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Tillage and Straw Management Practices Influences Soil Nutrient Distribution: A Case Study from North-Eastern Romania

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Abstract: Tillage practices govern crop quality and quantity through soil nutrient availability and crop root systems. A deeper knowledge of the impact of conservation tillage on soil chemical characteristics (such as pH, soil organic carbon, macro and micronutrient storage and distribution) is required for both the promotion of agricultural sustainability and environmental preservation. This study assesses the changes in soil features and properties in the context of a long-field experiment with different tillage systems and straw management practices. Research findings revealed that compared with conventional tillage (CT) conservative tillage with partial straw retention (MT) and no-tillage with straw mulching (NT) substantially boosted the organic carbon (OC) (by 6–19%), total nitrogen (TN) (by 2–12%), and available potassium content (AK) (by 2–5%), in 0–30 cm soil depth. However, the stratification trend was observed for available macro and micronutrient content (Zn, Fe, Mn) in both conservative management practices. The concentration of Cu indicates a constant pattern through a 0–30 cm soil profile with a higher concentration under MT (1.41 mg kg^{-1}) compared to NT (1.10 mg kg^{-1}). In particular, the results failed to establish if conservation tillage can increase the total phosphorus (TP) and potassium content (TK), where only in surface 0–10 cm an increase was observed. This research also suggested that the X-ray fluorescence analysis (XRF) of total micronutrient content (Zn, Cu, Fe, Mn) is minimal or unpredictable with no substantial differences between the tillage systems and straw return management practices. These findings suggest that conservation tillage in north-eastern Romania might be optimal to maintain soil quality status and sustain high yields.

Keywords: tillage systems; straw management; soil quality; nutrient distribution

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1. Introduction

Soil management practices and fertilizer applications are factors responsible for various changes in soil chemical, physical and biological features [1–3]. Soil, a complex terrestrial system, preserves and promotes biodiversity, focusing on productivity, providing water and nutrients for plant growth and food for living organisms [4–6].

Plow-tillage management an extremely adopted traditional practice, accelerates soil warming and water evaporation in humid areas, integrates straw residues and temporarily enhances soil physico-chemical conditions for plant growth [7–9]. This conventional management technique is a high energy consumption method, that leads to higher yields but it is accompanied by detrimental effects on soil fertility, water resources, and soil structural stability disintegration, with consequences on inconsistent crop qualities [10–12]. According to Chetan et al. [11] excessive tillage promotes soil hierarchy aggregation, leading to soils more vulnerable to runoff and erosion. Furthermore, it threatens soil productivity and accelerates desertification inducing the decline of significant ecosystem services such as nutrient storage and cycling, retention availability of water in the soil, and overall crop yields. Therefore, conservation tillage practices (such as minimum and no-tillage) that eliminate or reduce soil disturbance can improve soil quality status and sensibility linked to extensive tillage.

Across Europe, intensive research into various aspects of conservation tillage has been conducted, but compared with other regions of the world, their adoption in Romania has been modest [9,13–15]. In Europe, conservation tillage techniques are particularly implemented as a means of soil protection from erosion and water infiltration control, although the magnitude of this impact varies considerably from area to area; therefore, farmers are reticent to make the transition from traditional methods to conservative ones due to economic considerations [14–16]. Evaluating the outcomes is frequently challenging since numerous variables throughout experiments like the length of the experiment, and interaction between tillage practices and weeds are the major constraints in conservation tillage [17]. However, limited attention has been given to the magnitude and direction of changes in soil nutrient distribution in response to different tillage and straw management practices. European Union Common Agricultural Policy (CAP) aims to ensure the practice of these environmental and sustainable methods to manage soil nutrients and maintain ecosystem services as a fundamental climate-smart agriculture management technique. Additionally, conservation tillage could ensure sustainable food security (under climate changes), reduce energy use and economic inputs, conserve soil water capacity, maintain soil fertility, and intensify nutrient supply and crop yields [1,13,15,18].

Conservation tillage minimizes or completely eliminates soil disturbance and has the capacity to limit soil organic carbon depletion driven by intense tillage [19]. Through increased soil aggregation, conservation tillage promotes soil organic carbon storage and secures soil organic carbon in aggregate particles. Nevertheless, nutrients and soil organic carbon stratification, soil compactness, and acidification associated with pest resistance present challenges to sustaining crop yields in the long-term application of a conservation tillage system [20]. Additionally, straw mulching—burying on the soil surface could hinder seed germination while nutrients accumulated within the soil surface might boost the risk of loss through erosion, leaching, and volatilization [21].

The major guidelines for soil chemical attributes and characteristics comprise the total carbon with inorganic and organic carbon, organic matter, the content of nutrients, pH, and exchangeable cations which are indexes of the soil quality [22]. For instance, soil organic carbon and nitrogen play a key function in the stability of soil aggregates and structure, which are important factors that influence the fertility of the soil [23]. According to the available data, the content of organic carbon in the topsoil layer of conservative tillage is significantly more extensive than in conventional tillage due to the additional crop residue and other variables, particularly in soil biology and experimental conditions [5,24]. However, other researchers have found no distinctions in soil organic carbon content between different tillage systems due to soil and crop type, climatic conditions and implementation length [25]. Therefore, there is still inadequate data on the specific impacts of conventional tillage on soil chemical and physical qualities over long-term periods for particular areas and crops, to supply farmers with reliable data and stimulate their implementation.

The results of Liang et al. [25] provided a complex spatial variability characteristic of soil organic carbon and nitrogen concentration and reported no differences between the parameters under the influence of both occasional tillage and no-tillage plots. Meanwhile, corn straw cover with no tillage practice improves gross (raw-total) N mineralization and preserves high quantities of NH_4-N while boosting soil organic carbon and total nitrogen accumulation [26]. In addition, the absence of soil disturbance under a no-tillage practice may inhibit organic N mineralization, establishing nutrient accessibility and soil disturbance together to manage nitrogen mineralization [27]. Concerning the phosphorus content, the intensity of accumulation is mostly determined by the management techniques, soil texture and mineralogy [28]. Generally, a no-tillage system increases the nutrient buildup in the surface layer, particularly phosphorus, which has low mobility and is easily fixed in different forms [29]. Significant proportions of soil phosphorus from the surface layer can be easily removed and washed by rainfall runoff and associated with the stratification process reducing the capacity of P efficiency that hinders crop growth and yield [1].

The mediators of soil aggregation comprise exchangeable metal cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^{+}) ions which can establish cationic bonds with clay particles and organic carbon to prevent organic matter from decomposing [30]. The adoption of conventional tillage was reported to increase the content in the exchangeable base as Ca^{2+} and Mg^{2+}, organic carbon and total nitrogen from aggregates in a sweet sorghum-based cropping system [31].

Soil micronutrients perform an important role in the plant's metabolic process, consequently, different quantities within each element are required depending on the plant's stage of growth [32]. Therefore, crop development depends on the availability of nutritional elements in their extraction area which is influenced by the soil properties and rooting depth. Among this approach, nutrient stratification under a no-tillage system may potentially contribute to nutrient imbalances within the crop. As the availability of Zn, Cu, Fe, and Mn may be decreased by the acidity driven by the increased level of N fertilizer treatment, stratification is a major limiting parameter for plant growth [33]. According to Janke et al., [34] tillage systems can also have consequences on soil pH, which has a significant effect on soil health and nutrient content. This suggests that maintaining agricultural productivity may depend significantly on managing soil tillage.

To extend the potential nutrient management techniques, the overview of nutrient content and their stratification can be explained by assessing the variation in the total and available macro and micronutrients through different depths and management strategies. Various studies have outlined the changes driven by tillage systems in the soil's chemical characteristics through better soil nutrient content and soil pH equilibrium. However, only a few research studies have enquired about the effect of different tillage and straw management impacts on soil quality patterns and how these correlations relate to European temperate conditions.

Based on the aforementioned concerns, it is hypothesized that the adoption of minimum tillage and straw retention is a good practice in terms of soil chemical quality enhancement. The objective of this study was to evaluate whether (1) conservation tillage increases soil organic carbon and available macro and micronutrients (N, P, K, Zn, Cu, Fe, and Mn; (2) macro and micronutrients stratification trend modified with tillage and straw management practice; (3) correlate measured plant available nutrients with soil organic carbon and pH (4) assess the impact of different tillage system and straw management practices on total micronutrient content. To consider our assumption, an analysis of contemporary and ancient data was performed to establish the trend and degree of modification in soil chemical characteristics as a consequence of straw management and tillage practices.

2. Materials and Methods

2.1. Research Site Description

The study site was located at the Research Station of Iasi University of Life Sciences (IULS), Romania (47°07′ N latitude, 27°30′ E longitude). The site has a 5% inclination and is 126 m above sea level. According to the Köppen Geiger climate classification, the experimental area belongs to a temperate humid subtropical climate—C_{fa} with a mean annual temperature and precipitation of 517.8 mm and 9.4 °C, respectively (Figure 1) (https://climateknowledgeportal.worldbank.org/country/romania, accessed on 17 April 2024). The soil is classified as Chernozem (WRB Classification) and clay-loam in texture with 35% clay, 25% silt and 36.9% sand. Prior to the start of the study, soil physicochemical properties in the 0–20 cm layer were medium in organic carbon (2.34%), available potassium (215 ppm), and total nitrogen content (0.117%), while low in available phosphorus (22.3 ppm) and neutral pH (6.71).

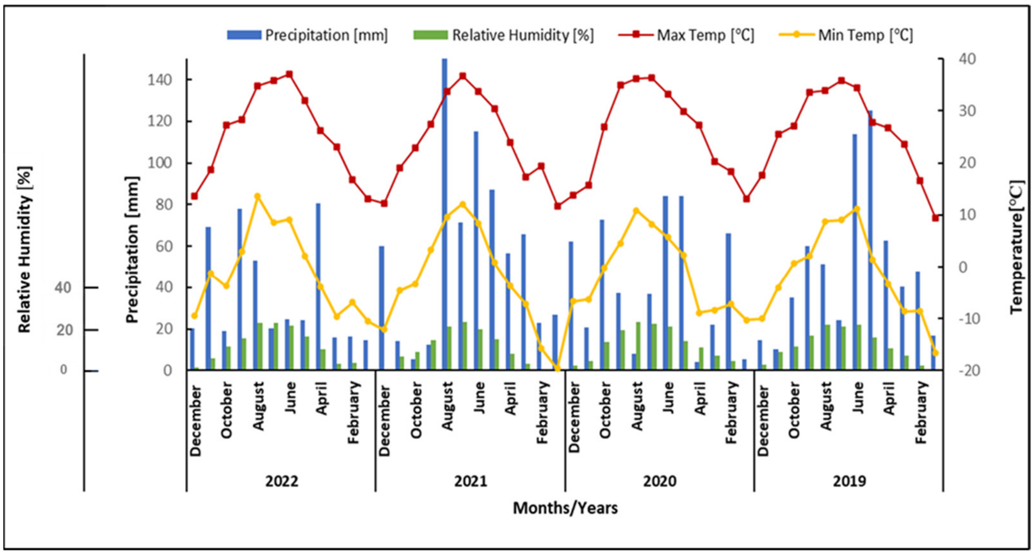

Figure 1. Precipitation, humidity and temperature data of the study area from 2019 to 2022 (www.fieldclimate.com, accessed on 1 March 2024).

2.2. Tillage Practices and Experimental Design

This study was carried out in the context of a long field experiment (that was) initially established in 2009 with various tillage practices and subsequently adapted (2019–2022) for incorporating and returning straw residues to the soil. The experiment was performed as a completely randomized block design with three replications (Figure 2). The size of each tillage plot was 60 m^2 with a soybean-winter wheat-maize rotation system, with the current experiment in maize. The experiment included three tillage practices with three straw management practices combined into (1) conventional tillage with straw burying (CT), (2) minimum tillage with partial straw retention (MT) and (3) no-tillage with straw mulching (NT).

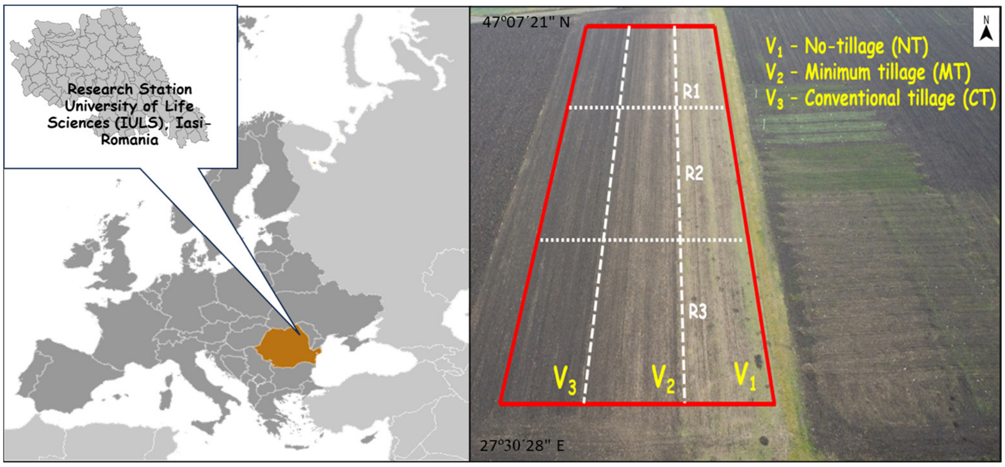

Figure 2. The location of the research plot in the map of Europa and the layout of the field experiment.

Excepting the tillage and its associated straw management practices, all other technology operations were similar overall plots. For the CT system, the straw was chopped to 3–5 cm lengths and then buried in the soil using moldboard plowing to a 30 cm depth. For NT, the straw was distributed across the plot, covering the soil surface—straw mulching. For MT the tillage was performed by a disc harrow treatment at 25 cm depth with partial removal of straw. Maize was sown with a no-till planter FABIMAG FG01 from 20 April to 1 May and harvested at the beginning of 1–5 September. During the maize growing season, the fertilizing strategy consists of the recommended dose of 100 kg/ha urea (46% N) applied as base fertilizer before sowing to all plots, while 180 kg/ha NPK (12:32:16) complex fertilizers were applied at planting (in NT) and on the vegetative stage of maize (in CT and MT). The experiment was managed under rainfed conditions without irrigation, while for weeds control, initially a rate of 3 L/ha glyphosate was used while on vegetation 0.6 L/ha 6.25 g/L florasulam + 300 g/L acid 2.4-D EHE.

2.3. Soil Sampling and Analysis

Soil samples at 0–10, 10–20, and 20–30 cm, respectively, were randomly collected from each plot after the maize harvest on 5 September 2022. Plant residues were removed and the sampled soil was air-dried, mixed thoroughly, sieved through a 2 mm mesh, and stored at 4 °C before further analysis. The soil pH was determined in a soil: water ratio of 1:2.5 and registered with a Mettler Toledo S210 pH meter. The modified Walkley and Black method was used for soil organic carbon determination, while total nitrogen followed the standard Kjeldahl method [35]. The available potassium and phosphorous were extracted with 1 N NH_4Oac and quantified using a Specord Plus UV-Vis Spectrophotometer (Analytikjena, Jena, Germany) at 715 nm. The soil Zn, Cu, Fe, and Mn DTPA extractable micronutrients were shaken for 2 h at a soil solution ratio of 1:2 at pH 7.3 and determined using an Atomic Absorption Spectrometer (ContrAA700, Analytikjena, Jena, Germany).

The X-ray fluorescence measurements of total P, K, Zn, Cu, Fe, and Mn were performed using a lab-mounted Olympus device which operates from an X-ray tube 10–50 kV at 10–200 µA. The portable X-ray fluorescence device was previously calibrated with certified reference materials to quantify low, moderate, and high elemental concentrations [1,33,35].

Scans for 60s were performed on soil samples air dried and sieved to <2 mm covered with 5 µm thick polypropylene film as a sequence of three beams each set. The pXRF, a multielement and non-destructive technique, quantifies the elemental data of each macro or/and microelement by measuring the intensity of X-ray energy that each element generates after being exposed to an excitation source [33,35].

2.4. Statistical Analysis

Differences in soil organic carbon, pH and available and total macro-micronutrient content among tillage systems were reviewed by Tukey and Duncan's test at a 5% level of significance. Correlation among the soil properties and tillage/straw practices was verified by Pearson correlation test (2-tailed) at $p \leq 0.05$. SPSS for Windows (version 22.0; SPSS Inc., Chicago, IL, USA, 2007) was used for all statistical analysis.

3. Results and Discussion

3.1. Influence of Tillage System on Soil pH

Soil pH, a measure of soil acidity and alkalinity is an important and common indicator of soil quality [35]. The results obtained suggest that the tillage system and straw management practices affected the soil pH at 0–30 cm depth (Figure 3). The values of soil pH in all the plots ranged from moderately acidic to neutral as follows: CT < NT < MT. A greater increase in surface (0–10 cm depth) soil acidity with NT (6.38) was reported while at 0–30 cm depth an acidified soil layer was offered by CT.

The potential explanation for the constant acidified plowed soil layer (6.52) is the intense soil disturbance which promoted the distribution of straw residues within plowed areas and increased the rate of straw mineralization and decomposition due to increasing aeration [36]. Another reason for soil acidity could be fertilizer dispensing through the soil at 0–30 cm depth; fertilizers contain nitrogen in amide form and releasing protons-H^+ converts ammonium (NH_4-N) to nitrate (NO_3-N) and acidifies the soil. These findings are consistent with those achieved by Dwivedi et al. [30] where the tillage system caused an increase in soil acidity in both layers studied.

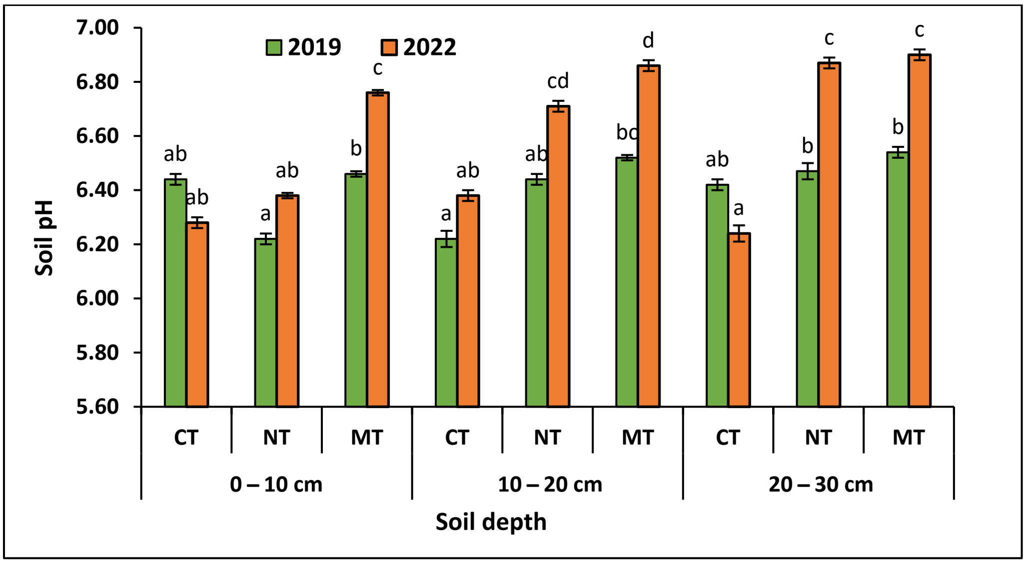

Figure 3. Variations and dynamics of soil pH at 0–30 cm depths under tillage and straw practices from 2019 to 2022. MT: minimum tillage; NT: no-tillage; CT: conventional tillage. Error bars represent the corresponding standard error of mean values. Different letters indicate significant differences between treatments during this period at the 0.05 level.

The value of pH was higher in MT compared to NT by 11.3% at 0–10 cm depth, while slight differences of 6.90 under NT and 6.97, respectively, were measured at 10–30 cm. It is possible that the neutral values of pH under MT could be attributed to the soil water leakage limiting phenomenon which balanced the pH value through an increased amount of Ca^{2+}, Mg^{2+} and Na^{+} exchangeable cations. The majority of straw residues contain moderate quantities of basic cations (Ca^{2+} and Mg^{2+}) providing buffering capacity towards soil pH fluctuations. Ca^{2+} and Mg^{2+} typically interact with proteins and amino acids and the simple networks formed can be easily assimilated by plants in order to prevent precipitation and fixing by anions like phosphate [1]. Generally, the minimum/no-tillage system increases the base saturation of the colloidal complexes by allowing increased adsorption for Ca^{2+} and Mg^{2+} through exchanges with H^{+} from organic functional groups [37]. Moreover, the straw effect on soil pH may be correlated with the content of nitrogen and concentration of organic anions from the residues through organic anion decarboxylation and ligand exchange with OH groups from iron or/and aluminum oxides.

Furthermore, under NT conditions a variable that might affect the acidity of the soil surface is the improvement of soil nitrification capacity and higher root development [38]. Secondly, NT minimizes soil disturbance on the surface and inhibits nitrate and ammonium fertilizers from reaching deeper soil layers, which accelerates surface acidity [22]. In contrast, CT promotes the uniform distribution of fertilizers across the plow layer, hence minimizing the surface acidity of the soil. Similar results were observed by Stihole et al. [39] which established that the surface acidity under no-tillage systems is due to a gradual increase in hydrogen ion production. Based on the results of Sadiq et al. [5] the lower values of soil pH under conventional tillage systems might be an occasional effect due to organic acids produced by straw mineralization and the process of respiration of soil microbes.

3.2. Influence of Tillage System on Soil Organic Carbon

The main component of soil organic matter is organic carbon, which is a useful indicator of soil productivity and fertility [40]. According to this research, MT and NT significantly boosted the organic carbon content in the 0–10 cm soil layer by 20.5% and 13.1% as compared with CT (Figure 4). Exclusively MT raised the organic carbon approximately 7.4%

towards 10–20 and 20–30 cm soil depth. In addition, MT increased the surface (0–10 cm) and sub-surface (10–30 cm) total organic carbon to 6.5% and 28.2%, respectively, relative to NT. Overall, the adoption of conservation tillage for three years (2019–2022) resulted in higher fertility of the surface soil with 0.12–0.17% compared with conventional tillage; minimum tillage with straw burying is advantageous for soil organic carbon improvement due to the straw area's contact with soil enzymes and microorganisms, which provide organic matter/humus buildup.

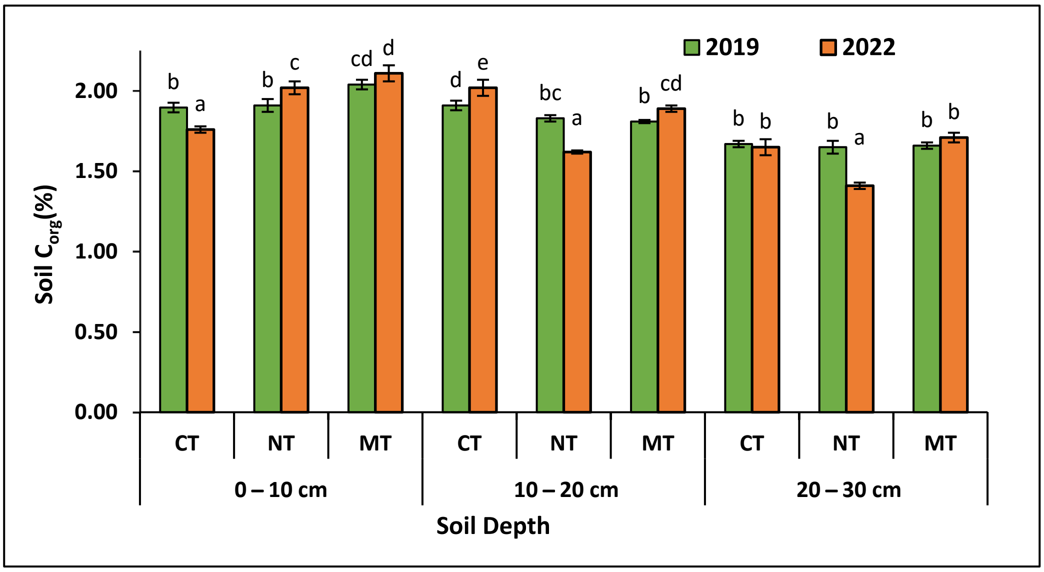

Figure 4. Variations and dynamics of soil organic carbon content in 0–30 cm depth under tillage and straw practices from 2019 to 2022. MT: minimum tillage; NT: no-tillage; CT: conventional tillage. Error bars represent the corresponding standard error of mean values. Different letters indicate significant differences between treatments during this period at the 0.05 level.

According to tillage practice, conservation tillage treatments, especially MT may maximize agricultural productivity through soil structure protection [41]. Due to straw burying and/or mulching and less physical disturbance, MT and NT might increase the proportion of macro-aggregates where greater contents of organic carbon could be found. A healthy soil structure allows for reducing soil bulk density, improves soil total porosity and retains greater quantities of water supporting the growth of the crop [34,42]. Moreover, conservation tillage lessens soil disturbance and compaction and forms stable agglomerate structures thereby protecting organic carbon from mineralization and oxidation by reducing the access of substrates to microorganisms [43].

In addition, MT improved surface soil organic content (0–10 cm), while at 10–30 cm depth soil organic stocks are within or close to that of the plow layer (0–30 cm depth). A minimum disturbance of tillage soil provides an opportunity to incorporate straw residues with soil which might balance the potential soil organic carbon loss through aggregate breakdown [44]. These findings reveal that minimum tillage treatments and straw retention promote the progressive formation of organic carbon stocks, which is in accordance with the suggestions of previous findings [45–47].

Figure 4 shows the soil carbon stratification phenomenon limited in the surface layers of conservative tillage systems which can be attributed to the absence of organic matter mixing through lower levels. The enhanced organic matter content in 0–10 cm depth might be further connected to changes in root development and biological activity [48,49]. Recently, Novak et al. [50] showed that conservative tillage generally induces carbon stratification, generating C build-up in surface soil layers. Moreover, the content of OC and stratification is more pronounced in MT, which is attributed to the straw residue which remained in the 0–10 cm depth whereas part reached the 20–30 cm soil layer. According to the short-term research experiment, MT enhanced the chernozem biological and chemical characteristics compared to CT. Generally, relative to NT, CT will cause long-term degradation of soil quality indices through reduced soil organic matter content with accelerating SOM breakdown and soil aggregate disturbance. Soil organic matter long-term depletion often causes increased surface crusting and erosion, decreased biological activity, aggregate stability and water infiltration and storage [36]

Field data summarized by meta-analysis balancing the conservative and conventional system under temperate conditions, showed that conventional tillage was connected with a greater accumulation of organic matter [51]. Because MT reduces soil turnover, which promotes microbial activity, soil organic matter and nutrients accumulate; MT might be advantageous to CT [52]. Increased soil organic carbon contents were obtained in the NT system indicating higher soil organic matter and microbial activity under this treatment compared to the CT tillage. According to field research by Mloza-Banda et al. [53] conservative agriculture showed consistent results of greater soil organic carbon levels while Wang et al. [54] proposed 11 years of conservation tillage, which might substantially boost soil organic matter content and maize productivity. In contrast, other investigations conducted by Pawlson et al. [55] and Guo et al. [56] found no substantial variations in soil organic carbon amounts among no-tillage and conventional systems. These contradictory results highlight whether SOC content variation resulting from environmental factors can impact the efficacy of conventional practices.

3.3. Influence of Tillage System on Soil Available N, P and K

Through their high bioavailability, soil-available nutrients, nitrogen (N), phosphorus (P) and potassium (K) generally reflect soil productivity [57]. According to this research, the soil available N content (NH_4^+-N and NO_3^--N) was significantly influenced by the tillage practices. We found that NT and MT increased the subsoil NH_4^+-N content in 10–30 cm soil depth compared with CT practices. Moreover, compared with MT, NT significantly increased the NH_4^+-N content in both surface and subsurface soil by 10 and 2%, respectively. Substantial NH_4^+-N concentration under no-tillage practices suggests that nitrifying organisms were probably absent and otherwise restricted by the soil environmental factors [58]. Likewise, Lopez-Bellido et al. [59] reported greater NH_4^+-N content under no-tillage treatments due to the microbial biomass and reduced content of organic material protection of no-tillage macro aggregates. Our results are in accordance with the results of Huang et al. [60] which showed increased NH^{4+}-N content under no-tillage practice due to soil compaction state which decreases the microbial N-immobilization. In soil with adequate airflow, such as CT, NH_4^+-N rapidly converts in $NO_3{}^-$-N which generates a higher NO_3^--N concentration for conventional tillage, which is also demonstrated in the current study. Tian et al. [20] reported that mixed or buried straw with different tillage systems had a positive effect on increasing the available content of soil NO_3^--N, promoting soil enzyme activity.

Phosphorus, an essential plant nutrient, is frequently required in consistent and regular quantities to ensure crop yield. According to Figure 5, the 0–30 cm soil available phosphorus content increased by 2% and 36%, respectively, under NT and MT compared with CT. In addition, mainly MT increased the surface 0–10 cm depth available P content by 32% while conventional tillage depicted a constant trend in 0–30 cm soil profile by 54 ppm. This constant trend could be explained by the mineralization and breakdown of soil organic matter induced by tillage practice which changes the variety and activity of soil enzymes and microbial community and influences the quantity and stoichiometry of soil phosphorus [61]. Under CT, the buffer plant available P capacity is decreased, as these fractions are wasted greater relative to overall P content [62]. The reduced C content in the plow layer of this tillage system and the phosphate ions exhibition towards new soil adsorption sites are responsible for phosphate interactions (to positive surface charges from Fe and Al), decreasing its accessibility and strength of desorption [63,64].

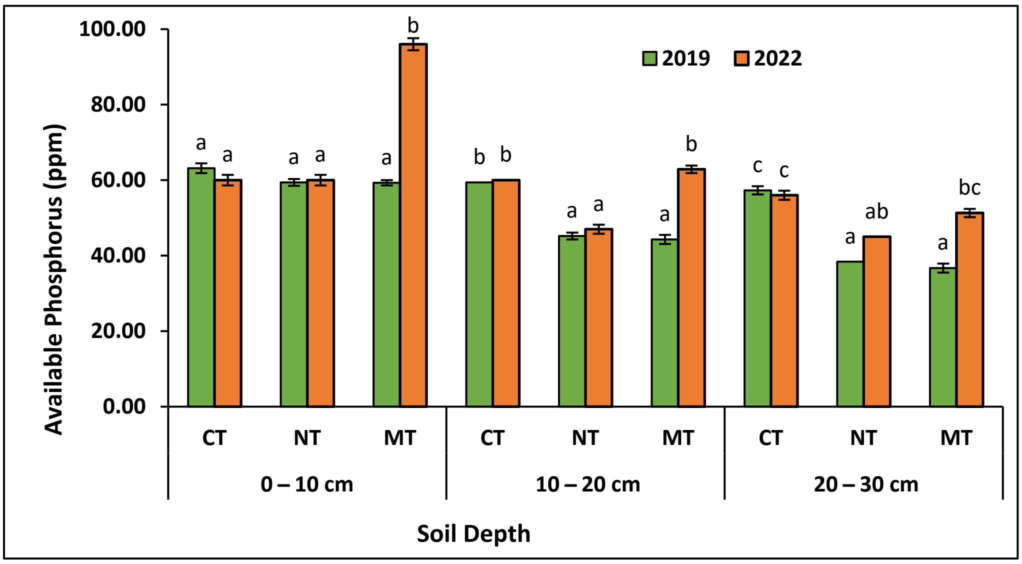

Figure 5. Variations and dynamics of soil available phosphorus content at 0–30 cm depth under tillage and straw practices from 2019 to 2022. MT: minimum tillage; NT: no-tillage; CT: conventional tillage. Error bars represent the corresponding standard error of mean values. Different letters indicate significant differences between treatments during this period at the 0.05 level.

According to our results, the surface 0–10 cm depth of the minimum-tillage system increased the available P content. The increased P content in MT may be related to greater soil organic carbon content because organic matter may simultaneously adsorb P and obstruct de-adsorption centers from the clay surfaces, aluminum and iron oxides. Based on the results of Tiecher et al. [62] and Lozier et al. [65] the increased values of available P are due to the increased soil organic matter chelating the inorganic P associated with the improvement of organic-inorganic P pool equilibrium. These results correspond with those conducted in temperate areas, where no-tillage practices generate a higher content of accessible P and total N, which provides optimal chemical, biological and physical conditions for plant growth [52]. Similarly, other studies reported that conservation tillage maintains biological activity and accelerates the mineralization of organic P and facilitates its availability for P absorption [66]. Recently, Sepat et al. [67] revealed that 12 years of permanent beds and zero tillage practices influenced the phosphorus dynamics in soil by improving the available fraction for plant growth. According to various research, the length of the experiment and the environmental conditions may have an impact on soil macro and micronutrients (N, P, K, Zn, Cu, Fe, Mn). The long-term application of no-tillage hinders the transport of nutrients to the soil layer depths due to the increase in soil physical properties: compactness and bulk density. Additionally, Lv et al. [1] showed that conservation tillage with different length periods has an impact on soil available nutrients P, N and K and particularly on organic carbon and matter. Boudiar et al. [68] observed that the soil available P content was higher in short-term zero tillage practice than in long-term conventional tillage.

The distribution of soil-available potassium content in a 0–30 cm soil profile, followed a pattern similar to that of available phosphorus during the experiment (Figure 6). The soil available K in 0–10 cm depth was higher in the no-tillage system (214 ppm) compared to conventional tillage (190 ppm). Moreover, compared with NT, MT increased the 0–30 cm soil profile by 2%, which might be due to the mineralization and decomposition of organic matter [69]. Soil pH plays an important role in the availability of K, which was higher in soil under MT, due to H+ and hydroxyl Al ions which compete with K^+ ions for adsorption or exchange centers, keeping more ions in soil solution and minimizing fixing susceptibility. Another reason for the greater available K content across soil profiles could be the addition of considerable quantities of K through straw residues [70].

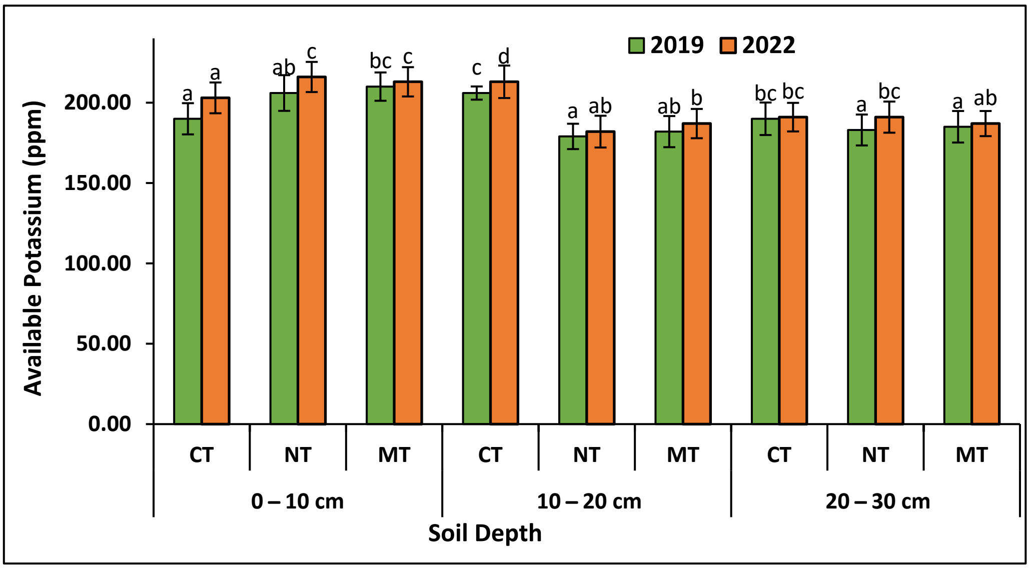

Figure 6. Variations and dynamics of soil available potassium content at 0–30 cm depth under tillage and straw practices from 2019 to 2022. MT: minimum tillage; NT: no-tillage; CT: conventional tillage. Error bars represent the corresponding standard error of mean values. Different letters indicate significant differences between treatments during this period at the 0.05 level.

High quantities of total potassium are present in straw residues and this macroelement is quickly converted to available forms for plant uptake. These results are consistent with other studies that found greater concentrations of plant-available potassium in surfaces 0–20 cm under a no-tillage system while no differences were observed at deeper soil depths [71]. Zahid et al. [72] reported that compared to other tillage and residue management techniques, the rice/wheat residues retained with a zero tillage drill at 3 to 5 cm depth—SC5 treatment had significantly higher available K content. According to various research, the impact of conservation tillage on soil-available potassium is questionable and diverse and could vary according to soil properties and crop species. Particularly, K^+ ions compete with H^+ ions and hydroxyl-aluminum ions for exchange or interaction through adsorption sites of acidic soils, which leads to increased K^+ ions in the soil phase solution [1].

3.4. Influence of Tillage System on Soil Total N, P and K

Nitrogen, potassium, and phosphorus are essential nutrients for worldwide crop yields, particularly in wheat, maize, or rice-based systems. While the demand for food continues to expand globally, preserving and minimizing soil macronutrient content is critical for both agricultural yield and environmental security. Overall, non-inversion tillage and soil straw mulching/burring are designed to improve soil health [73].

Conservation tillage system and straw impact on soil total nitrogen content were noticeable exclusively in the 0–10 cm layer with an increase of 21.7 and 14.4%, respectively, compared to the CT. Although compared with NT, MT significantly increased in both the 10–20 and 20–30 cm layer total nitrogen by 17.1 and 23.7%. These results are consistent with previous studies which reported that the conservation tillage adoption improves the soil's total N content. Fiorini et al. [74] revealed that after 8 years, soil total nitrogen accumulation was higher under NT and MT. Consistent with our hypothesis, Omara et al. [75] revealed the benefits of NT on total soil N and soil organic carbon in 0–15 cm soil depth. The implementation of a no-tillage system with residue retention led to a greater nitrogen ratio and deposits but was limited to the surface soil layer due to the surface microbial decompositions which create stable organic molecules such as humus [76].

Soil organic matter is a significant source of organic nitrogen and its storage and dynamics are frequently associated with those of organic carbon/matter [77]. The impact of

NT was significantly reduced with depth indicating N stratification within the soil profile (Table 1). This suggests that the straw residues that are retained and preserved on the soil surface due to the absence of tillage practice, hinder soil mixing, although decreased nitrogen stocks at 10–20 cm and 20–30 cm depth (under NT). This finding is consistent with Jenkinson et al. [78] who related no differences in deeper soil N content after 100 years of no-tillage practices. Xue et al. [79] observed variable amounts of straw returned under a short-term no-tillage practice, decreasing the subsoil nitrogen content but increasing the topsoil by 0–5 cm total nitrogen. An observation of Parajuli et al. [80] after 40 years of tillage management suggests the contrasting impacts of conservative and conventional tillage on soil carbon and nitrogen stocks. Recently, Mondal et al. [76] enunciated through their meta-analysis, a perceptible impact of no-tillage in terms of soil nitrogen concentrations and stocks in continental and temperate zones and crop rotations.

Table 1. Effect of tillage and straw practices on soil total nitrogen.

	Year	Soil Depth (cm)	MT	NT	CT
Soil Total Nitrogen (%)	2019	0–10	0.175 ± 0.01 cd	0.167 ± 0.02 bc	0.163 ± 0.01 ab
		10–20	0.160 ± 0.01 b	0.160 ± 0.02 b	0.166 ± 0.03 bc
		20–30	0.145 ± 0.02 b	0.143 ± 0.03 b	0.147 ± 0.02 b
	2022	0–10	0.185 ± 0.01 d	0.173 ± 0.01 bc	0.153 ± 0.02 a
		10–20	0.162 ± 0.02 b	0.146 ± 0.02 a	0.167 ± 0.02 c
		20–30	0.143 ± 0.02 b	0.126 ± 0.02 a	0.140 ± 0.01 b

MT: minimum tillage; NT: no-tillage; CT: conventional tillage. The date represents means ± SD. Different letters indicate significant differences between treatments at the 0.05 level.

Next to nitrogen, phosphorus is an essential mineral element for optimal plant development and growth. These results suggest that the distribution of total phosphorus content was influenced by the tillage system with a marked stratification pattern of no-tillage practices. With depth, the total phosphorus content increased under NT compared to the lower distribution variability of CT practices. While total phosphorus content in surface 0–10 cm depth under conventional practices was consistently higher than in no-tillage practice, at subsurface 20–30 cm, the content was lower than for minimum tillage. Currently, it is questionable if conservation tillage might boost the soil's total phosphorus content. For instance, Wei et al. [61] noticed that 10 years of different tillage management had no impact on the total phosphorus content, while the addition of P fertilizers increased the total form for NT practices due to crop cultivation having diluted the soil concentration elements. In a similar context, Tang et al. [3] obtained major differences in organic carbon content in Australian soils after 50 years of no-tillage practices with no changes in soil total phosphorus content. The phosphorus absorption and removal by plants from the soil profile may clarify the decreased total phosphorus content from the topsoil to the subsurface soil in the specific experimental condition of Germany [81]. According to certain research, no-tillage practice can induce P nutrient stratification possibly raising the runoff loss risk among topsoil [1,82,83]. Generally concentrated in the 0–10 cm soil depth and stratified, P is easily fixed and washed through the soil profile and is useful for plant growth and development [84].

Similar to the tendency of total nitrogen, NT increased the surface 0–10 cm depth total potassium content by only 4.3% compared with CT practices. The values of total potassium for NT range from 9665 to 10,134 ppm, while for CT range between 9602 and 9891 ppm. Soil TK distribution within CT is relatively uniform due to soil and fertilizers mixing through the plowed layer.

3.5. *Influence of Tillage System on Soil Available and Total Zn, Cu, Fe and Mn*

Within their involvement in the synthesis of nucleic acids, chlorophyll, proteins and stress tolerance, micronutrients like Zn, Cu, Fe and Mn perform an essential role in plant metabolic processes [32]. The content of available micronutrients appears to be impacted by different tillage systems, exhibiting an overall pattern of distribution that followed the order CT > MT > NT. According to Table 2, the 0–30 cm soil available microelements exhibit a higher content and constant trend under CT compared with conservative tillage systems ranging from 1.47 to 1.55 mg kg^{-1} (Zn) 1.71 to 2.07 mg kg^{-1} (Cu), 19.55 to 22.8 mg kg^{-1} (Fe) and 38.58 to 40.30 mg kg^{-1} (Mn), respectively. Among conservative practices, only Cu indicates a constant pattern through the 0–30 cm soil profile with a higher concentration under MT (1.41 mg kg^{-1}) compared to NT (1.10 mg kg^{-1}). Meanwhile, for available Zn, Fe and Mn content, the stratification pattern/trend was observed in both conservative practices, indicating the influence of the tillage on these microelements with higher values under MT compared with NT [85]. Under conservative practices, the micronutrient decreased concentration in the soil solution correlates with soil pH where the high values from 10 to 20 and 20 to 30 cm depth result in less soluble forms that range between 0.55 and 0.89 mg kg^{-1} for Zn, 10.94 and 15.45 mg kg^{-1} for Cu and 34 and 53–39.99 mg kg^{-1} for Mn. Recently, Zulu et al. [86] found the highest concentration of micronutrients in the case of NT with a low percentage of adsorption is because of the low pH concentration. There were no differences in the mean Mn content through the 0–30 cm soil profile in CT (41.04 mg kg^{-1}) and MT (41.67 mg kg^{-1}) but a constant trend in CT while in MT and NT a decrease in concentration with sampling depths was noticed. Zulu et al. [86] reported no influence of tillage practice on Mn availability after 4 years of nutrient stratification under silty clay loam soil [85].

Table 2. Effect of tillage and straw practices on soil available micronutrients.

	Soil Available Micronutrients (mg kg^{-1})			
Practice	**Zn**	**Cu**	**Fe**	**Mn**
		0–30 cm		
CT	3.8 ± 0.06 a	1.8 ± 0.03 a	20.9 ± 0.81 a	41.1 ± 0.57 a
NT	0.6 ± 0.02 c	1.1 ± 0.01 c	12.6 ± 0.23 c	36.8 ± 0.67 b
MT	1.1 ± 0.02 b	1.4 ± 0.04 b	14.9 ± 0.11 b	40.6 ± 1.04 a

MT: minimum tillage; NT: no-tillage; CT: conventional tillage. The date represents means ± SD. Different letters indicate significant differences at the 0.05 level.

These findings were in contrast with the results of previous research which revealed that the soil's available micronutrients impacted by conservation tillage were greater compared to CT practices [85,87]. According to a number of studies, the impact of conservation tillage on soil micronutrient availability, solubility and mobility is extensive and uncertain and varies based on soil properties (such as soil reaction and organic carbon content), environmental conditions, etc. [88].

The XRF analysis of total micronutrient content revealed no differences between varying tillage and straw return management practices. There were no changes in the total Zn, Fe and Mn content with depth and tillage practice, and no indication of stratification. The values obtained range between 112 and 129 mg kg^{-1} for Zn, 32,356 and 33,866 mg kg^{-1} for Fe and 950 and 1114 mg kg^{-1} for Mn. The XRF Cu constant content (63 mg kg^{-1}) was decreased in MT by 18% in the 0–30 cm soil profile compared with the mean values concentration of CT (82 mg kg^{-1}).

According to this research, the XRF micronutrient content has not changed to an extent that can be identified through existing analytical techniques. This study was carried out in the context of a long field experiment where no micronutrients were applied as fertilizers except nutrient export from harvested crops. Based on the fact that chernozem soils are fertile and have a high nutritional quality, micronutrient stocks are not exhausted and adequate management of the soil for boosting the micronutrient availability will impact the plant development and growth.

3.6. Correlation of Tillage and Straw Management Practices with Soil Chemical Properties

A Pearson correlation test was used to assess the linear relationship between tillage system/straw management practice and soil chemical properties (Table 3). The results indicate that soil organic carbon content was significantly positively correlated with soil total nitrogen content ($p < 0.01$) and available phosphorus content ($p < 0.01$), negatively correlated with Zn and positively correlated with soil available potassium ($p < 0.05$).

Table 3. Inter-relationship patterns between soil chemical properties.

	pH	**C_{org}**	**N_t**	**P**	**K**	**Fe**	**Zn**	**Cu**	**Mn**
pH	1								
C_{org}	0.030	1							
N_t	0.031	1.000 **	1						
P	0.244	0.848 **	0.852 **	1					
K	−0.162	0.736 *	0.743 *	0.688 *	1				
Fe	−0.749 *	0.105	0.097	0.015	0.014	1			
Zn	−0.785 *	−0.115	−0.118	−0.066	−0.054	0.924 **	1		
Cu	−0.564	0.010	0.009	0.175	0.008	0.867 **	0.934 **	1	
Mn	−0.174	0.663	0.665	0.836 **	0.576	0.339	0.347	0.510	1

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

The positive correlation of soil organic carbon with total nitrogen and phosphorus content can be attributed to straw return causing a high C:N substrate for soil microorganisms, thus influencing soil nutrient availability. Zibilske et al. [89] in their study of residue retention, reported an increase in P concentration due to the redistribution of P mined from the lower depth. As the soil's organic carbon content increases, soil aggregate stability is promoted, indicating the ability of the soil to maintain and catch nutrients.

The soil pH had a strong positive correlation with the organic carbon and phosphorus content and negatively correlated with the content of micronutrients, especially Fe and Zn ($p < 0.05$). In addition, soil potassium content was negatively correlated with soil pH and positively correlated with all other parameters. Soil tillage management significantly impacts soil pH which is connected to soil nutrient cycling. A lower soil pH may affect the soil macro and micronutrient accessibility and availability, impacting the yields.

4. Implication and Limitation of the Study

The research we performed investigated the soil properties preservation potential of different tillage management practices. The implementation of conservation tillage in the Romanian cropping system has been rather low and had variable effects on soil fertility and quality in an average term. Within various conservation soil management strategies, minimum tillage appears as the optimal alternative to traditional tillage. Our results sustain soil quality through the more efficient use of soil resources and boost organic carbon and nitrogen content, decreasing soil compaction and promoting soil aggregation. However, the length of the conservation tillage period may be a limiting factor that contributed to the total carbon and nitrogen, pH, and available nutrient content while having no significant effect on the soil's available micronutrients. Additionally, our results would also be useful for balancing the soil pH and designing the extent and direction of soil chemical properties modification (topsoil and subsoil layer). Further studies should consider different environmental factors (soil porosity, structure, texture, water capacity and microorganisms) while justifying the process that governs the impact of conservation tillage on the soil chemical properties since temperate conditions influence the tillage effects on yield. However, we concentrated on the soil's chemical features and preserved soil quality through conservative tillage systems, which can reveal the soil's chemical protection.

5. Conclusions

Our research, in the context of a long field experiment, increased the knowledge of conservative tillage's impact on the characteristics and properties of soil and crop quality and quantity. Considering the positive impacts on soil productivity, the results indicate that conservation tillage with partial straw retention could be implemented as a practical management alternative in the European conventional farming system. MT modifies soil chemical properties by lowering soil acidification and boosting the availability of macronutrients while sustaining the organic carbon and total nitrogen in a 0–30 cm soil profile. Compared with CT, the stratification trend was observed for available micronutrient content (Zn, Cu, Fe, Mn) in both conservative management practices. Moreover, the conventional tillage practice could not establish the profitability for improving the soil's total macronutrient content (P and K). However, there was no significant difference in the XRF analysis of total micronutrient content (Zn, Cu, Fe, Mn) between conventional and conservative tillage. Further studies are required to provide important guidance in deciding optimal soil management practices that maintain or increase soil health status and yields.

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