



Seasonal and depth variation of soil physical parameters irrigated with treated wastewater in the case of light textured soil

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Abstract

In places with scarce water supplies, treated wastewater (TWW) can be used for irrigation. This is the case in many places on the Mediterranean coast. In order to examine changes in soil physical properties irrigated with secondary-treated wastewater for >38 years, a study was conducted under real agricultural conditions and three different sampling seasons (Summer, autumn and winter). Five soil depth distribution (0-20, 20-40, 40-60, 60-80 and 80-100 cm) was also investigated. The soil parameters studied were: salinity (EC), permeability (K) and structural stability (IS). The results demonstrate that K and IS depended significantly on the season and varied throughout the soil profile. However, only the depth had an impact on the EC. The maximum EC and K were observed in summer at 0-60 and 0-20 cm, respectively. The highest IS, although, was detected during the winter at 40-60 cm depth layer. More interestingly, to take into consideration the interactions of both factors, a positive correlations were shown between K and EC, and IS ($r = 0.56^{***}$, $r = 0.62^{***}$, respectively) and between EC and IS ($r = 0.44^{**}$) in summer. In contrast, only K and EC showed a negative correlation ($r = -0.35^*$) in the autumn, but no correlation was detected between all parameters in winter. The results indicate that treated wastewater is a suitable alternative during hot seasons, especially in sandy soils. Further research is required to investigate the effect of this wastewater on crops responses.

1. INTRODUCTION

In arid and semi-arid countries, the water demand is continuously rising and the world is facing to an intensification of water scarcity. In Mediterranean countries such as Tunisia, there is an increasing and urgent need to keep and protect water resources. Water is a vital resource but a severely limited one in these countries (Ventura et al., 2019). Therefore, wastewater reuse is gaining attention because it is an option to increase available water supplies (Ibekwe et al., 2018). The water scarcity is the consequence of several problems such as: inefficient water distribution networks, no

emergency plan to face decreasing rainfall and basic infrastructure, poor wastewater treatment, environmental resource degradation, and climate change (Urbano et al., 2017). To face these problems, it is crucial to look for strategies to decrease the demand for potable water. Consequently, the interest in reusing wastewater for agriculture is rapidly increasing and water of higher quality is preserved for drinking purposes (Partyka and Bond, 2022).

In Tunisia, reusing treated wastewater (TWW) in agriculture is not a novel practice. It was first created in 1965 when the first Soukra wastewater perimeter was built (National Sanitation Utility 2019). With 122 plants treating

284 mm³ and 8435 hectares of agricultural land to service, the number of perimeter and treatment plants has risen substantially since the turn of the century.

The environmental impacts caused by using wastewater in agriculture can be positive and negative (Gao et al., 2021). Moreover, irrigation with TWW is considered an environmentally sound wastewater disposal practice that helps in minimizing the pollution of the ecosystem subjected to contamination by direct disposal of wastewater into surface or groundwater (Zhang et al., 2017). In addition, wastewater is a valuable source for plant nutrients and organic matter needed for maintaining fertility and productivity of arid soils (Ofori et al., 2021). However, reuse of wastewater for irrigation may potentially create environmental problems if not properly treated and managed (Shakir et al., 2017). Indeed, TWW differs from its fresh water of origin in numerous aspects. Concentrations of electrolytes, organic matter, and suspended solids are higher in TWW than water from other sources (Koul et al., 2022). In Tunisia, the permitted loads of organic matter and suspended solids in TWW were based, for many years, on the criteria published by the National Institute for Standardisation and Industrial Property in 1989, which required that the biochemical oxidation demand (BOD) and total suspended solids (TSS) in TWW used for irrigation not exceed 30 mg/l, both. Also, the limit of electrolyte concentration was 7 mS/cm. However, many authors confirmed that application of TWW increase the soil salinity and sodicity (Gao et al., 2021). In the other hand, probable hazards to soil structural stability and soil hydraulic properties following irrigation with saline-sodic TWW could arise from the higher loads of Electrical Conductivity (EC) (Bekir et al., 2022) and Sodium Adsorption Ratio (SAR) (Vallejos et al., 2022) in these waters compared with water from other sources. Indeed, Azouzi et al. (2016) have studied the depth distribution of different parameters of soil treated with wastewater, observing an increase of permeability on the soil surface when the soil had a low bulk density. However, Jaramillo and Restrepo (2017) confirmed that the reuse of wastewater on irrigation decrease the soil permeability of tilled layers due to submersion. This was explained by biological and physical pore clogging, or by high sodium concentration induced soil swelling and dispersion effects (Tunc and Sahin, 2015). Similar results were obtained by Albalasmeh et al. (2020) in the

vadose zone as a result of using treated wastewater for irrigation.

Soil structure is an important factor, frequently ignored by most, in the proper functioning of numerous soil processes, such as water storage and filtration and runoff reduction (Levy, 2011). The decline of soil structure is increasingly seen as a form of soil degradation (Chalise et al., 2019). Soil structure speaks of the size, shape, and placement of the solids and voids in the soil, as well as the continuity of the pores and voids. Indeed, soil structure directly affects the soil's capacity to retain and transport water and organic and inorganic constituents. In addition, soil structure influences important field-scale phenomena such as soil water movement and retention, erosion, crusting, nutrient recycling, root penetration, and crop yield (Obalum et al., 2017). Hence, favorable soil structure and stable aggregates are crucial in order to enhance soil quality, raise agronomic productivity and sustainability, increase soil porosity, and reducing soil erodibility. Many processes can adversely affect soil structural stability such as clay swelling and dispersion, aggregate break down through slaking, and the impact of water drops of high kinetic energy (e.g., rainfall). More importantly, these processes are expected to occur mainly in winter, when the soil is leached with rainwater (i.e., water free of electrolytes). Under these conditions, the soil clay's sensitivity to swelling and dispersion is high as well as the aggregates' susceptibility to slaking (Levy et al., 2003). More interestingly, TWW application can enhance the processes of clay swelling and dispersion relative to irrigation with fresh water because of the higher SAR in TWW, since sodic conditions make the soil clays more sensitive to swelling and dispersion (Leuther et al., 2019). Soil salinity, permeability and structural stability are also affected by seasonal variations and increase in months with higher temperature and moisture (Shi et al., 2013).

In Tunisia, there is consensus in the scientific literature on the impact of wastewater irrigation on the physical and chemical properties of soil (Bekir et al., 2022). However, there is little information on the effect of irrigation season on soil salinity, permeability and structural stability. Consequently, there is an need to understand the potential seasonal impacts of this practice, especially in developing countries such as Tunisia. For this reason, in this work, we studied the seasonal and vertical changes of soil salinity, structural stability and permeability and consequently the physical fertility of soil.

2. MATERIAL AND METHODS

2.1. Geographic location and general description of the field site

A field experiment was conducted from January to September 2017 at the irrigated perimeter of Oued Souhil in the North semi-arid area of Tunisia (Fig. 1). Oued Souhil is among the most important oueds of the Nabeul region. The perimeter of Oued Souhil (36°27'24"N 10°42'43"E, 22m) covers 240 ha. The soil at the Oued Souhil perimeter is sandy with an average of 79% sand, 7.5% silt and 13.5% clay.

The TWW is collected downstream of the Nabeul

treatment plant for wastewater. The wastewater treatment plant receives domestic and industrial effluents. During the wastewater assessment, the applied TWW exhibits a slightly lower pH with a greater level of electrical conductivity (EC) than the potable water. Additionally, TWW contains higher amounts of calcium, magnesium and potassium and, a lower amount of sodium compared to potable water. In addition, the suspended solids (SS) and, the chemical and the biological oxygen demand are higher in TWW than potable water (Table 1). These parameters are all below Tunisian standards for the reuse of wastewater in irrigation (NT 106.03).

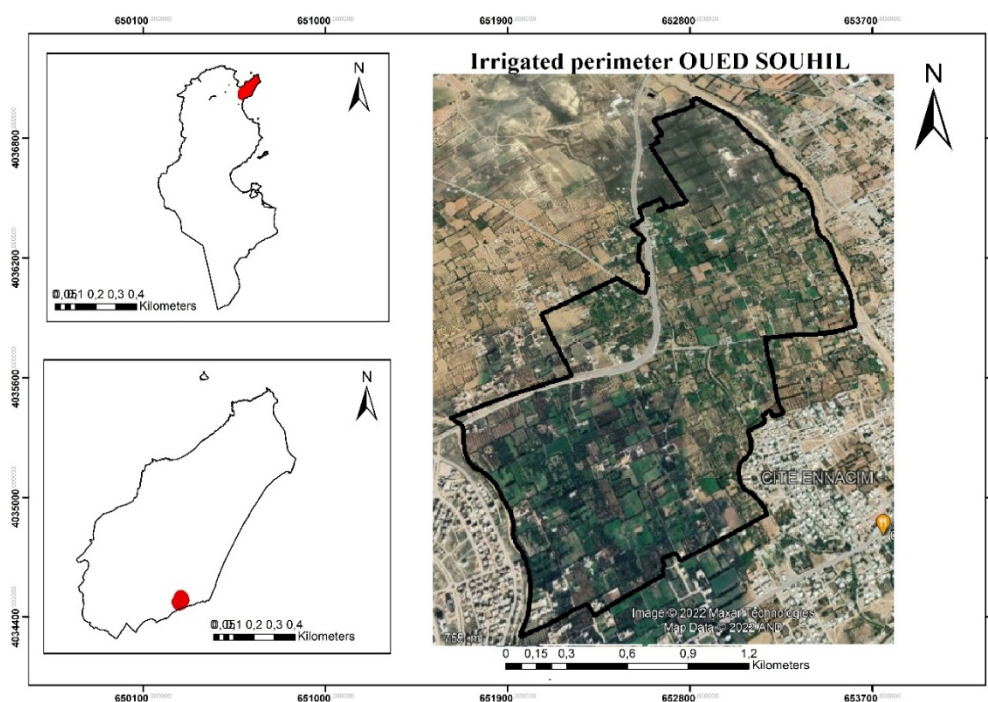


Fig. 1. Localization of irrigated perimeter Oued Souhil (Google earth)

Table 1. Mean values of samples characterized since 2016.

Parameter	TWW	Potable water	Standards *	Parameter	TWW	Potable water	Standards *
pH	7,7±0,2	8,08±0,3	6,5-8,5	Ca ²⁺ (mg/l)	25±0,8	12±0,4	-
EC (dS/m)	4±0,3	3,5±0,3	7	Mg ²⁺ (mg/l)	30±1,2	3±0,01	-
Cl ⁻ (mg/l)	705±3	390±2	2000	SS (mg/l)	17±0,5	4,3±0,05	30
Na ⁺ (mg/l)	516±4	590±3,2	-	COD (mg/l)	56±1,6	19±0,6	90
K ⁺ (mg/l)	41,5±1,7	25±1,2	-	BOD ₅ (mg/l)	30±1,1	4,27±0,07	30

*Tunisian standards for wastewater reuse (NT 106.03). EC: Electrical conductivity; SS: Suspended solids; COD: Chemical oxygen demand; BOD₅: biological oxygen demand.

The studied area is characterized by a warm winter and a hot summer, with sometimes a sudden warming in spring. The monthly average temperature ranged between 12.15 °C and 29.05 °C in January and August respectively for the two years 2016 and 2017. During the same period, the average annual rainfall was 393.5 mm. The seasonal distribution of rainfall showed that the rainiest season was the winter followed by the autumn season with 63% and 33%, respectively, whereas the driest season was the summer with 1%.

The predominant winds of the studied area were recorded from the north to the west (National research Institute of rural engineering, Water and Forests 2017).

2.2. Soil sampling

Sampling was carried out by taking soil at three different seasons (winter, summer and autumn) from the five depth layers: (0-20, 20-40, 40-60, 60-80 and 80-100 cm). Five plots were considered in these experiments. Samples were randomly collected using an auger with three replications for each plot for a total of fifteen samples for each depth. Collected soil samples were transported to the laboratory, and then air dried and sieved at 2 mm.

Three sampling seasons were taken. Winter, autumn and summer. In winter season, only rainfall was accounted and recognized as a control treatment. In summer, farmers irrigate only with TWW because of less rainfall, however, in autumn, the two water sources are considered (rainfall and TWW).

2.3. Field and laboratory measurements

Salinity was determined using the standard method (Rhoades et al., 1982) for the preparation of the saturated pastes, 200 g of air-dried soil were used and the soil pastes were left for 24 h to reach equilibrium. Subsequently, the vacuum extracts were collected and electrical conductivity (EC) was measured by a conductivity meter.

Permeability (K) was measured by the constant-head procedure (Klute, 1986). This method was used to determine the amount of water that percolates through the soil during a time (T). The soil was introduced into a tube. A constant load of water was applied to the surface of the tube. After a period of time (T), the volume of water (V) percolating through the tube, the height of the soil (L) and the height of the water at the tube were measured (H) and the section of

the tube (S). K was determined in cm/h according to Darcy's law (Equation 1).

$$K \text{ (cm/h)} = \frac{V * L}{H * S * T} \quad (1)$$

One of the most important parameters of soil structure is the aggregate stability. The aggregate stability analysis test provides an index of structural stability (IS) which essentially considers the effects of organic matter. IS was measured according to Henin et al. (1958) (Equation 2) who makes possible to classify soils. IS varies from 0.1 for soils rich in organic matter, which are very stable, to over 100 for very unstable sodium soils. Henin and Monnier (1956) estimated that by applying standard "aggregate" analyses in water to samples pretreated with alcohol, either benzene or untreated, the structural stability of several samples can be compared. After agitation in water, the soil fraction > 0.2 mm was collected by sieving, and the soil fraction < 0.02 mm was determined by sedimentation.

$$IS = \frac{(C + FS)}{\left(\frac{Agb + Agw + Aga}{3}\right) - 0.9 * CS} \quad (2)$$

C: percentage of clay after pretreatment of soil with benzene; FS: percentage of fine silt after pretreatment of soil with benzene; Agb: percentage of aggregate obtained after pretreatment of soil with benzene; Agw: percentage of aggregate obtained after pretreatment of soil with water; Aga: percentage of aggregate obtained after pretreatment of soil with alcohol; CS: percentage of coarse sands after pretreatment of soil with benzene.

Henin et al. (1958) asserted that higher soil organic matter levels result in a higher percentage of aggregate after benzene pretreatment (Agb). In the same context, when the soil is rich in flocculent cations (i.e., Ca²⁺, Mg²⁺), the percentage of aggregate after pretreatment with water (Agw) is higher.

2.4. Statistical analysis

Two-ways ANOVA were used to analyze the effect of season and soil depth on soil salinity, permeability, structural stability, Agw and Agb parameters. Data were analyzed using the SPSS software, Version 16 S . Differences were considered significant if P < 0.05. Data are presented as mean ± standard deviation (SD). Pearson correlation analyses were conducted between EC, K and IS for the five depth increments in winter (S1) summer (S2) and autumn (S3), respectively.

3. RESULTS AND DISCUSSIONS

3.1. Changes in soil salinity

The ANOVA analysis showed that salinity depended significantly ($P < 0.001$) on the season (S), the depth (D) and the double interaction (S x D) (Table 2). Overall, the highest and lowest values of salinity were obtained in summer and winter, respectively. Such result could be explained by the relatively high salinity of the wastewater and the high evaporation in summer (Kallel et al., 2012; Farhadkhani et al., 2018), and the leaching of salts in winter. Indeed, wastewater irrigation may cause temporal soil salinization due to its salts content. Similar results were obtained in a tomato cultivated farm irrigated with treated wastewater experienced temporal salinization during the summer period but return to normalcy at the end of the winter period (Vergine et al., 2017). The authors attributed the temporal increase to high irrigation regime and lack of rainfall which resulted in the accumulation of salts from wastewater. Several studies have confirmed the positive impact of rainfall on soil salinity. For instance, the research of (Kanzari et al., 2012) examined how rain affects salt movement through the soil profile. Additionally, the soil's

sandy texture is a beneficial property that facilitates salt leaching. Regarding the soil depth, data revealed that salinity decreased by 19% from soil surface (0-20 cm) to 80-100 cm. Our experiment revealed that at 0-60 cm, the maximum EC was showed in summer with 5.69 mS/cm, while at 60-100 cm, the EC registered was more pronounced in autumn with 4.51 mS/cm (Fig. 2). The increase of salinity in depth in autumn is due to the action of the irrigation with TWW that bring salts to the soil and the rains of autumn leach them in depth (Azouzi et al., 2016). Our results concur with those reported by Liu et al. (2020) who also explained this trend by the dispersion of soil salinity from autumn to winter and an accumulation trend from autumn to summer caused mainly by the irrigation with TWW. In addition, according to Changati et al. (2021), this results in salt accumulation in the top soil in summer due to inadequate salt leaching caused by the arid climate of this region that is characterized by high temperatures in summer and absence of precipitations and irrigation water application (TWW) not exceeding evapotranspiration flux.

3.2. Changes in soil permeability

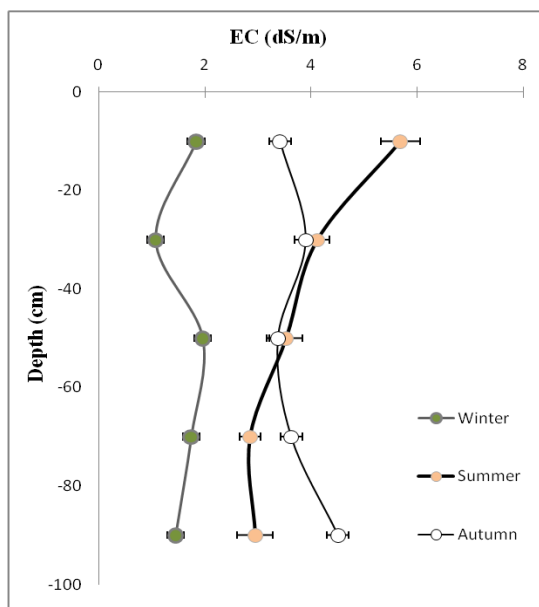


Fig. 2. Salinity as affected by soil depth (0-20, 20-40, 40-60, 60-80 and 80-100 cm) and seasons (winter, summer and autumn). Curves are mean of three replicates \pm SD.

Soil permeability was significantly ($P < 0.001$) affected by season (S), depth (D) and the double interaction (S x D) (Table 2). Generally, the summer season exhibited the maximum permeability with two times and 23% higher than autumn and winter, respectively. Concerning the depth effect, the topsoil surface (0-40 cm) revealed the biggest permeability followed by the depth layer (40-100 cm). The behaviour of this parameter is similar in all seasons (Fig. 3). In the same context, Azouzi et al.

(2016) showed that the reuse of TWW on irrigation provides the increase of the hydraulic conductivity in the case of sandy soils at the top soil. Particularly, in the summer season, the irrigation with wastewater provided the greatest permeability at the soil surface (0-20 cm) with 77.78 cm/h (Fig. 3). These results could be linked to the favorable effect of organic matter in the TWW. Indeed, many soils in arid and semiarid regions contain precipitated sources of calcium as CaCO_3 within their profiles

Table 2. Season (winter, summer and autumn) and soil depth (D) effects on soil salinity (EC), permeability (K) and structural stability (IS)

		Salinity (EC: mS/cm)	Permeability (K:cm/h)	Structural stability (IS)
Season (S)	Winter	1,61±0,01c	21,11±1,02b	3,023±0,22b
	Summer	3,82±0.05a	27,53±1.32a	2,90±0.01c
	Autumn	3,76±0.06b	13,18±0.28c	4,20±0.03a
Depth (D)	0-20 cm	3,64±0.23a	30,85±1.87a	2,01±0.02d
	20-40 cm	3,030±0.16b	24,54±1.36cd	1,97±0.00e
	40-60 cm	2.95±0.07bc	28,78±1.95b	5,14±0.4a
	60-80cm	2.74±0.05c	26,32±1.06c	4,01±0.36b
	80-100 cm	2,96±0.02bc	22,45±2.01d	3,73±0.02c
ANOVA	Season (S)	***	***	***
	Depth (D)	***	***	***
	S x D	***	***	***

, * Significant at $P < 0.01$ and $P < 0.001$, respectively.

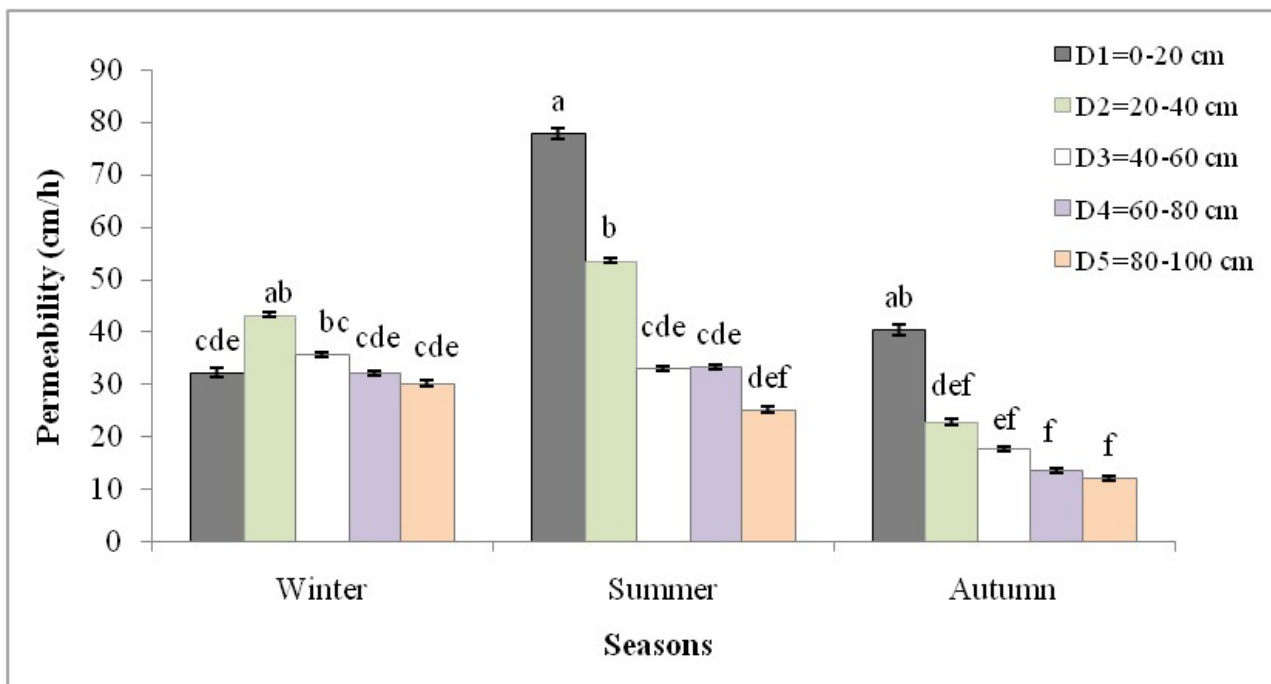


Fig. 3. Permeability as affected by soil depth and seasons.

(Batarseh, 2017). Nevertheless, the natural dissolution of CaCO₃ is low due to its negligible solubility. Thus, it does not supply sufficient calcium amounts to affect soil amelioration under ordinary management conditions (Qadir et al., 2007). Hence, the organic acids released from organic matter degradation in soil can be a practical and sustainable way to improve calcite solubility (Naramabuye and Haynes, 2006). Decomposition of organic matter produces high amounts of CO₂ and Hydrogen is released when CO₂ gas is dissolved in water, thus forming carbonic acid (H₂CO₃). The dissociation of this acid increases CaCO₃ dissolution resulting in more calcium in the soil, which ensures clay flocculation (Amer and Hashem, 2018). Furthermore, divalent cations like calcium can prevent clay swelling and dispersion, resulting in a significant increase in soil hydraulic characteristics (Qadir et al., 2007). Similar results have reported by Leuther et al. (2019), which observed an increase of porosity by TWW compared to rainfall due to the eluviation of dispersed clay minerals, which was reflected by a reduced soil water retention and greater visible porosity. With regard to the long history of TWW application on soil, the detected changes

for the top soil were marginal. Other authors have found similar trends: summer is the season with greater soil permeability both in natural semi-arid soils and in agricultural fields (Cerdà, 1996; Osawa et al., 2017). Normally, the highest infiltration rates were found during the dry and hot season (Gifford, 1972), increasing from winter to summer and decreasing from winter to autumn (Bertoni et al., 1958; Luo et al., 2023), reaching the maximum in late summer. Some authors found that land management practices (Gifford, 1972; Osawa et al., 2017) control the seasonal changes of soil hydraulic conductivity due to the addition of organic matter to the soil, plant growth, and the activity of soil fauna and flora.

3.3. Changes of soil structural stability

Soil structural stability changed significantly ($P < 0.001$) with respect to season, soil depth as well as the double interaction (S x D) (Table 2). Regardless soil depth and considering the IS variation among seasons, the average maximum values was observed in autumn with a two-fold increase compared to values registered in summer. However, Fig. 4 revealed that the greatest Agb was registered in summer with

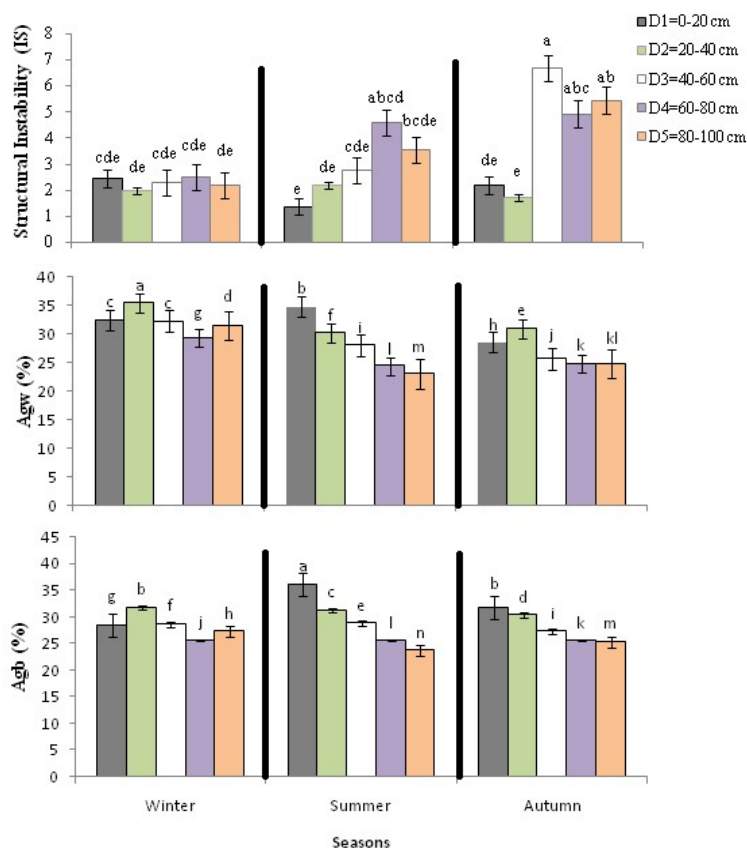


Fig. 4. Structural stability (IS), percentage of aggregate obtained after pretreatment of soil with benzene (Agb) and percentage of aggregate obtained after pretreatment of soil with water (Agw) as affected by soil depth and seasons.

29.1% and the greatest Agw was obtained in winter with 32.1%. The increasing trend of Agb in summer season is due to the accumulation of organic matter in the soil irrigating from TWW irrigation. This result of IS reduction in sandy soils in summer was in line with the findings of Leuther et al. (2019) mainly due to the enhancing of soil permeability in summer compared to the autumn and winter seasons. At the same time, it is well known that soil structure is to a large extent formed by soil biota (Oades, 1993) and that the quality and quantity of organic matter in irrigation water can shape the structure of soil biological communities (Ibekwe et al., 2018). Hence, organic compounds introduced through TWW irrigation in summer are expected to affect soil structure and thereby soil water dynamics. Rohoskova et al. (2009) founded the similar seasonal variation of soil aggregate stability: increasing in summer and decreasing in autumn.

On the other hand, the improvement of soil structural stability in winter is not attributed to the enrichment of soil with organic matter arriving from TWW. But, it is due to the leaching of monovalent cations (i.e., Na⁺, K⁺) by rainfall. Indeed, the high Na⁺ concentrations in soil arriving from TWW can cause the loss of physical soil structure as a result of clay swelling and dispersion due to an interlayer cationic replacement by Na⁺ ions (Alcívar et al., 2018). According to Changati et al. (2021), water from wastewater irrigation enhanced the exchangeable sodium concentration (Na⁺) and exchangeable sodium cation percentage (ESP) because of the higher electrical conductivity,

total dissolved solids, and major ion concentrations.

According to depth, in summer and autumn, there is a trend of decrease of Agb and Agw from topsoil to deeper soil. Contrary to the winter which registered a maximum of Agb and Agw at the medium layers (20-60 cm) with 30.2 and 33.8%, respectively. This is primarily due to the irrigation with the organic carbon-rich TWW, which increases the level of organic matter, especially in the top soil (Morugan-Coronado et al., 2011). Indeed, organic matter can bind soil mineral particles together because of the forces of attraction and binding (Rengasamy 2018). Jueschke et al. (2008) observed the same accumulation trend of soil organic carbon in the topsoil over a long period of TWW application. More interestingly, in summer and autumn, the maximum IS were registered at the depth layers. In contrast, the lowest IS values were showed at the topsoil. Differently, in winter, the significant structural stability has been achieved at 40-60 cm depth layer, while the lowest at 20-40 cm (Fig. 4). These possible scenarios are expected in summer and autumn due to the trend of decreasing permeability and organic matter from surface to depth contributed to the decrease in structural stability. Therefore, irrigation with TWW in summer and autumn can increase salinity and sodicity of soils at depths down to 1 m (Bedbabis et al., 2014), accompanied with clay migration due to dispersion of clay minerals in the top soil (Bardhan et al., 2016). The latter can enhance soil sealing, reduce infiltration, and increase soil

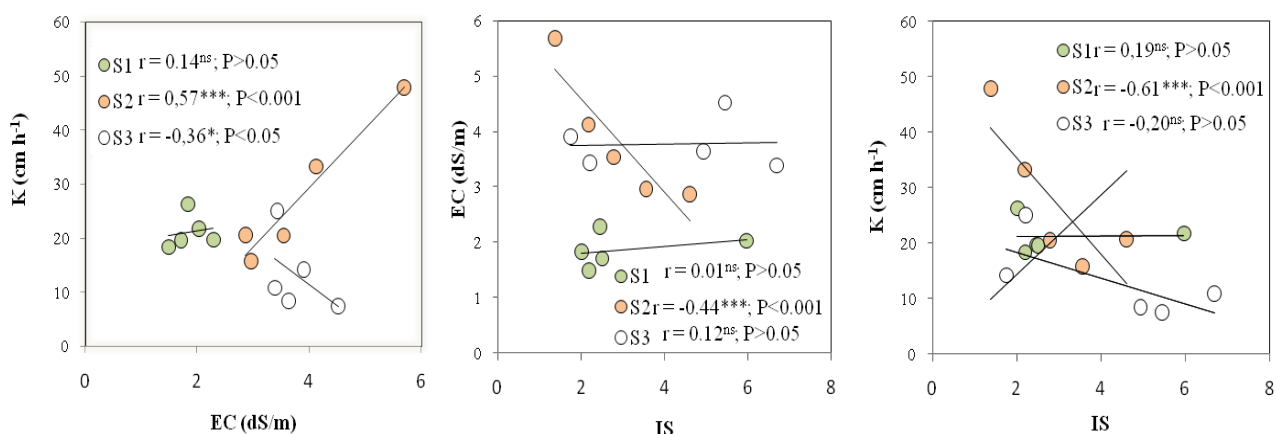


Fig. 5. The linear relationship between electrical conductivity (EC), permeability (K) and structural stability (IS) at winter (S1), summer (S2) and autumn (S3). Each point is the average value of five replicates of five depths *, **, *** Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively; ns = Not significant

loss in sandy soils (Lado et al., 2005).

3.4. Interaction between soil parameters according to seasons

To fully understand the role of season and soil depths on soil salinity, permeability and structural stability, we will need to encompass both factors interactions. The correlation between K, EC and, IS was assessed at the three distincts seasons (Fig. 5). At S1, correlation analysis demonstrated that no relationship was found between all parameters. These obtained data might be attributed to the dominant effect of rainfall on the different parameters in this period. Whereas, at S2, a significant correlation was obtained between K and EC, K and IS ($r = 0.576^{***}$, $r = -0.628^{***}$, respectively) and between EC and IS ($r = 0.448^{***}$). It's worth noting that the findings of this study revealed that there was no organic matter leaching during this season, resulting in CaCO₃ dissolution and, as a result, a rise in salinity and permeability, leading to enhanced structural stability. At S3, we occurred a negative correlation only among K and EC ($r = -0.358^*$) (Fig. 5). These findings could be ascribed to organic matter leaching by rain, resulting in no dissociation of CaCO₃ and subsequently a limitation in Ca²⁺ release. Simultaneously, there is inadequate monovalent cation leaching, that reduces soil permeability.

Step-wise regression was performed to find out the critical soil physical parameter traits, according to the seasons (S1, S2 and S3), which was significantly associated with structural stability (Table 3). Overall, the K is the only predictor variable that explained the variation of IS at the second season S2 (summer). This finding supports the idea that an increase in soil permeability during the summer is the primary cause of the decrease in soil IS (Leuther et al., 2019).

Table 3. Multiple linear regressions (step-wise) explaining structural stability (IS) variation in each season (S1: winter, S2: summer and S3:autumn), as a dependent variable, K and EC as independent variables

Dependant variables	Seasons	Variable chosen	R ²
IS	S1	-	-
	S2	K	0,35*
	S3	-	-

* = $P < 0.05$

4. CONCLUSIONS

The effects of using wastewater on permeability and structural stability are important findings which need to be studied in a long term experiment especially in degraded soils that characterized by a very poor physical properties. After 38 years of applied TWW irrigation; we found several seasonal variations in the soil properties. Particularly, at the top soil; an increase of the electrical conductivity and permeability of soil in summer linked to the wastewater irrigation. For both seasons (summer and autumn), depth variability of structural stability was mainly influenced by the accumulation of organic matter and the high permeability of topsoil. On the contrary, in winter, the improved structural stability was due to the leaching of salts by rainfall. Indeed, further research is required to investigate the effects of these wastewater on crops and on other soil chemical, physical and biologicals properties in degraded agricultural soils.

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