations are declining, because of the repeated swelling and shrinking cycles, and because of dispersion and migration of clay particles that eventually clog the pores of the soil. In their study, Henderson et al. (2002005) revealed a decrease in saturated hydraulic conductivity with the increase of clay and silt percentages in graded sand mixture, which was attributed to a decrease in the cross-sectional area available for water flow by fine particle accumulation. Similar results have been provided by Dianqing et al. (2004) and bulk density increase results in hydraulic conductivity decreasing for different soil textures. A higher sand content was used by McCoy for a very rapid rate of hydraulic conductivity in the soils. A soil that had 70% sand content provided a conductivity of 6.3 cm•h^{-1}. This value was further dramatically increased when sand content reached 75%. Also, Al-Khatib proved that the saturated hydraulic conductivity decreases with the increase in the percentage of clay content. It showed a strong negative linear relationship between them as the correlation coefficients were -0.92 and -0.99. Coskun et al. also indicated that the effect of clay content for hydraulic conductivity was more significant than that of silt content in different soil textures. Higher bulk density results in lower hydraulic conductivity because of more compacted soil which leads to the reduced connection between pores and hence restricted flow of water. The impact of clay content is very strong because clay particles result in reducing pore size and increase soil swelling; thus, it causes further limitation in conductivity. On the other hand, an increase in sand content increases permeability which further increases the hydraulic conductivity. Such relationships need to be understood well for efficient management of soil and optimizing water infiltration in agricultural and environmental uses.

1-7- The Effect of Organic Residues on Hydraulic Conductivity

Two main factors are believed to play a significant role in the biochar impact on soil physical properties. One is the addition of a porous material to the soil, which raises soil porosity, reduces bulk density, increases hydraulic conductivity, and improves soil water retention capacity. And the second is the enhancement of soil structure indirectly by organic material; in other words, it provides microbial activity with which organic matter promotes. These microorganisms catalyze organic and adhesive compounds to facilitate soil particle aggregation, root penetration, and stability of soil aggregates, hence enhancing the porosity of soils (Burrell et al., 2016; Khamees et al., 2023). The detailed mechanisms by which biochar influences soil aggregation and structure are not fully understood (Burrell et al., 2016; Dawod et al., 2024). For example, sandy loam soil mixed with animal residues has a much higher hydraulic conductivity because of its higher organic content due to which the involving ability of that soil for water is enhanced. Also, Al-Wali et al. Organic residues have been confirmed to positively influence saturated hydraulic conductivity since they decompose and enrich the soil with organic matter, which in turn binds soil particles and therefore improves the structure of the soil as well as increasing the total pore size distribution. This lowers bulk density and enhances water flow. All in all, the input of organic residues into the soil greatly adds to aggregation, porosity, and movement of water. It is a practice that proves very valuable for soil hydraulic properties and for soils to sustain their health.

1-8- The Effect of Carbonate Mineral Content on Hydraulic Conductivity

Soil hydraulic conductivity primarily depends on pore size distribution and the volume of pores through which water can flow in unconfined conditions; the free flow of water occurs only through interconnected pores containing water (Vanapalli and Lobbezoo 2002). The presence of carbonate minerals in a soil mass has a magnitude impact on hydraulic conductivity, depending on the variation in texture, structure, and distribution of carbonates in the soil. A study carried out by Awad and El-Rawi (1981) on the effect of additions of carbonate minerals to hydraulic conductivity proved that their effect depends on the type of soil. In granular soils, an increase in carbonate content decreases hydraulic conductivity because carbonates fill the inter-particle porosity between the soil grains, thereby restricting water movement (Ryan and Bruce 2004; Razzak et al., 2018). On the contrary in fine-grained soils, hydraulic conductivity tends to increase where carbonate content increases, especially with an increase in bulk density.

Mainly, carbonate minerals improve hydraulic conductivity mostly via changes in the soil structure. Such includes the fact that Ca^{2+} reduces the diffuse double layer thickness, hence promoting flocculation as well as aggregate formation, therefore improving soil permeability. Multiple studies have confirmed, among other related factors, that higher carbonate content results in increased hydraulic conductivity. The reviewed carbonate minerals influence hydraulic conductivity in the selected sources of soil. Carbonates may seal pore spaces against flow in coarse-textured soils and enhance conductivity in fine-textured soils. Since calcium ions also have a major role in aggregate formation, carbonate-rich soils always show improved permeability and good movement of water.

1-9- The Effect of Clay Mineral Type on Hydraulic Conductivity

Clay minerals have the most critical contribution to soil dispersion and hydraulic conductivity due to their type and content. The presence of different clay minerals influences stability, swelling behavior, and sodium adsorption characteristics of soil. These have been supported by findings from previous studies by McNeal, Salem & Atee (2007), Ati (1999), and Coleman (1966). Compared to those with a montmorillonite type, structural stability is more pronounced in soils where kaolinite is the dominant clay mineral; they are less prone to dispersion and reduced hydraulic conductivity. Soils with high montmorillonite contents are highly sensitive to increases in SAR and ESP levels (Ayers & Westcot, 1976). This is because the existence of a layered crystalline structure in montmorillonite imparts a large number of exchange sites for binding sodium; hence, clay dispersion, swelling, and related decrease in permeability. Montmorillonite swell ability is high with a specific surface area up to 700 m^2/g, which gives soils containing this mineral an increased possibility of being expansive (Hillel 1980a; Sadeghi and Ali Panahi 2020; Ayada et al. 2024; Ati et al. 2013). Even more sensitive to sodium accumulation than montmorillonite is allophane clay since it has a high exchangeable affinity for sodium; thereby, it accelerates soil dispersion, as found by studies of Alperovitch et al. (1985) and Oster et al. (1980). The clay mineral type that dominates and the soil texture are key important factors for determining soil dispersion and permeability. According to Felhendler et al. (1974), the increase of silt content decreases saturated hydraulic conductivity significantly, under the condition of SAR, EC, and clay mineral types being constant. Similarly, Pupiskya & Shinberg (1979) observed an increase in Ksat (saturated hydraulic conductivity) in sandy soils containing both montmorillonite and kaolinite, attributing this to reduced clay dispersion and improved water movement. Conversely, McNeal et al. (1968) found that hydraulic conductivity decreases in sodic soils with higher clay content, as sodium promotes particle dispersion and pore clogging. Beyond mineralogy, other factors also influence hydraulic conductivity. EZLIT (2009) reported that aggregate stability is primarily controlled by organic matter content when it exceeds 5%. However, in calcareous soils such as those found in Iraq, carbonate minerals play a crucial role in soil stability, as calcium absorption onto exchange sites reduces the impact of sodium, preventing structural collapse. The cation exchange capacity (CEC) further governs soil response to salinity and sodality, where carbonate minerals coat soil aggregates, reducing the number of active exchange sites and lowering soil CEC. A study by Al-Dulaimi (2012) highlighted the deterioration of soil properties due to increased salt concentrations, particularly sodium, which exacerbates dispersion and permeability loss in montmorillonite-rich soils. The accumulation of clay fractions intensifies soil salinity issues, transitioning into sodic-saline conditions. Differences in the adsorption and swelling behavior of clay minerals influence their response to sodium, with non-expanding clays such as chlorite and mica (when exceeding 30%) mitigating swelling effects even under high sodium conditions (Mahdee et al., 2023; Salih & Alwzzan, 2022; Ati & Jabbar, 2024). In addition to these factors, hydraulic conductivity is highly variable, as it depends on both soil properties and the infiltrating liquid. A study by Al-Ruslani & Al-Fartousi (2006) examined the effect of pesticides on saturated hydraulic conductivity in clay and sandy loam soils. Their results showed significant variation depending on the type of pesticide used, with a statistically significant difference at the 0.01 level. The study also found a positive correlation (0.44) between hydraulic conductivity and volumetric moisture content (PV). Moreover, after washing the soil with tap water, saturated hydraulic conductivity remained stable, suggesting that pesticide residues influence soil permeability but can be mitigated through leaching. The type of clay mineral plays a critical role in hydraulic conductivity, with montmorillonite causing strong swelling and pore clogging, whereas kaolinite and non-expanding minerals (chlorite, mica) contribute to higher permeability. Soil texture, silt content, carbonate minerals, and organic matter also modify the impact of clay minerals on water movement and aggregation stability. Proper management of soil amendments, irrigation water composition, and organic matter inputs is essential to maintain soil permeability and prevent salinity-induced degradation.

2-Conclusions

Based on the results obtained from previous studies, the following conclusions can be drawn:

1. Saturated hydraulic conductivity (Ksat) significantly increases with higher gypsum content in soil. However, Ksat decreases with increasing SAR unless the gypsum content exceeds 450 $g \cdot kg^{-1}$, where an opposite effect is observed.
2. In general, hydraulic conductivity increases with higher soil salinity, particularly with an increased concentration of Ca^{2+} and Mg^{2+} ions, which promote soil particle aggregation. However, an increase in Na^{+} concentration causes soil dispersion, reducing hydraulic conductivity. Some studies indicate that high Mg^{2+} levels behave similarly to Na^{+}, leading to soil structure deterioration and reduced water permeability.
3. An increase in clay content leads to a decline in hydraulic conductivity, a problem that worsens when SAR and ESP exceed 5%. This decline is attributed to soil structure degradation, reduced aggregate stability, and the occurrence of swelling and dispersion.
4. Tillage improves hydraulic conductivity, with the chisel plow outperforming other tillage methods in enhancing soil permeability.
5. Higher bulk density reduces hydraulic conductivity due to soil compaction, which decreases the volume of macropores responsible for water movement.
6. Hydraulic conductivity increases with the addition of biochar (either animal- or plant-derived) and organic residues, regardless of their quantity. These amendments enhance soil porosity, lower bulk density, and improve soil water transmission properties.

7. Carbonate minerals enhance hydraulic conductivity due to the presence of Ca^{2+} ions, which reduce the thickness of the diffuse double layer and promote soil aggregation.
8. Soils dominated by montmorillonite exhibit lower hydraulic conductivity than those containing kaolinite, mica, or allophane. This issue worsens with higher Na^{+} concentrations, leading to soil swelling and clay particle dispersion, further reducing water flow.

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