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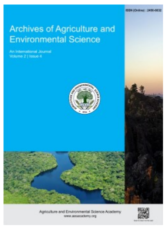

ORIGINAL RESEARCH ARTICLE

Impact of irrigated and non-irrigated cropping systems on soil physicochemical properties in a small-scale irrigation farming system in Eastern Uganda

Issa Kaduyu[1*] and **Patrick Musinguzi**[2]

[1]Department of Agricultural and Biosystems Engineering, Botswana University of Agriculture and Natural Resources, Private Bag 0027, Gaborone, BOTSWANA
[2]Department of Agricultural Production, School of Agricultural Sciences, Makerere University, P.O Box 7062, Kampala, UGANDA
[*]Corresponding author's E-mail: kaduyuissa@gmail.com

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ABSTRACT

This study evaluated the impact of irrigation and cropping on soil physicochemical properties at Kyekide small scale irrigation farm in Jinja district, eastern Uganda. Treatments included Land-use systems under perennial and annual cropping with and without irrigation for over 20 years. The hypothesis was that there were insignificant differences in physicochemical properties of the soil under irrigated and non-irrigated cropping systems. Soil physical properties except hydraulic conductivity was not significantly different with irrigation and cropping. The pH of the soils ranged from moderately acidic to neutral pH (5.17-7.40), with irrigated soils tending to be more neutral than non-irrigated soils. SOM content was higher in the irrigated soils and perennial soils than in the non-irrigated and annual soils. The soils were moderately deficient in N and severely deficient in P (mean values =0.175% N and 1.183mg kg^{-1} P) compared with the critical of 0.2% and 15 mg kg^{-1}, respectively. Irrigated soils had a significantly higher Na^{+} content than non-irrigated soils, with a mean value of 2.985cmol/kg. The K^{+}, Ca^{2+}, and Mg^{2+} contents were higher in irrigated and perennial soils than non-irrigated and annual soils. The study suggested monitoring the soils under an irrigation scheme to prevent degradation due to increased salt accumulation or chemical fertility decline. Overall, monitoring of soil quality is vital in irrigation schemes to monitor the impacts of water on the environment.

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INTRODUCTION

Globally, irrigation remains key to food supplies. Its importance will rise in future when the demand for food increases, whilst the reliability of yields from rain-fed agriculture may decline due to climate change. There has been an increase in climate scenarios in many agro-ecological regions globally (Lobell and Gourdji, 2012). The increasing intensity of climate change has significantly impacted global crop productivity (Lobell *et al.*, 2011). Climate change has become a threat to food security, especially in developing countries. Therefore, tomorrow's agriculture is challenged by increasing global demand for food, scarcity of arable lands, and resources alongside multiple environmental pressures, presenting the need to be managed smartly through sustainable and eco-efficient approaches.

Several farming communities have widely adopted irrigation practices to improve crop water availability during water scarcity induced by climate change. In recent decades, the amount of land irrigated, the type of irrigated cropping systems and the quantity of irrigation water used have increased substantially. These trends are expected to increase in the future. It is therefore ideal for assessing the impact of irrigation on soil quality. However, despite the varying nature of the impact of irrigation, most studies only assess impacts of water quality on soil properties (Abd-Elwahed, 2018, 2019; Alrajhi *et al.*, 2017; Ayoub *et al.*, 2016; Bastida *et al.*, 2017; Che *et al.*, 2021; Ganjegunte *et al.*, 2017; Eid *et al.*, 2021). Other studies assessed the variation of soil properties between irrigated and rain-fed (Makoi, 2016), while others compare impacts across time intervals (Shang *et al.*, 2019). The impact of irrigation across different cropping systems has attracted less attention.

The effects of cropping systems vary differently across different soil types and management practices (Nataliya and Lenssen, 2018). Variation of soil quality in different cropping systems has attracted increasing interest in assessing soil physicochemical and biological properties. Although the design of most cropping systems ensures maximum crop yields and returns, it is necessary to maintain soil health and productivity (Subhadip *et al.*, 2019). Existing studies on cropping systems have majorly focused on crop yields as influenced by soil fertility and their effect on soil properties without considering management practices (Amsili *et al.*, 2021; Mikha *et al.*, 2006; Wienhold *et al.*, 2006; Yang *et al.*, 2020). Nataliya and Andrew (2018) compared the soil quality of fertilised and unfertilised cropping systems on different soil types in South-Central Uganda. Tesfahunegn and Gebru (2020) examined variation in soil properties across different cropping systems and land-use systems in northern Ethiopia. Tesfahunegn and Gebru (2019) also examined variation in soil properties in the long term irrigated and non-irrigated cropping and land-use systems in Ethiopia. However, the sustainability of cropping systems in maintaining soil quality is highly dependent on how farmers understand the response of their soils to site-specific land management practices.

Despite the numerous studies on irrigation and cropping systems, the environmental impact of irrigation is site-specific and highly variable yet, not well documented in developing countries. In Uganda, the effect of different land uses on the physiochemical soil properties is evident (Dissanayake *et al.*, 2015; Mugagga, 2015). Nevertheless, knowledge of the variation of soil chemical and physical properties of irrigated soils under different cropping systems remains limited amongst farmers in Uganda. However, some of the impacts of irrigation and cropping systems can be severe, as demonstrated in different studies. Lack of knowledge about soil quality and management among farmers exacerbates farming communities' food security challenges, putting at stake the livelihoods of over 90% of Ugandan farmers (Mutegi *et al.*, 2012; Nkonya *et al.*, 2004). In addition, the relationship between soil quality decline under different land-use practices in Uganda has attracted less attention among farmers. There is an urgent requirement to assess the impact of irrigation and cropping systems on soil properties in different parts of Uganda.

Most government and non-government agencies have increased efforts to scale out irrigation on small-scale farms in Uganda. However, the lack of knowledge on its effect on soil properties jeopardises the sustainability of irrigated agriculture in Eastern Uganda. The effort to characterise the impact of irrigation practices under different cropping systems on a spatial and temporal scale is critical in understanding ecosystem changes and designing improved soil management practices to ensure sustainable production under irrigated agriculture. This study; i) evaluated the impact of irrigation on the physical and chemical soil properties and ii) determined the impact of irrigated and non-irrigated fields under annual and perennial cropping systems on physical and chemical soil properties in a small irrigation scheme in Jinja, Eastern Uganda. Therefore, farmers that might attain knowledge from this study would be aware of the effect of irrigation on soil quality and determine the best management of different irrigated cropping systems. Awareness of these impacts ensures the sustainability of irrigated agriculture and reduces the impact of irrigation and cropping systems on the environment.

MATERIALS AND METHODS

Description of the study area

The present study was conducted at Kyekide small scale irrigation farm in Eastern Uganda. The farm is located at 0°29'26 N and 33°10'32 E, 1148 m above sea level along Jinja-Kamuli High way in Kyekide village, Buwenda Parish, Mafubira Sub County, Jinja district. The irrigation scheme covers over twenty acres of land in the East of Jinja district. The favourable tropical climate is characterised by bimodal rainfall, and temperatures between 17 °C and 28 °C have favoured crop production. Irrigation practices ensure continuous productivity all year round. Clayey soils are the predominant soil type. Perennial and annual cropping has been carried out for over 20 years, both under sprinkler irrigation and rain-fed. Several perennial crops are grown at the farm, including; ivy gourd (*Coccinia grandis*), sugarcane (*Saccharum officinarum*), and coffee. On the other hand, annual crops grown include; maise (*Zea mays*), bitter gourd (*Momordica charantia*), eggplants (*Solanum melongena*), cucumber (*Cucumis sativus*), bottle gourd (*Lagenaria siceraria*), kale, spinach, common beans, sweet potatoes and tomatoes.

Experimental design and treatments

A completely randomised design was used for the study. Four treatments were considered for this study: Irrigated Perennial, Non-irrigated Perennial, Irrigated annual and non-irrigated annual fields. A single plot of ≥ 0.5 acres was selected for each of the treatments. A plot of irrigated ivy gourd (*Coccinia grandis*) was selected for irrigated perennial, irrigated bitter gourd (*Momordica charantia*) for the irrigated annual field, rain-fed maize (*Zea mays*) plot for non-irrigated annual field and a plot of rain-fed sugarcane (*Saccharum officinarum*) for the non-irrigated perennial field. The study plots were randomly selected, and the management history of the study plots was recorded for the previous years.

Soil sampling

At each study plot, four replicate plots, each measuring 20 m × 30 m, were demarcated before sampling. The soil was sampled randomly between plants and rows using soil core rings along a transect within each replicate plot. Samples were collected to a 0-30cm depth after removing litter and surface residues (Okalebo *et al.*, 2002). The soil cores were air tightened and placed in plastic bags. Sixteen soil core rings (4 treatment plots × four replicate plots) were collected for bulk density and hydraulic conductivity laboratory analyses. An additional four composite samples were collected using a soil auger to determine soil chemical properties in each plot. Four random samples were collected for each replicate plot, thoroughly mixed, and a composite sample was picked for analysis of soil texture, pH, electrical conductivity (EC), total soil organic carbon (SOM), total Nitrogen (TN), available phosphorous (P), Calcium (Ca^{2+}), Potassium (K^{+}), sodium (Na^{+}) and Magnesium (Mg^{2+}).

Laboratory analysis

Laboratory soil analysis was carried out using standard laboratory procedures at Makerere University Soil and plant analytical laboratory. Soil samples were sieved through a 2-mm mesh after air drying to discard roots and coarse plant debris. The soil hydraulic conductivity was determined using the constant head method (Diminescu *et al*., 2019), and bulk density (g cm^{-3}) was determined using the soil core rings and calculated according to the weight of the soil in the core ring of known volume after oven drying at 105 °C for 48 hours. Sieved (<2mm) air-dried soil was used to determine soil texture using the Bouyoucos hydrometer method (Okalebo *et al*., 2002).

The pH was measured with a pH meter at a ratio of distilled water: soil of 1:2.5, while EC was measured using a conductivity meter at a ratio of 1:1 of distilled water: soil. A Sieved (< 0.02 mm) air-dried soil sample was used for the determination of SOM (%) using Walkey-Black oxidation and titration methods (Okalebo *et al*., 2002). Exchangeable cations (K, Mg, Ca, and Na) were extracted using ammonium acetate solution. Na and K were then determined using flame photometry, while Ca and Mg by atomic absorption spectrophotometry. Total phosphorus was determined using the colorimetric method (Okalebo *et al*., 2002).

Data analysis

A two-way analysis of variance (ANOVA) was conducted using Gen-stat 14th Edition (VSN International, 2011) to determine the differences in soil chemical and physical properties at a 5% probability level. The Least Significant Difference (LSD) was used to separate the means at a 95% confidence interval.

RESULTS AND DISCUSSION

Impact on soil physical properties

Soil texture: Generally, no significant differences ($p > 0.05$) in the impact of irrigation were observed on sand, clay and silt content. However, non-irrigated soils had more clay than irrigated soil; thus, the irrigated soils had more sand and silt than the non-irrigated soils (Table 1). Additionally, the interactive impact of irrigation and cropping systems showed no significant ($p > 0.05$) variation (Table 2). Overall, the soils at the study site of both irrigated and non-irrigated fields were sandy clay loam with greater than 30% clay and more than 50% sand content. The lower clay content in the irrigated plots could be due to the leaching effect associated with irrigation. These results do not align with those of (Tesfahunegn and Gebru, 2019), who found significant differences in soil texture in irrigated and non-irrigated land uses. The differences in soil type and management practices applied could explain the differences. Variation in soil quality, therefore, seems site-specific and is driven by existing management practices.

Non-irrigated annual cropped soils registered higher sand content than perennial non-irrigated soils, and this may be due to erosion that carries away the fine particles leaving sandy particles, especially for the annual cropping. Cropping systems such as perennial cropping increase soil organic carbon and reduce soil degradation due to erosion that results from continuous tillage in the annual cropping systems (Jin *et al*., 2021). These processes explain the higher sand content in annually cropped soils left after erosion impacts.

Table 1. Variation in soil physical properties as influenced by irrigation.

	Texture			BD	Ksat
	Clay %	Sand %	Silt %	(mg/m^3)	(cm/hr)
Irrigated	30.50^{a}	49.25^{a}	20.25^{a}	0.952^{a}	0.291^{a}
Non-irrigated	34.38^{a}	48.62^{a}	17.00^{a}	1.034^{a}	0.231^{b}
LSD (5%)	4.0488^{NS}	4.1454^{NS}	3.5649^{NS}	0.0998^{NS}	0.0564**

** significant at $p<0.05$, NS Not significant.

Table 2. Variation in soil physical properties as influenced by irrigation and cropping.

	Texture			BD	Ksat
	Clay (%)	**Sand (%)**	**Silt (%)**	**(mg/m^3)**	**(cm/hr)**
Irrig. Anl	32.00^{a}	45.5^{a}	22.50^{a}	0.91^{a}	0.27^{ab}
Irri. Pnl	29.00^{a}	53.00^{b}	18.00^{ab}	0.98^{a}	0.31^{b}
Non. irri. Anl	32.625^{a}	50.00^{ab}	16.75^{b}	1.04^{a}	0.25^{ab}
Non. Irri. Pnl	32.625^{a}	47.25^{ab}	16.25^{b}	1.02^{a}	0.21^{a}
LSD (5%)	5.7259^{NS}	5.8624^{NS}	5.0416^{NS}	0.1411^{NS}	0.0797^{NS}

Irri- irrigated Nin-irri- Non-irrigated Anl- annual Pnl-perennial NS- Not significant.

Bulk density: Bulk density did not vary significantly ($p > 0.05$) with irrigation and cropping systems (Table 1). However, non-irrigated soils had higher bulk density than irrigated soils. Irrigated perennial cropped soils had a much lower bulk density than non-irrigated annual soil (Table 2). These results align with previous studies that reported non-significant bulk density variation with irrigation and cropping systems in Ethiopia (Tesfahunegn and Gebru, 2019). The lower bulk density for irrigated perennial and annual soils could be due to the higher organic matter content that improves the soil physical properties (Table 2). The lower bulk density of perennial irrigated soils accounts for the higher saturated hydraulic conductivity. Perennial irrigated soils accumulate more organic matter than non-irrigated perennial cropped soils due to minimal soil disturbances, thus less compaction. The average bulk density (0.993 mg/m^3) for the soil of the study area was above the critical range of 1.30 and 1.60 mg/m^{3}for fine-textured soils (Skopp, 2011).

Hydraulic conductivity: The hydraulic conductivity varied significantly ($p < 0.05$) with irrigation practices. Irrigated soils had a significantly higher saturated hydraulic conductivity than non-irrigated soils (Table 1). However, the interactive impact of irrigation and cropping had no significant impact on hydraulic conductivity (Table 2). The significant impact of irrigation suggests that irrigation rather than cropping has a considerable effect on hydraulic conductivity. These results do not align with Alrajhi *et al.* (2017), who found no significant differences in soil hydraulic conductivity for different irrigation scenarios. Soils with a low bulk density have more macrospores that allow more water through infiltration than soils with higher bulk density. Thus, the significantly higher Hydraulic conductivity of irrigated soils could be due to the low bulk density induced by the improved physical properties. The improved physical properties could be explained by the higher soil organic matter observed in irrigated soils. Availability of soil organic matter significantly reduces soil compaction resulting in improved hydraulic conductivity (Amsili *et al.*, 2021). These results, therefore, suggest an increase in macro-porosity in irrigated soils which accounts for the higher hydraulic conductivity.

Impact on chemical properties: Organic matter, total nitrogen and phosphorus: Results from the ANOVA indicate that Organic matter varied significantly ($p < 0.05$) with the impact of irrigation (Table 3).

Irrigated fields had significantly higher organic matter compared to non-irrigated fields. The higher SOM in irrigated soils could be due to the all-year crop growth enhanced by irrigation compared to rain-fed fields. Additionally, the increased cropping leads to more crop residues that decompose into soil organic matter. The accumulation of organic matter in the irrigated soils dramatically improves the soil chemical properties. The TN and P content varied significantly with the impact of irrigation. The TN and P content were higher in irrigated soils than non-irrigated soils. Irrigated soils had 0.064% more N and 88% more P than non-irrigated soils (Table 3). High organic matter content in the soils leads to higher soil nutrients and pH. For example, soils with high organic matter have higher N content released from the mineralisation process of organic matter.

Table 4 indicates the variations of chemical properties with irrigation and cropping system. The impact of irrigation on SOM had no significant differences ($p > 0.05$) under annual and perennial cropping. However, the higher SOM content observed in irrigated perennial and annual cropped soil is more noteworthy than non-irrigated perennial and annual cropped soils (Table 4). These results are consistent with previous studies showing more significant organic carbon in perennial cropped soils than annual ones (Sprunger *et al.*, 2019). Shang *et al.* (2019) also observed increased organic carbon in perennial forages for dry soils compared to annual crops. The significant increase is attributed to the continuous growth that enhances the below-ground biomass carbon pool (Shang *et al.*, 2019).

Total N and available P did not vary significantly ($p > 0.05$) with irrigation and cropping system. Perennial irrigated soils had a higher non-significant level of total N and P (Table 4). The higher TN and P implies that the above-ground crop residue in perennial cropped soils favoured the cycling of N and P compared to annually cropped soils (Ferrarini *et al.*, 2021; Liu *et al.*, 2021). The increased recycling could be due to the increased microbial activity in perennial cropped and irrigated soils compared to annually cropped soils (Ferrarini *et al.*, 2021; Pascazio *et al.*, 2018; Sprunger *et al.*, 2019). These results suggest that irrigation in cropping systems improves nitrogen and phosphorus availability, which are essential nutrients for crop growth. However, soils of the study area were moderately deficient in N and severely deficient in P with the mean values of 0.175% N and 1.183 mg kg^{-1} P compared with the critical values of 0.2% N and 15 mg kg^{-1} P, respectively (Okalebo *et al.*, 2002).

Table 3. Variation in soil chemical properties as influenced by irrigation.

	SOM	TN	pH	EC	P	K^+	Ca^{2+}	Mg^{2+}	Na^{2+}
	---%---			µS/cm	ppm	-----cmol/kg-----			
Irrigated	4.147^a	0.21^a	6.62^a	1.91^a	3.30^a	3.49^a	19.45^a	6.42^a	3.52^a
Non-irrigated	3.02^b	0.14^b	5.81^b	1.08^b	0.37^b	2.09^b	12.50^b	4.13^b	2.39^b
LSD (5%)	0.439***	0.034**	0.465**	0.252**	1.286***	0.270**	4.351**	1.436**	0.351***

** significant at $p<0.05$ *** significant at $p<0.001$.

Table 4. Variation in soil chemical properties as influenced by irrigation and cropping.

	SOM	N	pH	EC	P	K^+	Ca^{2+}	Mg^{2+}	Na^+
	---%---			(µS/cm)	ppm	-----Cmol/kg----			
Irrig. Annual	4.02 ^{a}	0.19^a	7.01^a	1.81^a	2.77^{ab}	2.87^a	21.40^a	7.06^a	4.06^a
Irri. Perennial	4.27^a	0.23^a	6.24^{ab}	2.00^a	3.84^b	4.10^b	17.50^a	5.78^{ab}	2.99^b
Non. irri. Anl	2.66^b	0.12^b	5.44^b	0.98^b	0.15^a	1.92^a	11.34^b	3.74^b	1.96^{ab}
Non. Irrg. Prnl	3.37^{ab}	0.17^a	6.18 ^{ab}	1.19^b	0.58^a	2.26^a	13.66^b	4.51^{ab}	2.83^b
LSD (5%)	0.621^{NS}	0.048^{NS}	0.658**	0.777^{NS}	1.819^{NS}	1.176^{NS}	6.153^{NS}	2.03^{NS}	0.496***

** significant at $p<0.05$ *** significant at $p<0.001$, NS-Not significant.

Leaving the soil under crop cover for more extended periods leads to the accumulation of organic carbon in the irrigated perennial cropped soil compared to annually cropped soils with seasonal tillage and harvesting (Sprunger *et al*., 2019). Previous studies have reported that long-standing vegetation increases organic matter content compared to short-lived vegetation (Overstreet and DeJong-Hughes, 2009). The lower SOM content in non-irrigated annual cropped soils could be due to the soil disturbances through tillage leading to increased SOM turnover due to soil aggregate breakdown (Sánchez–González *et al*., 2017). The increased aggregate breakdown results in increased soil erosion, lower carbon sequestration and reduced nutrient availability (Rodrigo-Comino *et al*., 2018).

pH and electrical conductivity: The soil pH and electrical conductivity also varied significantly ($p<0.05$) with the impact of irrigation (Table 3). Irrigated soils had a significantly higher pH (6.622±0.151) compared to non-irrigated soils (5.809±0.1783). Electrical conductivity was 43.13% higher for irrigated soils compared to non-irrigated soils. The higher pH in irrigated soils could be explained by improved SOM content than non-irrigated soils, while the higher EC could be due to increased salt accumulation in irrigated soils. The soil pH varied significantly ($p < 0.05$) with the impact of irrigation and cropping, while electrical conductivity showed no significant variation (Table 4). Irrigated perennial and annually cropped soils had a significantly higher pH compared to non-irrigated cropped soils. The significantly lower pH values in non-irrigated annual cropped soils may be due to the lower organic matter than perennial cropped non-irrigated soils (Table 4).

The grand mean pH of 6.22 for soils of the study area is still within the range of 5.5-6.5 that can favour crop growth (Okalebo *et al*., 2002). This study's results agree with those of Alrajhi *et al*. (2017), who found significant variations in soil pH for different irrigation water qualities, although irrigation scenarios had no significant effects. It appears like irrigation practices improve soil pH, attributed to the increase in soil organic matter that buffers soil acidity. The higher EC observed for irrigated soils is attributed to the increased accumulation of salts enhanced by irrigation.

Basic cations: The K+, Mg2+, Ca2+ and Na+ content were significantly (p<0.05) impacted by irrigation (Table 3). Irrigated fields had higher K+, Mg2+, Ca2+ and Na+ than non-irrigated soils. Irrigated soils had 40% higher K than non-irrigated soils. Similarly, irrigated soils had 35.74% more Ca and 35.72% more Mg than non-irrigated soils. Additionally, there were no significant differences ($p > 0.05$) in the impact of irrigation under perennial and annual cropping on the content of K^+, Ca^{2+} and Mg^{2+} of the soils under perennial and annual cropping (Table 4). However, irrigation and cropping had had significant impacts on the level of Na^+ of the soils under perennial and annual cropping (Table 4). Soils under irrigation had significantly higher basic cations K^+, Mg^{2+}, Ca^{2+} and Na^+ content, and this could also be due to the soil management practices such as the addition of animal manure. Farmers that irrigate their fields tend to adopt more improved cropping practices. Makone *et al*. (2021) also found that irrigation technologies improved agricultural production practices in Kenya. However, results from this study do not align with Adejumobi *et al*. (2014), who indicated that a decrease in Mg^{2+} and Ca^{2+} content in irrigated soils. The study area soils had a high K^+ content with a mean of 2.79 cmol/kg K compared to the critical level of 0.3–0.7cmol kg^{-1}(Hazelton and Murphy, 2017). Additionally, the mean $Mg^{2+}$and Ca^{2+} for the study area soils were above critical levels with 5.75 cmol/kg and 15.975 cmol/kg compared to the critical levels of 1–3 cmol kg^{-1} and 5–10 cmol $kg^{-1,}$ respectively (Hazelton and Murphy, 2017).

The average Na^+ observed for the study area was 2.93 cmol of Na/kg, which appears to be far greater than the recommended level of 0.1 cmol/kg for successful crop growth. The high sodium content for irrigated soils may be attributed to the study site's poor drainage and irrigation practices, as salts tend to accumulate in the topsoil over time. Several previous studies have also reported an increased salt accumulation with irrigation (Che *et al*., 2021; Makoi, 2016). High sodium levels have a dispersing impact in the soil leading to poor soil structure by dispersing soil colloids such as organic matter and clay (Awedat *et al*., 2021). Additionally, increased electrical conductivity due to salt accumulation due to irrigation also affects plant growth and other essential processes in the soil. These results suggest the need to ensure appropriate salt content of the irrigation water to prevent further accumulation of salts.

Conclusion

The cropping systems influence the sustainability of irrigation practices carried out for given land use. Hence, farming communities should adopt soil quality monitoring under a specific cropping system, and irrigation practice is critical. This study revealed that irrigated perennial cropped soils had better chemical properties and hydraulic conductivity than non-irrigated soils. Irrigation and perennial cropping seem to improve soil chemical properties better than rain-fed and annual cropping. Soils in the study area were adequate in basic cations (K^+, Ca^{2+} and Mg^{2+}) but moderately deficient in TN and severely deficient in P content. Increased salt accumulation in irrigated soils was evident in the study area. This study recommends continuous monitoring of soil properties to track the effect of irrigation and cropping systems on the environment. The study also recommends further investigation on the effect of irrigation and cropping systems for different irrigation methods and schemes to establish the variations in soil quality and prevent further soil degradation due to salt accumulation.

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