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Long-Term Impacts of Different Cropping Patterns on Soil Physico-Chemical Properties and Enzyme Activities in the Low Land Plain of North China

Florence Nyambura Gikonyo [1,2], Xinliang Dong [1], Peter Semba Mosongo [1,2], Kai Guo [1] and Xiaojing Liu [1,2,*]

[1] Hebei Key Laboratory of Soil Ecology, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, University of Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021, China; gikonyo.florence4@gmail.com (F.N.G.); xldong@sjziam.ac.cn (X.D.); mosongopeter@yahoo.com (P.S.M.); guokai@sjziam.ac.cn (K.G.)
[2] University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: xjliu@sjziam.ac.cn

Abstract: Various cropping patterns are extensively used on the North China Plain, which greatly alter various soil properties. Although these soil properties respond differently to the different cropping patterns, little is known about the possible effects of cropping patterns on desalinized soils. To assess the effects of the different cropping patterns on soil properties and enzyme activities, a long-term field experiment was conducted at the Nanpi Agro-Ecological Station in Hebei Province, China. The cropping patterns under study were the single-cropping patterns of winter wheat (*Triticum aestivum* L.), spring maize (*Zea mays*), and spring cotton (*Gossypium hirsutum*), and the double-cropping pattern of winter wheat–summer maize (WW–SM), which is the predominant cropping pattern on the North China Plain. Soil samples were collected at a depth of 0–100 cm, depending on the soil properties. Our results indicated that soil available phosphorous (P) and available potassium (K) concentrations at 0–20 cm were greater than those of the subsurfaces. Soil organic matter declined with depth, and WW–SM had the highest amount in the deep levels. The WW–SM cropping pattern also generally showed greater levels of enzyme activities than did the single-cropping patterns, proving that diverse crops can enhance enzyme activities. Soil pH generally increased with depth despite there being no significant differences between the cropping patterns. No significant effects were observed on soil electrical conductivity (EC). However, EC generally increased with depth in spring cotton and winter wheat and declined in spring maize and WW–SM. Winter wheat had a significant aggregate size (<0.053 mm) at 20–40 cm depth and generally showed the lowest amount of nutrients. This study suggests that a fallow period allows the soil to regenerate its structure, whereas WW–SM enhances high soil organic matter in the deep soil layers and promotes increased soil enzyme activities. This indicates that crop rotation could sustainably exploit soil resources without reducing fertility over a long period. There is a need to incorporate different soil management practices for single-cropping patterns to increase their productivity, especially in spring maize, whose organic matter declined the most. Our results also show a need to diversify to different crop rotations to utilize their benefits and enhance soil productivity while increasing crop output.

Keywords: cropping patterns; soil physical properties; soil chemical properties; crop rotation; enzyme activities

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1. Introduction

Soil quality is highly dependent on soil management practices, and it influences crop production. Assessing soil properties under different long-term cropping patterns is essential to preserving soil quality since soil plays an essential role in the ecosystem, linking soil nutrients, water availability, and crop growth [1]. As a developing country, China not only faces water scarcity problems but also the challenge to maintain soil health and guarantee food security [2].

The North China Plain (NCP), known for intensive cropping, is among the most notable agricultural production regions, producing about 61% and 45% of the nation's grain yields of wheat and maize, respectively, covering approximately 19% of the arable land [3]. The double-cropping pattern of winter wheat—summer maize (WW–SM) is the major form of crop production on the NCP, providing about a third of the Chinese food supply [4]. This cropping pattern consumes a lot of water, which is already scarce in this region. Cropping patterns, such as monocultures of maize and wheat and a three-crop pattern of winter wheat–summer maize–spring maize (WW–SM–SM3), have been highly researched and recommended to replace the double-cropping pattern of WW–SM due to its high water-consumption level [5–9]. These studies have provided a theoretical and practical basis for adapting to alternate cropping patterns that consume less water.

Soil salinity is another major concern affecting the NCP [10], and it has led to serious issues in regards to sustainable agricultural development in the area. Several projects on the reclamation and restoration of the saline soils [11] have been undertaken. However, because water scarcity is a major issue in the NCP, existing research work has focused on identifying alternative cropping patterns that would consume less water and how these cropping patterns affect water use, whereas studies based on soil properties, particularly in desalinized soils, are still scarce for the NCP.

Changes to different cropping patterns may have a major influence on soil properties, especially due to increased application of fertilizer and low nutrient-use efficiency, hence altering soil quality. The results of numerous studies show that an increase in crop yield becomes unsustainable due to changes in the soil chemical, physical, and biological properties, which are not beneficial to the agricultural pattern in the long run [2,12–14]. Soil changes reflect the different management practices applied to soil, such as crop rotation and the diversification of crops. These soil changes are not only related to tillage practices and fertilizer application, but also to crop types and different planting techniques in agricultural patterns [15]. Studies on cropping pattern effects on soil properties include Shi et al. [10], who reported that wheat and maize cropping patterns increase soil organic matter between 61.3–68.1% and 31.9–38.8%, respectively. Wang et al. [2] also reported a decrease in soil pH in a fallow–WW–SM rotation.

Assessing the influence of different cropping patterns should allow for the determination of the roles of crop type and rotation in soil properties and enzymatic activities on the NCP. Impacts of cropping patterns are observed in the soil surface, where crop residues are deposited, and to the depth where tillage is exerted [16], as soil organic matter is highly dependent on the decomposition of crop residues [17]. Different crop types affect C and N through their residues or root exudates, which are determined by root depth and distribution [18]. Crops with deep root systems increase soil organic matter more than those with shallow root systems, and winter wheat and spring cotton are identified as crops with deep root systems [19,20]. Crops that are grown in rotation also tend to increase soil organic matter due to the varying quality and quantity of plant biomass [21]. They have the potential to increase microbial activity and improve soil fertility, thereby increasing nutrient supply to crops through the mineralization and immobilization of nutrients [22]. Soil enzymes are useful biological soil indicators. They were studied due to their sensitivity and quick response to any soil management changes long before other soil quality indicators are detectable. Spring cotton was also included due to its high importance on China's economy.

High-quality soil conditions play an essential role in crop productivity [23], and several studies have demonstrated the cumulative effects of cropping patterns on soil enzymatic activities and soil properties after years of experimental trials [24,25]. However, little information is available on the NCP, especially under desalinized soils in long-term experimental studies. As a result, a long-term project was conducted at the Nanpi Agro-Ecological Station of the Chinese Academy of Sciences, located in Hebei Province, North China Plain, to investigate the effects of various cropping patterns on soil health. We included the major cropping patterns adapted on the NCP, which are the double-cropping pattern of winter wheat—summer maize (WW–SM) and the single-cropping patterns of winter wheat, spring maize, and spring cotton. Considering the limited research documentation on desalinized soils on the NCP, we focused on how different cropping patterns affect soil chemical and physical changes, excluding factors such as irrigation. Therefore, the objective of this study was to investigate the long-term impacts of different cropping patterns adapted on the NCP on soil physico-chemical properties and enzyme activities.

2. Materials and Methods

2.1. Site Description

An experiment evaluating different cropping patterns was established in 2010 at the Nanpi Agro-Ecological Station of the Chinese Academy of Sciences, located in Hebei Province, North China Plain (38°06′ N, 116°40′ E, 20 m above sea level). The experiment is located in an alluvial plain with an elevation of 11 m. The station is located in a semi-humid region characterized by a monsoon climate with an annual temperature of 15.3 °C and average annual precipitation of 576 mm, which is concentrated during the period of June to September in the summer season. The soil at the experimental site was previously desalinized [11] and is classified as fluvisol according to the FAO system.

2.2. Experimental Design and Treatment Management

The experiment consisted of different cropping patterns with plot sizes measuring 2 × 3.3 m. The treatments consisted of the double-cropping pattern of winter wheat–summer maize (WW–SM), and the single-cropping patterns of winter wheat, spring maize, and spring cotton. Throughout the 10 years of experimental study, cropping patterns relied on rainfall, and no irrigation was performed. However, plastic mulch was used in the spring cotton cropping pattern to conserve soil moisture. Compound fertilizer was applied manually, once per year in October for all crop patterns at uniform rates of 127.5 kg N ha^{-1} as urea (278 kg ha^{-1}), 127.5 kg P_2O_5 ha^{-1} as triple superphosphate (332 kg ha^{-1}), and 127.5 kg K_2O ha^{-1} as potassium sulfate (332 kg ha^{-1}). Tillage was similar for all plots, and it was carried out in October after the cotton and maize harvests and also before the wheat was sown. The 0–20 cm soil layer was hand-tilled, and only cotton below-ground biomass was removed, while that of wheat and maize was left in the ground. The above-ground biomass of all crops was removed.

The cropping patterns were sown in different seasons. Spring maize and spring cotton were sown in late April, and summer maize in early June. They were all harvested in early October, and the plots were left fallow between October and early June, during the winter season of each year. Winter wheat was grown in early October and harvested in early June every year. The winter wheat cropping pattern was left fallow between June and early October every year, and WW–SM was the only cropping pattern with crops throughout the year.

2.3. Soil Sampling and Analysis

In October 2020, soil samples were collected with a soil auger from 0–100 cm depth from the four cropping patterns and their three replicates, each separated into 0–20, 20–40, 40–60, 60–80, and 80–100 cm depths. To determine the chemical properties, samples were air-dried, ground, and sieved using a 2 mm sieve. Fresh soil samples were used for soil enzyme analysis. Soil samples were analyzed for bulk density, structural aggregate, soil ions, soil pH, EC, soil available phosphorous (P), soil available potassium (K), soil organic matter, and soil enzymes. Soil bulk density was determined by taking the soil samples with a metal ring, weighing them while wet, and then drying and weighing them again [26]. The metal ring had a diameter of 5 cm, and its height was 5.1 cm. The metal ring was placed on an undisturbed, flat, horizontal surface in the soil prepared with a spade. Soil structural aggregates were determined by obtaining the mass proportion of aggregates at different sizes and calculating the mean weight diameter (MWD) using procedures from [27]. The aggregate size fractions were determined using the wet-sieving method. Samples of 80 g of soil were air-dried and placed on top of the sieve nests with a series of seven sieves (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.106 mm, 0.053 mm, and <0.053 mm) to isolate seven aggregate size fractions. The air-dried soil in the sieves was submerged in water for 10 min before the start of the wet-sieving action. After that, wet-sieving was performed using a mechanical shaker with a stroke length of 4 cm vertical, a frequency of 30 cycle min^{-1}, and an oscillation time of 10 min. The material remaining on each sieve was collected, dried at 80 °C, and weighed. The stable aggregate distribution was calculated based on the percentage of total mass in each aggregate fraction by adding two aggregate sizes together. The seven aggregate-size fractions were used to determine the mean weight diameter.

Soil available phosphorous and available potassium were determined using a spectrophotometer at a 890 nm wavelength [28] and a flame photometer from procedures by [29], respectively. Soil pH and EC were determined by extracting a soil solution from a 1:5 suspension. EC and pH were determined using an electrical conductance meter and a pH meter, respectively. Soil ions that were detected were calcium ions, magnesium ions, potassium and sodium ions, chloride ions, bicarbonate ions, sulfate ions, and total soluble salts. A soil solution of 1:5 suspension was used for ion determination. These ions were determined using methods described by [30]. Briefly, bicarbonate ions were determined by double-indicator titration against standard hydrochloric acid, using methyl orange as an indicator. Chloride ion content was determined by silver nitrate titration. Sulfate, calcium, and magnesium ions were determined by the ethylenediaminetetraacetic acid (ETDA) titrimetric method, and potassium and sodium ions were measured by an atomic absorption spectrophotometer. Soil organic carbon determination was based on the Walkley–Black chromic acid wet oxidation method described by Walkley and Black [31], and soil organic matter was determined by multiplying organic carbon concentration by the Van Bemmelen factor of 1.724 [32].

Soil enzyme activities were analyzed using methods involving the base substrate p-nitrophenol [33]. Specifically, the activities of soil β-glucosidase (EC 3.2.1.21), urease (EC 3.5.1.5), alkaline phosphate (EC 3.1.3.1), and arylsulfatase (EC 3.1.6.1) were investigated using methods involving the base substrate p-nitrophenol. Soil β-glucosidase was measured by increasing the absorption rate to 405 nm. Standard mother liquor (1 mg/mL) was prepared, and 1 mL of distilled water was added to the standard Eppendorf PCR tube (EP). The mother liquor was diluted into a standard product with different concentration gradients. The EP tubes were added one by one: 200 μL of standard product, 130 μL of steaming water, 300 μL of tris-hydroxymethyl aminomethane, and 1 mL of 0.5 mol L^{-1} calcium chloride ($CaCl_2$). They were mixed well, 200 μL was placed into a 96-well plate, and the absorbance was read at 405 nm.

Urease activity was determined by incubating 2 g of soil for 24 h at 37 °C with urea solution, tris (hydroxymethyl) aminomethane (THAM) buffer, and toluene. Distilled water was added, mixed, and centrifuged at 12,000 pm at 25 °C for 10 min, and the supernatant was taken. It was placed at 37 °C for 20 min, and the absorbance value was read at 578 nm.

Alkaline phosphatase activity was measured by preheating a microplate reader for 30 min and adjusting the wavelength to 405 nm. An amount of 5 g of fresh soil, 2 mL of toluene, 10 mL of disodium phenyl phosphate solution and 10 mL of borate buffer were mixed. This mixture was centrifuged at 12,000 rpm for 10 min at room temperature. An amount of 200 μL of supernatant liquid was taken and transferred into a 96-well plate, and the absorbance value of each tube was read at 405 nm.

Arylsulfatase activity was determined by pre-heating the microplate for more than 30 min and adjusting the wavelength to 410 nm. Amounts of 10 μL of standard product, 10 μL of toluene, 240 μL of sodium hydroxide, and 250 μL of calcium chloride were added to the P tube and mixed well. An amount of 200 μL supernatant liquid was taken and transferred into a 96-well plate, and the absorbance value of each tube was measured at 410 nm.

2.4. Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics 20.0. One-way analysis of variance (ANOVA) was employed to test the significance of mean differences at a p-value of 0.05. A significant effect was determined at $p < 0.05$, and means were separated using Duncan's multiple range procedures. The fixed effects were cropping patterns, while the random effects were soil properties. Linear regression and Pearson correlation coefficients were used to determine the relationship between different soil properties.

3. Results and Discussion

3.1. Soil Physical Properties

3.1.1. Soil Aggregate Formation

The greatest mass proportion aggregate was observed at >1 mm in all cropping patterns at the 0–20 cm depth (Table 1). There were no significant differences of MWD, but generally, the greatest mean weight diameter (MWD) was obtained in the winter wheat cropping pattern with 0.73 mm in the 0–20 cm depth and the spring cotton cropping pattern at 20–40 cm depth with 0.68 mm. Significant differences were obtained only in the 20–40 cm depth at <0.053 mm aggregate size.

Table 1. Mean (±SD) Soil structural aggregation at different aggregate sizes: > 1 mm, 0.25–1 mm, 0.053–0.25 mm, <0.053 mm, and the mean weight diameter (MWD), as affected by different cropping patterns at 0–20 cm and 20–40 cm depths.

Soil Depth	Cropping Patterns	>1 mm (%)	0.25–1 mm (%)	0.053–0.25 (%)	<0.053 mm (%)	MWD (mm)
0–20 cm	Spring cotton	50.62 a (±3.71)	20.65 a (±9.49)	15.98 a (±1.93)	12.75 a (±1.09)	0.67 a (±0.01)
	Spring maize	51.33 a (±3.30)	39.18 a (±10.7)	18.68 a (±2.97)	8.63 a (±2.59)	0.61 a (±0.09)
	WW–SM	48.80 a (±4.49)	23.39 a (±6.76)	15.35 a (±1.58)	12.46 a (±1.77)	0.66 a (±0.01)
	Winter wheat	57.95 a (±4.96)	20.16 a (±9.55)	13.13 a (±2.87)	8.76 a (±2.61)	0.73 a (±0.08)
20–40 cm	Spring cotton	43.00 a (±6.94)	35.62 a (±5.93)	13.30 a (±4.77)	8.08 b (±3.71)	0.68 a (±0.07)
	Spring maize	37.53 a (±3.66)	28.15 a (±3.94)	20.07 a (±3.76)	14.25 ab (±4.91)	0.59 a (±0.10)
	WW–SM	31.60 a (±6.97)	33.81 a (±3.33)	22.57 a (±4.86)	12.02 ab (±4.78)	0.57 a (±0.03)
	Winter wheat	35.01 a (±3.90)	25.46 a (±5.99)	20.27 a (±3.78)	19.26 a (±3.15)	0.55 a (±0.08)

Note: The different cropping patterns are spring cotton; spring maize; WW–SM, winter wheat–summer maize; and winter wheat. Different letters on the table represent significant differences between cropping patterns within depth intervals ($p < 0.05$). (±) represents the mean standard deviation.

Soil structural aggregate size at <0.053 mm in the 20–40 cm depth was highest in winter wheat and lowest in spring cotton. This is probably due to the fact that, during that crop period, winter wheat was at a fallow period; hence, the abandonment of land and reduced physical disruptions in that period allowed the soil to restore its aggregate structure [34]. Baeva et al. [35] concluded that abandoning agricultural land promotes soil structure aggregate formation and stability. Burdukovskii et al. [36] also found fallow soils to have significantly better stability than frequently cultivated soils. An increase in clay and silt content in the 20–40 cm depth could also have caused differences due to translocation, especially after the summer rains. This occurred after all the cropping patterns were tilled in the upper layer [37]. Despite no significant differences in the MWD, there was a trend at both depths. At the 0–20 cm depth, winter wheat had the greatest MWD numerically, followed by spring cotton and WW–SM, whereas spring maize had the least. At the 20–40 cm depth, the trend was as follows: spring cotton, followed by spring maize, then WW–SM, and winter wheat had the lowest. Spring cotton, which generally had a high soil organic matter (Figure 1) also, had the greatest MWD at the 20–40 cm depth. Although this was not statistically significant, the trend was similar to that of Liu et al. [38], who reported that organic matter stabilizes soil aggregates. The soil organic matter could have promoted the rapid recovery of soil aggregate stability [39].

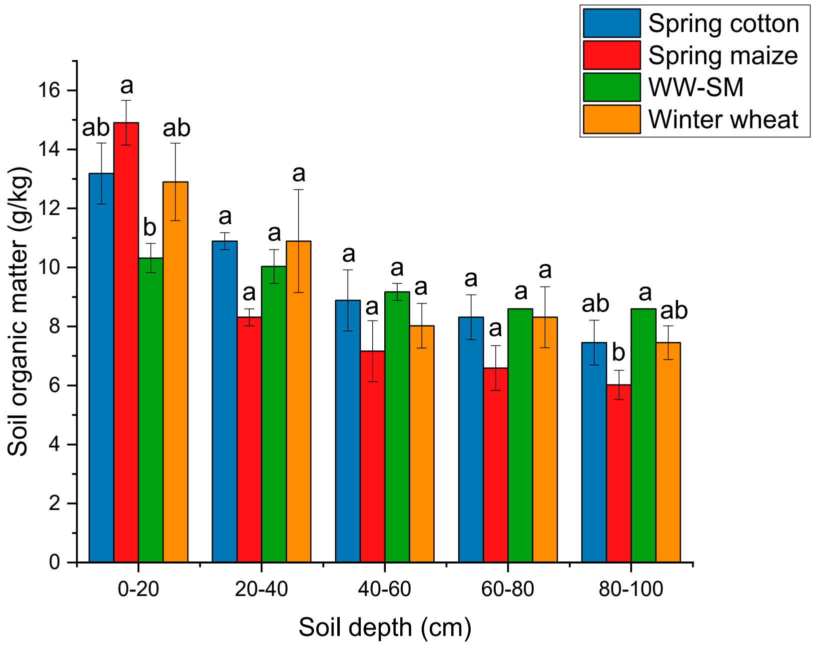

Figure 1. Soil organic matter showing multiple depths from 0 to 100 cm. Cropping patterns under different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters on the graph represent significant differences between cropping patterns within depth intervals ($p < 0.05$).

Generally, since cropping patterns had different MWDs, the results showed how every cropping pattern influences soil properties differently. Haynes and Beare [40] attributed root binding and less annual tillage to differences in crop-type aggregate stability. In this study, all cropping patterns had the same tillage application; therefore, root binding could have been a major factor in their differences. Zhang et al. [41] found that winter wheat is known to have deep roots, and in our study, the winter wheat below-ground biomass was not removed. Spring cotton, whose roots also grow deeper, but which were uprooted after the growing season, may have disrupted the soil profile and impacted on the structural aggregate. Corn grown in rotation had a higher proportion of aggregate size compared to continuous corn [42]. Our study obtained similar results where maize grown in rotation had generally higher aggregate size than the mono-cropped spring maize at the 0–20 cm depth.

3.1.2. Soil Bulk Density

The bulk density of the different crop patterns ranged from 1.16 to 1.34 g/cm^3, indicating that the bulk density was suitable for root growth and development since McKenzie et al. [43] reported that bulk densities greater than 1.6 g/cm^3 tend to restrict root growth. The effects of different cropping patterns varied in depth, with the 20–40 cm depth having a higher bulk density than the 0–20 cm depth. There were no significant differences between the cropping patterns on soil bulk density; however, it showed an increasing trend. At the 0–20 cm depth, bulk density increased from spring cotton to spring maize, followed by winter wheat, and then WW–SM. At the 20–40 cm depth, bulk density generally increased from winter wheat to spring maize, followed by WW–SM, and then spring cotton (Figure 2).

Our results were consistent with Huggins et al. [44], who reported no significant differences in bulk density among the cropping patterns regardless of crop types and tillage practices. Lower bulk density at the 0–20 cm depth was probably due to tillage performed at the surface depth [45], and also due to high soil organic matter in all cropping patterns at this depth (Figure 1). High soil organic matter decreases soil bulk density [46]. This was observed in our study, where low bulk density was observed at the 0–20 cm depth in all cropping patterns, while a decline in soil organic matter at the lower depth increased bulk density at the 20–40 cm due to increased compaction and less-dense humus and organic material [47]. At the 0–20 cm depth, spring cotton had numerically higher bulk density than the other cropping patterns. This was probably due to the complete removal of below-ground biomass, which altered the packing arrangement of the soil aggregates [48].

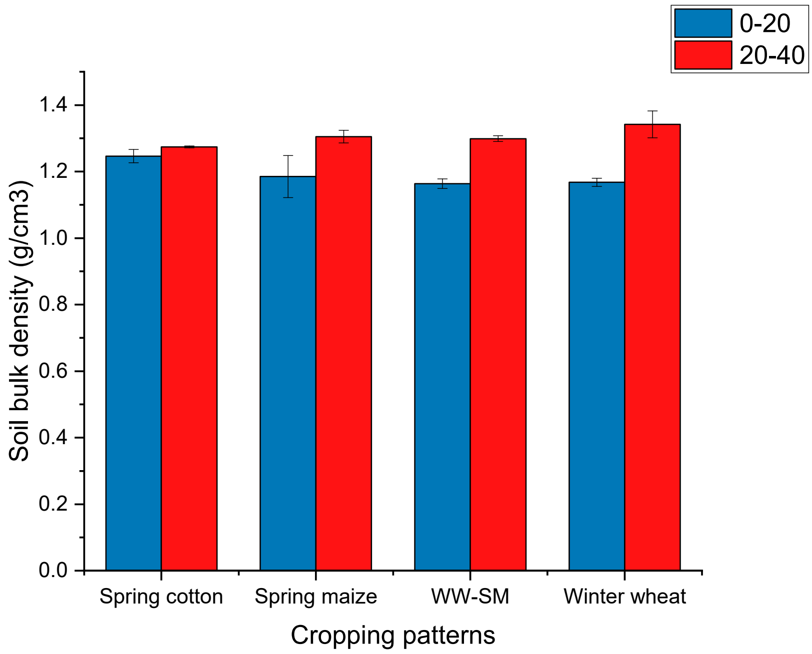

Figure 2. Soil bulk density at 0–20 and 20–40 cm depths, as affected by cropping patterns. Cropping patterns under different labels represent spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat.

Bulk density in monoculture treatments was numerically higher than that of the WW–SM rotation, with an average of 1.26, 1.25, 1.25, and 1.23 g/cm^3 for spring cotton, winter wheat, spring maize, and WW–SM, respectively. Crop rotation is known to decrease soil bulk density and maintain soil sustainability [49]. Wang et al. [50] also observed a decrease in soil bulk density in crop rotations. Our study was inconsistent with that of Nyamadzawo et al. [51], who concluded that bulk density was lower under fallow conditions as compared to the continuous maize-cropping system. Their study reported that fallowing improves soil organic matter in the fallowing phase, and these benefits are quickly lost during the cropping phase. The inconsistency in our results was probably due to the length of the fallow period of crops since the fallowing period was limited to an average of six months, whereas [51] had a fallow phase of up to two years. The benefits obtained from our fallow phase diminished rapidly for the monoculture crops.

3.2. Soil Chemical Properties

3.2.1. Soil Organic Matter

Soil organic matter (SOM) varied with depth with significant differences between the cropping patterns being observed at the 0–20 and 80–100 cm depths, as the organic matter declined with depth (Figure 1).

Spring maize had the highest soil organic matter, followed by spring cotton, winter wheat, and WW–SM had the least in the upper layer. However, spring maize had the least amount of soil organic matter along the soil profile, especially at the 80–100 cm depth, where significant differences were observed. This could have resulted from increased rates of decomposition, especially from a combination of its crop residues, increased water content from summer rains, and increased soil temperature in the summer. Lower SOM in spring maize could also have resulted from high amounts of soluble salts causing a reduction in soil organic matter additions in the soil [52]. Higher organic matter in the upper depth was probably due to increased crop residue combined with surface tillage. This could have caused high SOM in the upper depth. Higher soil organic matter in the WW than in the WW–SM in the upper layer was probably due to the fallow period, where the soil was undisturbed, as previous existing stable soil organic matter was protected [53]. Fallowing also helps soil to restore soil organic carbon, which converts to SOM [54].

Higher soil organic matter was observed in the single-cropping patterns compared to the double-cropping patterns at the 0–20 cm depth; however, with declining depth, the single-cropping patterns' organic matter declined compared to that of the WW–SM. This was probably due to the fact that the WW–SM cropping pattern increased crop residue from the wheat and maize compared to the monocrops. The double-cropping pattern below-ground biomass was also not removed; hence, it contained more residue. Decomposition rate decreases down the soil profile due to the decreased number of microorganisms [55]. This could explain why soil organic matter declined with depth in our study. Halvorson et al. [56] identified that the fallow period enhances organic matter mineralization through increased soil temperature and water content.

3.2.2. Soil Available Phosphorous and Available Potassium

Soil available phosphorous varied with depth, and significant differences ($p < 0.05$) between the cropping patterns were observed at all depths. Phosphorous was high at the 0–20 cm depth in all cropping patterns, but it declined with depth (Table 2).

Table 2. Mean (±SD) soil available phosphorous and potassium at 0–20 cm and 20–40 cm depths, as affected by cropping patterns.

Cropping Patterns	**0–20 cm**	**20–40 cm**
	Soil Available Phosphorous (mg/kg)	
Spring cotton	8.01 c (±0.06)	5.25 c (±0.10)
Spring maize	10.60 a (±0.08)	6.45 a (±0.22)
WW–SM	10.56 a (±0.07)	6.04 b (±0.09)
Winter wheat	9.33 b (±0.46)	4.71 d (±0.04)
	Soil available potassium (mg/kg)	
Spring cotton	202.77 a (±2.01)	176.42 c (±1.31)
Spring maize	195.60 b (±2.35)	195.61 a (±1.13)
WW–SM	197.16 b (±3.47)	190.83 b (±0.28)
Winter wheat	181.92 c (±0.43)	184.10 c (±11.1)

Note: Cropping patterns under different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters within a column represent significant differences at $p < 0.05$ between cropping patterns within depth intervals. (±) represents the mean standard deviation.

The upper soil surface across all treatments had a higher P compared to the subsurface layer, with an average of 9.62 and 5.61 mg/kg at 0–20 and 20–40 cm depth, respectively. The greater soil phosphorous amount at the 0–20 cm depth was probably a result of increased crop residue returned to the soil. Phosphorous is also known to not leach into soil; hence, its continuous application could lead to build-up over several growing seasons, especially in rain-fed soils [57,58]. Zuber et al. [59] observed similar results where the 0–20 cm depth had greater soil P and K than the soil below. Wright et al. [60] identified nutrient availability to increase with decreasing pH. This was evident in our study, where spring maize, which had the highest soil available phosphorous in the surface layer, had the lowest pH (Table 3).

High soil organic matter at the 0–20 cm depth in all cropping patterns was also probably the reason for high soil P at the same depth than at the lower depths. This was supported by spring maize, which had significantly higher soil organic matter at the 0–20 cm depth and higher soil P at the same depth. At the 20–40 cm depth, lower soil P was probably due to increased crop uptake. Sainju et al. [61] also observed higher Olsen -P at the 0–7.5 cm than at the 7.5–15 cm depth and reported that the immobile nature of P also caused the differences in P concentration. Balemi and Negisho [62] determined that soil P can decline due to its mineralization.

Table 3. Mean (±SD) soil pH showing multiple depths from 0 to 100 cm, as affected by cropping patterns.

Cropping Pattern	pH				
	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
Spring cotton	8.41 a (±0.17)	8.43 a (±0.24)	8.47 a (±0.25)	8.49 a (±0.01)	8.48 a (±0.01)
Spring maize	8.36 a (±0.20)	8.48 a (±0.12)	8.53 a (±0.12)	8.5 a (±0.1)	8.55 a (±0.01)
WW–SM	8.38 a (±0.11)	8.29 a (±0.06)	8.34 a (±0.02)	8.37 a (±0.01)	8.43 a (±0.01)
Winter wheat	8.45 a (±0.00)	8.42 a (±0.09)	8.46 a (±0.18)	8.48 a (±0.15)	8.48 a (±0.14)

Note: Cropping patterns under different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters within a column represent significant differences between cropping patterns within depth intervals ($p < 0.05$). (±) represents the mean standard deviation.

Spring maize and WW–SM had the highest levels of soil P compared to other cropping patterns, and in terms of crop needs, this proved that these cropping patterns have different nutrient needs and take up nutrients in different amounts since all cropping patterns received similar fertilizer applications. The maize crop pattern had higher soil P and K than the wheat crop pattern. This was probably due to the fact that the maize cropping pattern has a low capacity of up-taking nutrients. In terms of different nutrients' crop-uptake, Engel [63] identified maize as having a lower ability to adapt to root zone temperatures compared to wheat by increasing its biomass allocation towards the roots. Therefore, this causes great susceptibility of maize to nutrient deficiency by causing limited uptake through nutrient transport processes in the soil towards the roots. This means that, when P and K are difficult to be up-taken by the plant, then its concentration would be higher in the soil. Li et al. [64] also reported wheat to have a greater capability of acquiring nutrients compared to maize. The absence of crops in the winter wheat cropping pattern in its fallow period could also have resulted in low levels of P at both depths.

Soil available potassium varied with depth, and significant differences ($p < 0.05$) were observed between the cropping patterns on soil available potassium (Table 2). Similar to soil phosphorous, the 0–20 cm depth had higher available potassium with an average of 194.36 and 186.74 mg/kg at 0–20 and 20–40 cm. Soil potassium also declined with depth among the cropping patterns, except for the winter wheat pattern. This was probably due to the lack of crops and K fertilization during the fallow period. Soil K decline in all the treatments was consistent with the findings of Kazula et al. [46], where potassium concentrations also declined with depth among the cropping patterns.

Spring cotton had higher soil K at the 0–20 cm depth, probably due to its high exhaustive and sensitive nature, where it requires abundant amounts of K [65,66]. Hence, there was more deposition of K in the upper layer from mining in the lower soil depths [67,68]. Higher soil K amount in WW–SM than in the wheat–fallow cropping pattern was probably due to the WW–SM different crop rotation's ability to improve nutrient-use efficiency. At the 0–20 cm depth, the significant differences between crops grown and winter wheat indicated that the duration of crops grown has a significant effect on soil K. This occurred because a lower soil K in winter wheat was probably due to increased uptake during its growth season, which takes up to 9 months, while the growth period of maize and cotton is about 4 to 6 months. Non-significant differences between WW–SM and spring maize at the 0–20 cm depth and between spring cotton and winter wheat at the 20–40 cm depth suggested that these cropping patterns had no significant effect on K concentration on these crop types at those depths.

3.2.3. Soil pH

Soil pH ranged from 8.29 to 8.63 across all soil depths and cropping patterns (Table 3). There were no significant differences between the cropping patterns on soil pH.

Soil pH is considered a soil fertility indicator [69], due to its ability to influence the availability of factors that contribute to fertility, such as nutrients and organic matter. The pH for all treatments increased with depth (p = 0.027). There were no significant effects of cropping patterns on soil pH. However, there was a declining trend among the cropping patterns. Low soil pH at the surface depth was probably a result of N fertilization due to the presence of ammonium in the fertilizer. The ammonium was converted to nitrate in the soil through nitrification, causing the release of H^+. The nitrate released combined with cations, such as calcium and magnesium, and leached from the topsoil to the subsoil, and as these cations were removed and replaced by H^+, soil pH declined [70]. Similar results were observed by Sainju et al. [57] and Schlatter et al. [71], where soil pH was low in the surface layer as compared to the deeper layers in all the treatments. The results from our study were in contrast with Bowman and Halvorson [72], who reported a decrease in pH down the soil profile in different cropping patterns, and they attributed the decline to nitrification of ammoniacal N source over nitrate uptake by crops.

An increase in soil pH is known to result from an increase in soil carbonates and a decline in chloride ions [73]. In our study, the winter wheat crop pattern, which generally had the highest bicarbonate ions and lowest chloride ions, generally had the greatest pH in the surface layer. The general increase of soil pH down the soil profile was probably due to an increase in total salts down the depth [74]. There was also a positive correlation between soil pH and bicarbonate ions (HCO_3^-) (Table 4).

3.2.4. Soil Electrical Conductivity

Soil electrical conductivity (EC) ranged from 0.37 to 0.22 dS/m across all soil-depth and cropping patterns. Significant differences were only observed at the 80–100 cm depth for soil EC (Table 5).

Othaman et al. [75] reported that soil EC is directly proportional to nutrient concentration and that the higher the EC value, the higher the salt concentration. In this study, electrical conductivity was found in levels that do not affect crop development [11] since EC is a measure of soil salinity. There was a positive correlation between soil EC and soil chloride ions, sulfate ions, and potassium and sodium ions (Table 4). This indicated that an increase or decrease in these soil ions could lead to either an increase or decrease in soil EC. In our study, spring maize generally had the greatest EC and the highest concentration of these ions, followed by spring cotton, WW–SM, and winter wheat in the soil surface layer. Visconti et al. [76] also observed similar results where Na^+, Cl^-, Ca^{2+}, and SO_4^{2-} were positively correlated with the electrical conductivity with (r > 0.85).

Soil EC changes drastically with slight changes in soil water-content and is affected by the quality of fertilization and soil drainage properties. Spring cotton and spring maize patterns generally had greater soil EC, probably due to a loss of water through evapotranspiration and increased water uptake by the plants, causing the deposition of ions at the root depth. Significant differences at the 80–100 cm depth were probably due to the leaching of salts caused by summer rains. Nutrient leaching has been identified as diminishing soil fertility and reducing soil pH [77] at the 0–20 cm depth. Significantly high EC in spring cotton at the 80–100 cm depth was probably due to the existence of plastic mulch, which helped conserve water and minimize the rate of evaporation. Therefore, cotton's deep roots [78] may have contributed significantly to better water infiltration, which was retained at the deeper depths. This, in turn, caused high EC due to the mobilization of ions [78].

Table 4. Significant correlation coefficients (r) between different soil properties at $p = 0.05$ at the 0–20 cm depth.

Correlations	Soil EC	Soil pH	Soil HCO_3^-	Soil Cl^-	Soil Ca^{2+}	Soil Mg^{2+}	Soil SO_4^{2-}	Soil K^+ + Na^+	Soil Glucosidase	Soil Urease	Soil Alkaline Phosphatase	Soil Arylsulfatase
Soil EC	1											
Soil pH	−0.742	1										
Soil HCO_3^-	−0.812	0.951 *	1									
Soil Cl^-	0.953 *	−0.798	−0.922	1								
Soil Ca^{2+}	0.807	−0.986 *	−0.983 *	0.881	1							
Soil Mg^{2+}	0.349	−0.202	−0.514	0.574	0.346	1						
Soil SO_4^{2-}	0.952 *	−0.821	−0.955 *	0.990 *	0.904	0.638	1					
Soil K^+ + Na^+	0.985 *	−0.648	−0.773	0.954 *	0.739	0.464	0.904	1				
Soil glucosidase	−0.421	−0.253	0.015	−0.377	0.106	−0.532	−0.311	−0.558	1			
Soil urease	0.001	−0.629	−0.576	0.224	0.584	0.249	0.343	−0.073	0.67	1		
Soil alkaline phosphatase	0.958 *	−0.887	−0.878	0.918	0.912	0.206	0.882	0.898	−0.143	0.208	1	
Soil arylsulfatase	0.415	−0.913	−0.757	0.486	0.841	−0.043	0.535	0.284	0.626	0.803	0.648	1

* Correlation is significant at the 0.05 level (two-tailed). Note: Soil EC: electrical conductivity; HCO_3^-: bicarbonate ions; Cl^-: chloride ions; Ca^{2+}: calcium ions; Mg^{2+}: magnesium ions; SO_4^{2-}: sulfate ions; and K^+ + Na^+: potassium and sodium ions.

3.2.5. Soil Ions and Total Soluble Salts

Total soluble salts, calcium ions, magnesium ions, potassium and sodium ions, chloride ions, bicarbonate ions, and sulfate ions were studied in this experiment. Significant differences were observed in HCO_3^-, Ca^{2+}, K^+, and Na^+ (Table 6). Soil SO_4^{2-}, Ca^{2+}, and Mg^{2+} ions were high in the upper levels and declined with depth, with spring cotton, spring maize, and WW–SM cropping patterns having the highest levels of ion content while HCO_3^-, Cl^-, K^+, and Na^+ increased with depth. Soil ions without significant differences were not affected by cropping patterns. Significant differences in total soluble salts were observable at the 80–100 cm depth, with spring maize having the highest. The total salt concentration was numerically greater in the top layer and declined with depth in all cropping patterns except winter wheat.

Table 5. Mean (± SD) soil EC showing soil depth from 0 to 100 cm, as affected by cropping patterns.

Cropping Pattern	EC (dS/m)				
	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
Spring cotton	0.34 a (±0.23)	0.29 a (±0.13)	0.28 a (±0.03)	0.31 a (±0.01)	0.37 a (±0.01)
Spring maize	0.48 a (±0.11)	0.31 a (±0.09)	0.31 a (±0.07)	0.29 a (±0.01)	0.31 ab (±0.01)
WW–SM	0.26 a (±0.07)	0.28 a (±0.07)	0.29 a (±0.07)	0.26 a (±0.01)	0.24 b (±0.01)
Winter wheat	0.22 a (±0.03)	0.24 a (±0.03)	0.26 a (±0.06)	0.28 a (±0.07)	0.30 ab (±0.09)

Note: Cropping patterns under different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters within a column represent significant differences between cropping patterns within depth intervals ($p < 0.05$). (±) represents the mean standard deviation.

Changes in soil ion concentration down a soil profile can result from seasonal moisture fluctuations and evapotranspiration [79]. In this study, total salt concentration was numerically greater in the upper depth and lower in the subsoil. Rengasamy [80] attributed high salt content in the surface depth to high evapotranspiration, which could also have been the reason for high salt content in the surface layer in our study.

Ca^{2+}, Mg^{2+} and SO_4^{2-}, and Cl^- declined with depth, meaning they were highly concentrated at the top surface. This was probably due to increased levels of evapotranspiration since, when water evaporates, salts are left behind. This took place in all cropping patterns; however, winter wheat generally had the lowest levels of these ion concentrations and total soluble salts. This was probably due to the fact that the crop was not grown in that crop period; hence, there was less evapotranspiration compared to the other cropping patterns [81]. Spring maize had the highest levels of potassium and sodium ions, which could have affected other nutrient properties, such as soil organic matter. The crop pattern also had the highest total soluble salts in the 80–100 cm.

Significant correlations were noted between soil ions and other soil properties (Table 6). There was a negative correlation between calcium ions and bicarbonate ions, sulfate and bicarbonate, and a positive correlation between chloride ions and sulfate ions, and between chloride ions and potassium and sodium ions.

3.3. Soil Enzyme Activities

The effects of the cropping patterns on soil enzymatic activities are represented in (Figure 3**).** In this study, the soil enzyme activities showed no significant changes among all cropping patterns; however, the four studied enzyme activities performed differently under the different cropping patterns. Glucosidase activity was generally greater in WW–SM, followed by winter wheat, spring maize, and spring cotton. Urease activity was also numerically greater in WW–SM and lowest in winter wheat. A similar trend occurred in arylsulfatase, while alkaline phosphatase activity was greater in spring maize, followed by WW–SM, spring cotton, and winter wheat.

Different types of cropping patterns may influence soil quality. The single-cropping patterns showed lower enzyme activities than WW–SM, probably due to the lack of surface residue during the fallow period. This reduced the level of microbial activity, as indicated by the lower enzyme activity rates. Williams et al. [82] indicated that reducing the fallow period could help increase soil activity and promote enzyme activity. This was evident in the WW–SM cropping pattern, which had no fallow period and generally had greater enzyme activity than the other cropping patterns. Similar results were observed by Dick [83], who identified crop rotations as increasing soil enzyme activities through larger plant diversity. In this study, enzyme activities were generally greater in the WW–SM cropping pattern, probably due to more below-ground biomass, which helped increase enzyme activity in the soil through soil microbial activity.

Table 6. Mean (±SD) soil calcium, magnesium, potassium and sodium ions, chloride, bicarbonate, sulfate, and total soluble salts, showing soil depth from 0 to 100 cm, as affected by cropping patterns.

Cropping Patterns	**0–20 cm**	**20–40 cm**	**40–60 cm**	**60–80 cm**	**80–100 cm**
		Ca^{2+} (cmol/kg)			
Spring cotton	0.78 ab (±0.36)	0.46 ab (±0.02)	0.45 a (±0.25)	0.28 a (±0.15)	0.21 a (±0.11)
Spring maize	1.06 a (±0.30)	0.46 ab (±0.15)	0.38 a (±0.10)	0.30 a (±0.05)	0.25 a (±0.05)
WW–SM	0.88 ab (±0.29)	0.70 a (±0.20)	0.43 a (±0.02)	0.40 a (±0.05	0.28 a (±0.05)
Winter wheat	0.43 b (±0.17)	0.38 b (±0.11)	0.30 a (±0.13)	0.28 a (±0.12)	0.25 a (±0.05)
		Mg^{2+} (cmol/kg)			
Spring cotton	0.65 a (±0.37)	0.46 a (±0.02)	0.31 b (±0.12)	0.21 b (±0.05)	0.16 a (±0.02)
Spring maize	0.43 a (±0.20)	0.20 c (±0)	0.23 b (±0.05)	0.18 b (±0.05)	0.16 a (±0.02)
WW–SM	0.41 a (±0.07)	0.31 b (±0.02)	0.53 a (±0.07)	0.48 a (±0.12)	0.31 a (±0.12)
Winter wheat	0.31 a (±0.12)	0.33 b (±0.10)	0.31 b (±0.14)	0.31 ab (±0.14)	0.26 a (±0.10)
		K^{+}+ Na^{+} (cmol/kg)			
Spring cotton	1.25 a (±0.91)	1.16 a (±0.56)	1.13 a (±0.20)	1.21 a (±0.18)	1.48 ab (±0.18)
Spring maize	1.53 a (±0.17)	1.35 a (±0.15)	1.4 a (±0.10)	1.56 a (±0.11)	1.73 a (±0.05)
WW–SM	0.91 a (±0.12)	1.05 a (±0.18)	1.01 a (±0.12)	1.10 a (±0.08)	1.16 b (±0.02)
Winter wheat	0.86 a (±0.34)	1.00 a (±0.26)	1.30 a (±0.45)	1.45 a (±0.58)	1.45 ab (±0.37)
		Cl^{-} (cmol/kg)			
Spring cotton	0.96 a (±0.80)	0.66 a (±0.28)	0.51 a (±0.10)	0.51 a (±0.02)	0.43 a (±0.05)
Spring maize	1.18 a (±0.25)	0.73 a (±0.15)	0.51 a (±0.20)	0.51 a (±0.07)	0.46 a (±0.07)
WW–SM	0.71 a (±0.28)	0.66 a (±0.23)	0.56 a (±0.05)	0.51 a (±0.05)	0.43 a (±0.05)
Winter wheat	0.43 a (±0.05)	0.43 a (±0.05)	0.5 a (±0.10)	0.46 a (±0.02)	0.43 a (±0.02)
		HCO_3^{-} (cmol/kg)			
Spring cotton	0.63 a (±0.02)	0.66 b (±0.05)	0.78 a (±0.02)	0.8 a (±0)	0.93 a (±0.23)
Spring maize	0.61 a (±0.07)	0.68 ab (±0.02)	0.88 a (±0.27)	0.93 a (±0.23)	0.93 a (±0.23)
WW–SM	0.63 a (±0.05)	0.7 ab (±0)	0.73 a (±0.02)	0.76 a (±0.05)	0.78 a (±0.02)
Winter wheat	0.68 a (±0.10)	0.76 a (±0.05)	0.83 a (±0.15)	0.93 a (±0.32)	0.96 a (±0.28)
		SO_4^{2-} (cmol/kg)			
Spring cotton	1.08 a (±0.79)	0.76 a (±0.35)	0.60 a (±0.20)	0.53 a (±0.10)	0.46 a (±0.11)
Spring maize	1.23 a (±0.34)	0.60 a (±0.18)	0.61 a (±0.18)	0.61 a (±0.10)	0.56 a (±0.10)
WW–SM	0.86 a (±0.20)	0.70 a (±0.10)	0.68 a (±0.10)	0.63 a (±0.20)	0.41 a (±0.02)
Winter wheat	0.50 a (±0)	0.51 a (±0.02)	0.58 a (±0.14)	0.58 a (±0.07)	0.46 a (±0.02)
		Total soluble salts (cmol/kg)			
Spring cotton	1.03 a (±0.69)	0.8 a (±0.31)	0.72 a (±0.07)	0.67 a (±0.04)	0.72 b (±0.02)
Spring maize	1.27a (±0.24)	0.80 a (±0.16)	0.8 a (±0.08)	0.82 a (±0.07)	0.85 a (±0.02)
WW–SM	0.88 a (±0.18)	0.81 a (±0.14)	0.71 a (±0.08)	0.71 a (±0.10)	0.62 b (±0.03)
Winter wheat	0.6 a (±0.07)	0.63 a (±0.06)	0.72 a (±0.11)	0.77 a (±0.16)	0.72 b (±0.10)

Note: Cropping patterns under different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters within a column represent significant differences between cropping patterns within depth intervals ($p < 0.05$). (±) represents the mean standard deviation.

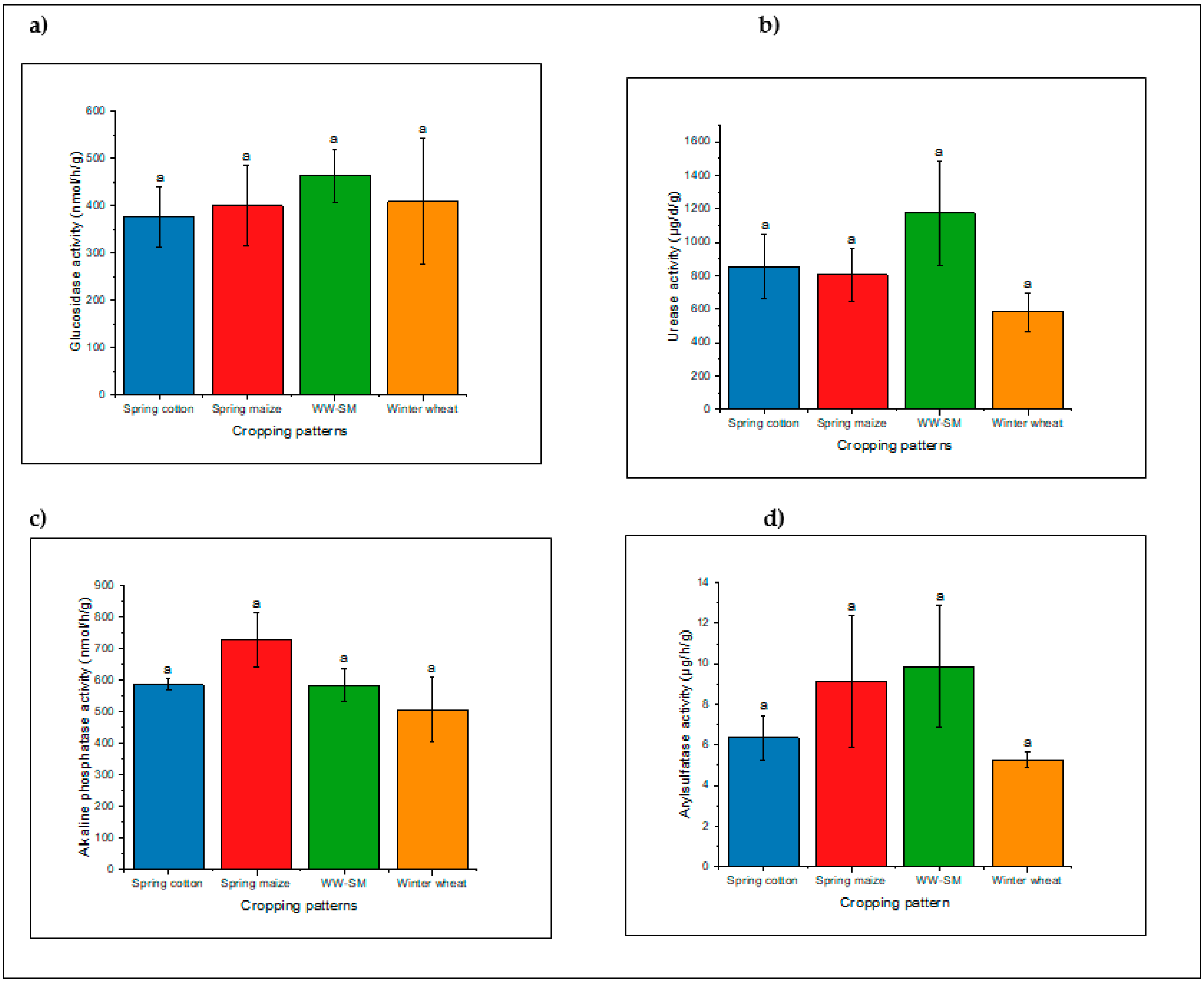

Figure 3. Enzyme activities of (**a**) Glucosidase; (**b**) Urease; (**c**) Alkaline phosphatase; and (**d**) Arylsulfatase activities at 0–20 cm depth. Different labels represent: spring cotton; spring maize; WW–SM: winter wheat–summer maize; and winter wheat. Different letters on the graph represent significant differences between cropping patterns within depth intervals ($p < 0.05$).

Enzyme activity in winter wheat was numerically lower than in the other cropping patterns; this was probably due to the fact that active enzyme activity had decreased after residues decomposed, and by the time soil was collected, enzyme activity had already gotten to a steadier state. Dou et al. [21] identified enzyme activity as peaking off immediately after residue incorporation and decreasing after residue decomposition. This shows that enzyme activity would probably be high in frequently cultivated fields that attain more residues. Spring cotton also had low enzyme activity, probably due to little or no crop residue return in the soil.

In this study, most enzyme activities were found to be higher in a frequently cultivated field compared to a fallow field, and higher in crop-rotated fields than in single-crop patterns. Kumar et al. [84] also found higher enzyme activity in cultivated fields compared to those with a fallow period. Different rates of enzyme activity between spring cotton, spring maize, and winter wheat indicated that crop species and amount of residue return played important roles in controlling microbial activity. There was a correlation between soil alkaline phosphatase and soil EC. Junnarkar et al. [85] also found correlations between alkaline phosphatase and EC.

Most soil properties were not significantly impacted by the cropping patterns. However, there were differences in trends in the cropping patterns. The cropping patterns had similar applications of tillage and fertilizer. Hence, differences taking place in the surface layer were attributed to different fallow periods in the single-cropping patterns and to the different amounts of crop residues returned to the soil. Winter wheat, which had no crops in summer, during which soil evaporation was high, led to reduced salt concentration and lower electrical conductivity in the cropping pattern, especially in the surface layer. It also had the least soil P and K at the 0–20 and 20–40 cm depths.

Crop needs also played an important factor. In spring cotton, this resulted in high soil available K in the surface layer, and due to increased crop uptake, it had the least in the subsoil. WW–SM showed greater trends than the other cropping patterns, probably due to increased crop residue return. From these results, the time of sampling could have greatly affected how the different cropping patterns influenced the soil properties.

Winter wheat showed a low concentration of nutrients, probably because sampling took place at the end of the summer cropping season before the application of fertilizer and after the summer rains. During that period, winter wheat aggregates were restructured, hence generally having greater MWD at the 0–20 cm depth. Winter wheat <0.053 mm aggregate size was also highly significant at the 20–40 cm depth, probably due to translocation of clay and silt to the lower depth and a fallow period which allowed for aggregate formation. High soluble salts could affect decomposition in the deep layers, which can cause a decline in soil organic matter. Spring maize had high soil organic matter at the 0–20 cm depth, probably due to returning residue. However, probably due to higher total soluble salts than other cropping patterns, this could have caused its soil organic matter to decline down the soil profile. An increased rate of decomposition, combined with increased water and temperature, could have attributed to its decline.

Spring cotton's below- and above-ground crop residues were removed, but its soil organic matter decline was lower than that of the other single-cropping patterns. This shows that the addition of crop residues can enhance soil organic matter, hence promoting soil fertility and productivity. This shows that time of crop growth, sampling time, and residue treatment affected soil properties. However, more research on the long-term impacts of different cropping patterns is required. Sampling after winter crops is also needed to identify how crop patterns influence soil properties during that season. This information would be helpful to identifying which cropping pattern can promote sustainable agriculture and thus allow the implementation of appropriate crop-specific management practices.

4. Conclusions

On the basis that fertilizer and tillage application were the same for all cropping patterns, the long-term impacts of these cropping patterns on soil properties were studied. The results indicated that factors such as evapotranspiration, residue return, and the fallow period had an influence on the effects of cropping patterns, especially in the surface layer. The values of soil nutrients mainly depended on crops that were in season before sampling time. The crop rotation effect of WW–SM showed the potential for increasing soil organic matter, especially down the soil profile. The single-cropping patterns showed the potential for enhancing soil health; however, more management practices need to be adapted.

These findings will be useful for understanding the relationships between soil properties and cropping patterns, and how factors such as evapotranspiration, residue return, crop needs, and the fallow period influence their interactions. The findings also provide valuable information with the intent of applying suitable measurements for agricultural practices and promoting the increase of soil organic matter, hence increasing soil productivity, in the North China Plain to improve crop output.

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