

Review

Deep Plowing (DP) Combined with Green Manure (GM) Enhances Soil Physicochemical Properties in Salt-Affected Soils of Ukraine

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Abstract

This study evaluated the rehabilitation of salt-affected ordinary chernozem in Ukraine using a combination of deep plowing (75 cm) and green manure application (100 t/ha), a highly effective and sustainable technique for reclaiming salt-affected ordinary chernozem (a process termed self-amelioration). Calcium salts were mobilized from deeper soil layers to the surface using the integrated strategy, a process known as “self-amelioration”. This increased the humus horizon from 50 to 75 cm and significantly improved water-related physical characteristics and soil structure. The carbonate concentration increased to 8.7%, while the soil bulk density (SBD) dropped from 1.2 to 0.98 g/cm³. Higher calcium levels (8.3–8.7%) and the improved calcium saturation of the soil-absorbing complex decreased alkalization, increasing the soil’s buffer capacity. “The percentages of absorbed sodium, potassium, and other exchangeable cations decreased from 6.6–7.0% to 4.3–5.2% of all exchangeable cations”. In addition to increasing soil organic carbon (SOC) and total NPK levels, the addition of green manure significantly reduced the amount of salt in the soil. However, effectiveness depends on local conditions, such as soil salinity, precipitation, and temperature, with the greatest soil organic carbon improvements observed in moderately saline, dry environments. Crop yields increased by 21–38% under this treatment. The results suggest that integrating deep plowing with green manure use is an effective and sustainable approach for restoring salt-affected soils.

Keywords: alkalization; green manure; deep plowing; reclamation; salt-affected soil; soil-absorbing complex; soil organic carbon (SOC); soil physicochemical properties

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1. Introduction

Land salinization ranks among the leading global environmental challenges in semi-arid and arid areas [1,2]. Soil affected by salt is a worldwide problem. As a result, the issues related to categorizing salinity-impacted soils, their effects on fertility and soil properties, and developing strategies to improve productivity and quality are vital concerns for many countries [3,4]. A recent FAO assessment indicated that a large portion of the world’s soil resources is degrading, and this issue is steadily worsening [5]. Saline soils are soils that contain high amounts of soluble salts. The salts found in such soils are made up of sodium chloride (NaCl), calcium sulfate (CaSO₄), magnesium sulfate (MgSO₄), and other types of soluble salts. Sodic soils are soils in which the dominant exchangeable

ions are Na^+ . Such soils have low amounts of Ca^{2+} and Mg^{2+} compared to Na^+ . Saline–sodic soils refer to soils that are a mixture of saline and sodic soils. In other words, these are soils that contain both high amounts of soluble salts (as in saline soils) and high amounts of Na^+ in exchangeable ions (as in sodic soils).

Such soils hinder plant growth and reduce soil fertility. The productive capacity of sodic soils is limited owing to their poor physical and chemical properties, especially with regard to water infiltration in the soil [6–9]. Saline soils in Ukraine represent a relatively minor portion (7%) of 1.92 million hectares (Mha). Out of these, 1.71 million hectares are utilized for farming. Around 350 thousand hectares of irrigated farmland contain salinity-affected soils. Alkalinization and land salinization are the most common and extensive issues limiting crop yield in irrigated farmland [10,11]. The extent of salt-affected soils has significantly grown due to these dynamic processes, which have become increasingly associated with desertification [12]. Secondary salinization and alkalinization arise from unsustainable agricultural management techniques, primarily influenced by improper irrigation methods, insufficient or ineffective drainage, and low-quality irrigation water [13]. Soil salinity influences plant development by inducing osmotic stress, growth impairment, ion toxicity, photosynthetic disruption, and mineral shortages [14–17]. The use of physical measures such as deep plowing, subsoiling, scraping, mulching, sanding, and leveling helps to enhance the soil structure, increase the water infiltration rate, and prevent the buildup of excess salts in the root zones. Chemical remediation techniques include the use of chemicals such as acids, gypsum, and phosphogypsum, as well as essential nutrients such as nitrogen, phosphorus, potassium, and magnesium, to replace exchangeable sodium ions. Physicochemical measures involve the addition of organic materials, such as green manures, that help to improve soil fertility and increase its water-holding and nutrient content. Water management techniques, which include leaching and proper irrigation practices, aid in the reduction of soluble salts in the soil profile. Biological methods entail the use of phytoremediation and microbial remediation to reduce the effects of salinity in the soil through the use of salt-tolerant crops and beneficial microorganisms. The biological measures can help in the successful reclamation of saline soils. All these measures will help to increase soil structure and prevent the accumulation of salts through improving water drainage and root development. Plowing and subsoiling can help overcome soil compaction by making way for roots to penetrate the soil, as well as facilitating water drainage, whereas scraping helps to remove salt crusts on the soil surface [18–24].

Deep plowing (DP) led to a significant long-term (40–50 years) enhancement of the structure and fertility of the soils that were treated [6]. Alcántara et al. (2016) [25] examined DP, which is costly, and discovered that machinery and extra fuel expenses were offset by better soil structure and crop yield (subsoil CaCO_3 , increased aeration, and reduced compaction). Sodidity and soil salinity levels, land use type, and the potential for organic fertilizer application all affect the kind of tillage management that ought to be implemented [26,27]. Green manure application combined with deep tillage has been proven to be more effective than conventional tillage [28]. DP can manage water and salt dynamics by altering the soil's physical structure to enhance infiltration and reduce evaporation and salinity leaching [29]. Deep plowing is an agricultural technique for restoring saline–alkali soils. It enhances water infiltration, root penetration, and the drainage of surplus salts from the root zone by disrupting compacted layers and enhancing soil structure. In affected regions, this mechanical approach can improve soil fertility and productivity, particularly when combined with appropriate organic amendments or irrigation. Various plowing techniques can influence soil water and bulk density, subsequently affecting the movement of surface water in the soil [30,31]. Deep plowing, characterized by a restricted

region of loose soil, causes soil blocks to increase in size after tillage, impacting crop development [32].

Green manure plants can absorb saline ions from the soil through their root systems and aggregate them in their tissues. By removing these salts from the soil during growth and harvesting, green manure plants contribute directly to the physical desalination of the land, thereby mitigating soil salinization. This biological approach provides a sustainable method for reclaiming salt-affected soils [32]. Utilizing green manure can also produce numerous organisms that can be reintroduced to farmland, thereby supplying significant quantities of soil N, soil organic matter, soil K⁺, and soil P, all of which enhance agricultural productivity. The application of green manure for salinized soil enhancement has slowly improved. Soil organic matter, nitrogen, phosphorus, and potassium are important metrics of farmland eco-systems' productivity, and critical indicators for assessing the effectiveness of salty soil amelioration. Green manure can increase soil organic carbon [33–36].

This study aims to investigate deep plowing combined with green manure to enhance the biological and physicochemical characteristics of salt-affected ordinary chernozem soils, which are irrigated and have a secondary medium level of salt-affectedness.

2. Experimental Design and Site Location

The field study was conducted in a saline agricultural area of the north-eastern Ukrainian region (Yasinovatsky district of Donetsk region). The defining characteristic of the study site is a temperate continental climate with pronounced seasonality. The average annual value of air temperature varied from 8.5 to 10.7 °C within the period of the experiment, lasting for 8 years (2015–2022). In winter (January–February), the average monthly temperatures varied from −7 to −3 °C, whereas in summer (June–August), they varied from 21 to 26 °C, with peaks above 30 °C. The test zone in the Yasinovatsky district (near Yasynuvata, Donetsk region) has a temperate continental climate, characterized by an even distribution of rainfall throughout the year. The average annual rainfall in this test zone is about 570–580 mm, while the maximum rainfall occurs during late spring and early summer.

2.1. Experimental Methodology

The use of the split-split plot design within RCBD with three replicates adequately controls for the high variability inherent in field experiments. Each experimental plot was 4 m² in size. Four particular experimental variations are the subject of the results reported in this paper. Green manure was applied uniformly to the soil surface.

- 1—Control treatments.
- 2—Green manure (100 t/ha) into the 0–25 cm plow horizon.
- 3—Deep plowing (75 cm) + green manure (100 t/ha) into the 0–25 cm plow horizon.
- 4—Calcium ameliorant of a soda plant (CaCO₃), chemically decomposed with sulfuric acid.

2.2. Deep Plowing and Tillage Operation

In order to ameliorate the physicochemical properties of salt-affected soils, over-deep plowing is an ameliorative tillage practice done to a depth of 75 cm, beyond the carbonate horizon. When the field trial was initiated in the Ukraine in 2015, over-DP was conducted once to a depth of 75 cm. The subsequent eight-year study period (2015 to 2022) has been utilized to study the after-effects of this single operation in over-deep plowing. After manual plowing in the fall using a spade, green manure was applied to the 0–25 cm layer of the soil in treatments 2 and 3 at a rate of 100 t/ha (40 kg/plot). The ameliorative mixing of naturally occurring Ca compounds within a 35–60 cm layer of soil is made possible by

deep plowing. The crops used in this rotation were wheat, winter buckwheat, grain maize, alfalfa, and barley to improve soil productivity and make crop production sustainable under irrigation. Barley is yet another cereal crop that can thrive in relatively dry and salty conditions. According to the irrigated crop rotation design, the following crops were grown: winter buckwheat, wheat, maize for grain, alfalfa, and barley in the first and second years. Depending on the weather and crop conditions, irrigation is applied. Every year, soil sampling is conducted in the spring (before planting) and fall (after harvesting). Every year, crop yields, salinity parameters, exchangeable cations, and soil physicochemical characteristics were measured [37].

2.3. Irrigation Scheduling

Depending on weather conditions and crop growth stages, irrigation was performed after sowing and then at regular intervals of 7 to 14 days. The water needs of crops and the monitoring of soil moisture levels were also used to schedule irrigation. The gravimetric method was used to determine the amount of moisture present in the soil. This was also called a soil moisture meter or tensiometer. Under the experiment described in Section 3.1, irrigation water was supplied from an agricultural pond near the field. The pond was supplied with water from rainfall and canals. The plots were irrigated with sprinklers. This system was used to decrease the chances of salt build-up in the soil. However, sensitive crops can be affected by salts deposited on the leaves. Overall, deep soil salinity was lessened, while water distribution for crop growth was ensured with the sprinkler system [38].

Furthermore, soil organic carbon, soil organic matter, total nitrogen, phosphorus, potassium, and land salinization were assessed as crucial indicators of fertility and soil health [39]. Initial soil characteristics of the experimental field (0–25 cm layer) are given below in Table 1.

Table 1. Original soil properties of the test plot (0–25 cm layer) [37].

Parameter	Value/Description
Soil classification (WRB)	Chernozem Chernic (ordinary low-humus chernozem)
Parent material	Loess
Groundwater depth	>10 m
Particle size: physical clay (<0.01 mm)	65%
Textural class	Clay loam
Humus content	4.4%
pH (H ₂ O)	8.0
Total calcium carbonate (CaCO ₃)	1.6%
Water-soluble salts (total)	0.10%
Toxic salts	0.06%
Soluble cations (mmol(eq)/100 g soil)	
Calcium (Ca ²⁺)	0.46
Sodium (Na ⁺)	0.59
Ca:Na soluble ratio	0.8
Mineral nitrogen	18.5 mg/kg
Available phosphorus (P ₂ O ₅)	240 mg/kg
Available potassium (K ₂ O)	198 mg/kg
Exchangeable cations	
Calcium	38.8 mg/kg
Sodium (Na ⁺)	2.9 mg/kg
Exchangeable sodium percentage (ESP)	6.6–7.0

Water from nearby ponds was used to irrigate the field experiment. This water was categorized as unsuitable due to the risk of soil sodification and only moderately suitable due to the risk of soil salinity based on conventional irrigation water quality recommendations. Winter barley, buckwheat, wheat, maize (for grain), and first- and second-year alfalfa made up the experimental crop rotation. Irrigation rates ranged from 800 to 1200 m³/ha, depending on crop needs and the current climate conditions. This study assessed how important soil processes, characteristics, and the profile morphology of a typical chernozem were affected by deep plowing under these irrigation conditions. To investigate soil horizons, soil pits were excavated to a depth of 1.5 m. Every year, samples were taken from genetic horizons and the following layers, following harvest (fall) and prior to planting (spring): 0–25, 25–50, 50–75, and 75–100 cm [37]. The description of genetic horizons in a chernozem soil profile is mentioned in Table 2.

Table 2. Description of genetic horizons in a chernozem soil profile (0–115 cm) [37].

Depth (cm)	Horizon	Description
0–25	A	Dark black topsoil, high organic matter
25–50	AB	Slightly lighter, transition
50–75	Bk	Accumulation of carbonates
75–115	C	Parent material

2.4. Data Calculation

Soil organic carbon content (g kg^{−1}) was calculated from soil organic matter content (g kg^{−1}) using a conversion coefficient of 0.58 [40], in cases where soil organic matter values were stated but soil organic carbon values were not provided. The conversion formula was as follows:

$$\text{Soil organic carbon} = \text{Soil organic matter} \times 0.58 \quad (1)$$

where soil organic matter has the units (g kg^{−1}).

2.5. Data Classification

The impact of green manure on saline soil enhancement was analyzed by categorizing the data into several key subgroups for mean annual temperature (MAT), mean annual precipitation (MAP), initial soil salt content (ISSC), green manure types, returning methods, and experimental years. MAT has been divided into 3 tiers with a range of roughly 15 °C, whereas MAP was categorized into 4 groups centered around 800 mm. Four classifications were created from the ISSC: 1 to 3, 3 to 5, 5 to 10, and >10 g kg^{−1}. Green manure varieties were divided into 3 categories: mixed, non-legumes, and legumes. The returning method was defined as either incorporation or non-incorporation. The experimental periods were classified based on the actual length of the respective studies [39].

2.6. Soil Sample Collection and Testing

After each growing season, subsequent to the harvest of cultivated crops, soil samples were collected for chemical analysis. Soil samples were collected from each repetition at depths of 0–25, 25–50, 50–75, and 75–100 cm. Soil samples were allowed to air-dry before being treated and sieved through a 1 mm sieve. Following a seven-year study, a soil pit was excavated at the deep plowing plots to determine the soil bulk density (SBD) of agro-transformed ordinary chernozem and the morphological structure of the soil profile. SBD samples were obtained using metal sampler rings, along with the cutting ring technique. Samples were taken in four-fold repetitions according to the genetic horizons of the soil. A field test utilizing 10% hydrochloric acid was conducted to identify the presence

of CaCO_3 . Acid drops were applied with a pipette throughout the entire soil profile. If gas bubbles were detected, then carbonates exist in this layer [41–43].

2.7. Analytical Methods

In the current investigation, the different physicochemical properties of soil samples were investigated using laboratory methods. To determine soil bulk density, a core sampler, oven, and electronic balance were used. Electrical conductivity and soil pH were analyzed using an EC meter and EC probe and a pH meter and pH probe, respectively, in the solution containing the soil. Water-soluble sodium and potassium contents were analyzed using a flame photometer, and exchangeable cations in the soil were analyzed using the Tyurin method based on national standards.

2.8. Statistical Analysis

Data will be examined through analysis of variance (ANOVA) to compare the means of treatments at a 5% significance level. In order to determine the impact of ameliorative strategies on soil parameters and crop yield, the least significant difference (LSD) was employed as a post hoc test to characterize the significance of the difference between the experimental treatments at $p < 0.05$ [43].

3. Results

3.1. Irrigation Water Quality

The range of water mineralization in the pond during the 8-year experiment was from 3.0 g/L, and the pH varied from 7.9 to 8.1 (Table 3). The range of Na^+ and K^+ varied from 27.4 to 13.0. Sodium is very important in the calculation of SAR (sodicity risk), whereas potassium is a nutrient. High sodium levels can harm plant growth and soil structure. The irrigation water was considered unsuitable for irrigation because of the risk of soil alkalization, and was considered to be of marginal suitability because of the risk of soil salinization. The chemical analysis of the water is given in Table 3.

Table 3. Average data on the chemical composition of irrigation water [37].

Mineralization of Water g/dm ³	pH	Ion Content, meq/dm ³					
		Bicarbonate Ion	Chloride Ion	Sulfate Ion	Calcium	Magnesium	Sodium Potassium
3.0	8.1	7.6	13.0	25.2	7.9	10.5	27.4

3.2. The Effect of Deep Plowing with a Green Manure Application of 100 tons/ha on the Profile and Morphological Structure of Ordinary Chernozem

Deep plowing altered the natural arrangement of soil layers and horizons, resulting in modifications to the profile structure and morphology of the ordinary chernozem in the study area. To assess this long-term effect, a soil pit in the over-deep plowing treatment variant was excavated and described eight years after the initial intervention. The morphological characteristics of the resulting soil horizons are presented in Figure 1. The morphological properties of the genetic profiles of the plowed soil are given in Table 4. Due to deep plowing (and green manure), the depth of the humus profile, as well as the root zone, rose from 50 cm to 75 cm. The contents of exchangeable calcium in the soils subjected to over-deep plowing were always greater than those of the control soils during the entire period of the eight-year study. However, the percentage contents of exchangeable Na^+ and K^+ ions were found to be less in the soils subjected to over-deep plowing, ranging from 4.3 to 5.2%, as compared to the control, where they ranged from 6.6 to 7.0%.

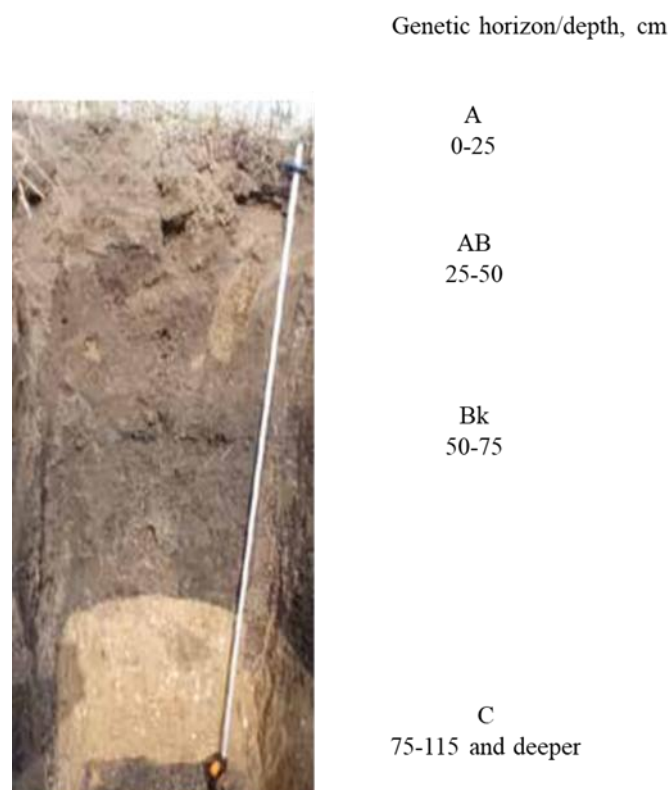


Figure 1. Morphological profile of ordinary chernozem after over-deep plowing [37].

Table 4. Morphological characteristics of the genetic horizons of ordinary chernozem treated with deep plowing (DP), according to the national classification [43].

Genetic Horizon, m	Morphology
Upper arable layer of soil after DP (and manuring), 0–25	Heterogeneous in color, dark pale, fresh, loose, lumpy-powdery in structure, calcareous, violently effervescent from 10% hydrochloric acid, penetrated by plant roots; there are passages of shrews; gradual transition in color and density.
Transitional plowing, 25–50	The soil is heterogeneous, darker than the one above, with alternate grey-brown and dark brown patches. Its texture is cloddy and granular, damp and friable, full of root-lets, and faintly effervescing on the addition of 10 percent hydrochloric acid. There are traces of shrew burrows, and a gradation of color.
Lower transitional horizon, 50–75	Darker than the upper horizon, loamy in texture with an uneven lumpy-nutty feel, rich with plant root penetration, and weakly effervescent upon application of 10% HCL. The change is clear-cut both in color and texture.
Loess-like loam, 75–115 and deeper	Pale yellow, moist, dense, and compacted, with humus streaks and pedogenic carbonates present as soft masses, which effervesce violently when treated with 10% HCL.

The CaCO_3 content of the topsoil in the control treatment was comparatively low, ranging from 1.6% to 2.0%. As the subsurface depth increased, so did its concentration. CaCO_3 was transferred from its build-up horizon toward the surface due to over-deep plowing, which caused the CaCO_3 concentration in the 0–50 cm layer to sharply increase to 8.3–8.7%. During irrigation, natural calcium compounds slowly dissolve, offering a long-lasting ameliorative effect. The presence of CaCO_3 indicates that ordinary chernozem has a high buffering ability to reduce alkalization during irrigation. Consequently, when irrigated chernozem was exposed to mineralized or marginal-quality water, its ability to prevent salinization was enhanced.

Salt distribution and content varied seasonally and annually, with sulfate–soda and calcium–sodium being the most common salt forms.

In variation 3, the soil pH ranged from 7.9 to 8.1 in the 0–50 cm layer, indicating an alkaline reaction typical of ordinary chernozem under irrigation. Consistent with the natural profile characteristics of the control soil, organic matter (OM) content—a key indicator of soil fertility—progressively lessened from the surface to deeper layers. On the other hand, humus distribution changed as a result of surface humus layers moving downward, improving the humus horizon's thickness and promoting plant development. There was a slight decrease in humus content in the arable layers throughout the first several years of the study. Humus levels were kept constant in the treatment that received 100 t/ha of integrated green manure, preventing its depletion. The total humus content in the 0–25 cm layer had not yet reached the control level six years after deep plowing (3.3% vs. 4.6%), but it rose to 4.9% in deeper levels.

Soil alkalinization was caused by irrigation with saline water, especially in the 0–50 cm layer, where the exchange complex revealed a reduction in Ca and an increase in sodium and potassium cations. Because of the absorbed potassium and sodium, the soil in the control treatment showed a moderate level of alkalinization. The site's initial conditions were impacted by long-term intense irrigation-based crop rotation prior to the field experiment.

Quantitative and qualitative changes in the soil exchange complex were observed after deep plowing, which significantly affected the fertility of the ordinary chernozem soil and soil processes. One year after the intervention, there was a significant rise in the saturation of the soil exchange complex with calcium, as well as a decrease in the saturation with exchangeable Na^+ in the 0–50 cm soil layer. The dynamic changes in the content of exchangeable Na^+ and Ca in the variants are presented in Figures 2 and 3, respectively.

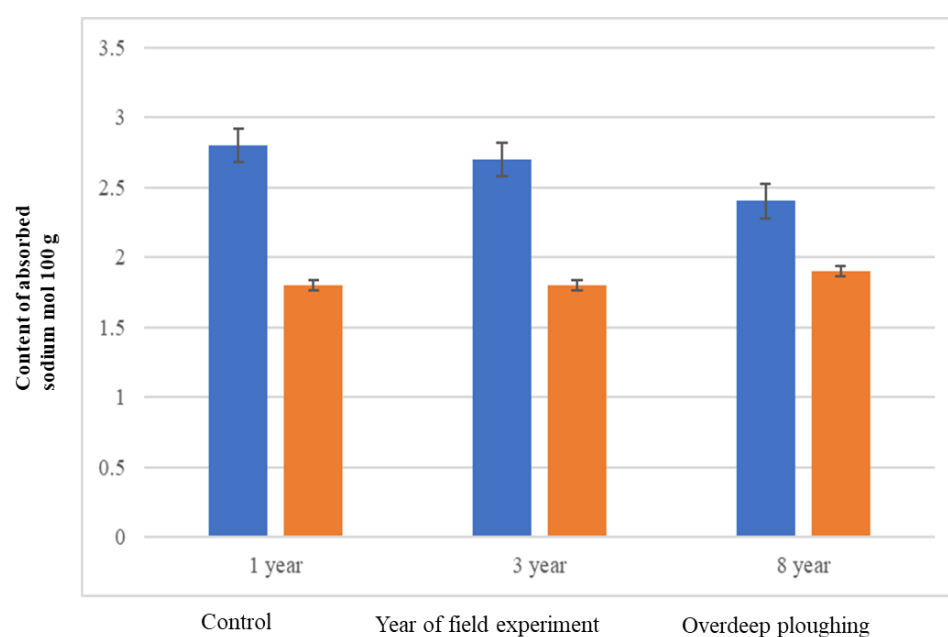


Figure 2. Content of absorbed sodium in ordinary chernozem (0–50 cm) [37]. Statistical analysis: Data presented are in terms of mean values $\pm$ SE for three replicates of soil samples at different times. The significance of differences in sodium content between the control and over-deep plowing treatments at the respective time periods (one year, three years, and eight years) was analyzed using one-way ANOVA and the post hoc test ($p < 0.05$). It can be noted that the over-deep plowing treatment resulted in significantly lower sodium levels than the control.

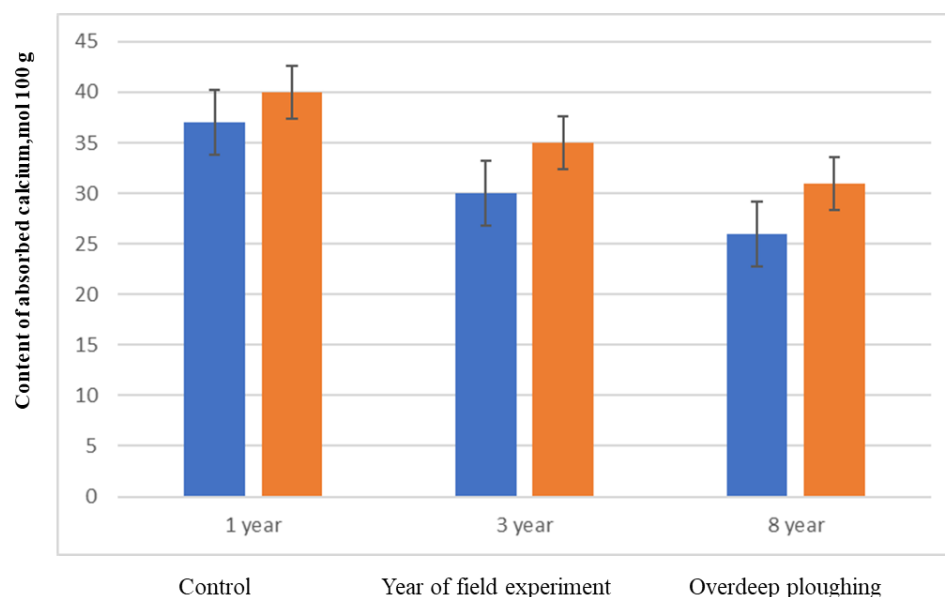


Figure 3. Content of absorbed Ca in ordinary chernozem (0–50 cm) [37]. Statistical analysis: The data are shown with respect to means $\pm$ SE at different time points (year 1, year 3, and year 8) for both groups. It can be seen that over-deep plowing always results in higher calcium (Ca) absorption than the control.

The content of absorbed Ca in the plantation-plowed soil remained consistently higher than that in the control throughout the eight-year experiment, indicating sustained enhancement. This steady trend indicates that the beneficial effects of deep plowing persisted over time without any decline.

At the same time, as the duration of the plowing after-effect was increased, so did the concentration of absorbed Ca. Thus, in comparison to the control variant, the Ca content was higher by 6% after one year, by 14% after three years, and by 19% after eight years. As for the control soil, there was 6.6–7.0% of absorbed Na^+ and K, expressed as a percentage of the total sum of absorbed cations.

The outcomes obtained revealed that in the plantation-plowed soil with green manure, the initial values of the major indicators were lower than in the control variant. However, as the after-effect period of the applied agro-ameliorative technique was prolonged, the micro-flora population in the soil increased, and the degradation level lessened. The lower efficiency in the initial years was related to the reduced amount of humus in the 0–25 cm soil layer, which resulted in a reduced total micro-flora amount. Crop yield is one of the major indicators of the efficiency of the applied agro-ameliorative practices. In the control variant, the crop yield was lower in comparison with the plantation-plowed variant. In the field experiment, the yield of the cultivated crops in the third variant with deep plowing increased by 21–38% in comparison to the control variant (Figure 4).

In addition, when the crops were cultivated for two years, the growth of green mass in alfalfa crops was greater than that of the other crops. This is because there was an increase of 38%. The alfalfa crops have a deeper root system that can reach deeper horizons and utilize nutrients. In the plantation-plowed soil, there was an increase in the root layer. This is because the deeper layers had more nutrients and humus. This impacted crop growth. However, other crops used in the field experiment had a shallow root system.

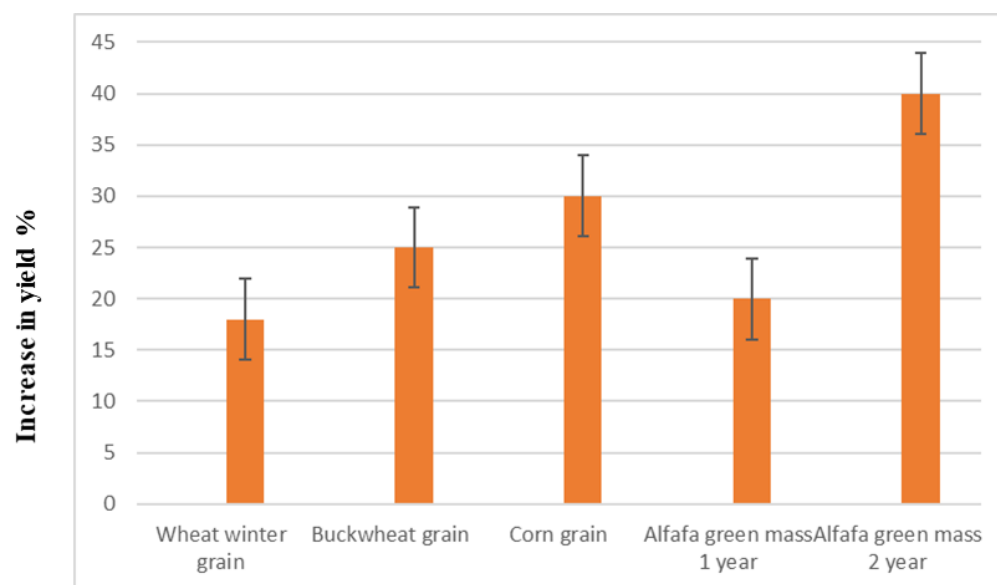


Figure 4. Increase in the yield of crops in the 3rd variant with DP (compared to control) [37]. Statistical analysis: The data are presented as means $\pm$ SE for each kind of crop used. Significance of the difference of the 3rd variant (over-deep plowing) from the control sample was obtained via ANOVA, and further confirmed via a post hoc analysis ($p < 0.05$). All kinds of crops (wheat, buckwheat, corn, and green mass of alfalfa) have demonstrated a significant increase in yields compared to the control.

3.3. Soil Organic Carbon (SOC) Changes Due to Green Manure (GM)

Organic material, including litter and roots from GM, is recycled into the soil, where it experiences mineralization and decomposition, releasing vital nutrients and enhancing soil carbon storage [44,45]. Root exudates and humus from GM join soil particles to form bigger aggregates that enclose organic carbon. This physical protective mechanism reduces the breakdown and use of organic carbon, thereby increasing its storage in the soil. Moreover, GM improves surface vegetation coverage and minimizes soil erosion [46,47].

This could be due to the fact that GM crops typically have a particular level of salt tolerance when cultivated in saline settings. Salts can improve the amount of organic carbon added to the soil by promoting the growth of green manure at low salinity levels. However, significant salt stress inhibits the growth of green manure. Moreover, land salinization affects the mineralization of organic carbon by affecting soil microbes and the soil's C and N fixation capability [48]. As a result, increased soil organic carbon is likely to build up in saline soils with moderate salt concentrations (1 to 3 g per kilogram). It is also worth mentioning that the largest increases in soil organic carbon (SOC) were frequently seen in soils that initially contained low levels of organic carbon. The increase in soil organic matter (SOM) after GM cultivation was notably greater in saline soils with salt concentrations exceeding 10 g kg^{-1} than in soils with lower salinity levels (≤ 3 , 3–5, and 5– 10 g kg^{-1}). Rainfall and temperature are essential climate elements that affect how green manure impacts SOC accumulation in saline soils (Figure 5). Erosion and runoff are deeply connected to variations in soil organic carbon. The plant cover offered by green manure crops reduces runoff and erosion, thus enhancing SOC build-up [49]. In warm and humid regions, higher surface and subsurface runoff, more intense hydraulic erosion, and increased microbial activity may result in larger losses of soil organic carbon. With rising humidity and temperatures, soil respiration, carbon, and microbial biomass are enhanced, leading to faster carbon loss [50]. Mo et al. (2022) [51] additionally indicated that the microbial priming affecting plant organic matter enhances the breakdown of existing soil carbon and serves as a key factor in the loss of SOC. In warm and humid areas, this priming effect is more pronounced, leading to increased loss of SOC. Consequently, in

these climates, SOC reductions caused by microbial and climatic factors may surpass the carbon benefits from GM integration, leading to a negligible net increase in SOC [39].

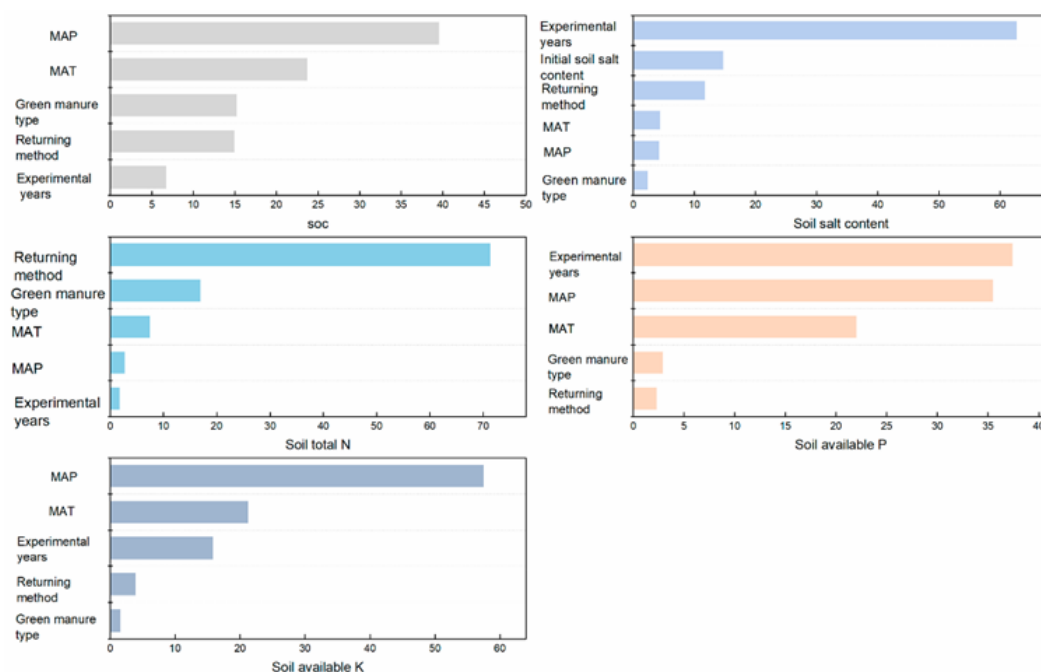


Figure 5. The relative influence (RI: %) of mean annual precipitation (MAP), mean annual temperature (MAT), initial soil salt content (ISSC), green manure type, types of returning method, and experimental years on SOC, soil salt content, soil total nitrogen, soil available phosphorus, and soil available potassium [39].

Warmer climates promote higher biomasses of green manure and more surface vegetation, both of which have the potential to significantly lower the salt content of soil. According to the study on relative importance, the effect of planting GM on soil salinity is only 2.68% and 7.37%, influenced by yearly precipitation and temperature, respectively. The most important factor influencing the sodium (Na^+) concentration of saline soil is the number of experimental years (Figure 5). The soil salt concentration gradually drops as the number of planting years increases, indicating that long-term GM planting can significantly reduce salty soil and promote soil desalination.

The following illustration represents how various environmental and managerial elements, such as MAP, MAT, green manure type, method of returning, and experimental years, impact the properties of soil. First, we can identify that precipitation (MAP) and temperature (MAT) have a significant impact on SOC, soil nitrogen, phosphorus, and potassium content, as well as the soil salt content in connection to experimental years. However, management measures also play a role in affecting soil nutrient and salt contents, albeit to a much lesser degree.

3.4. Soil and NPK Changes Due to Green Manure (GM)

Green manure greatly improved the overall N, P, and K levels of the soil. Leguminous green manure varieties can assimilate symbiotic rhizobia via atmospheric nitrogen, thus enhancing the soil's total N content (Lee, 2021) [52]. Although non-legume green manures lack the ability to fix atmospheric N, their deep root systems can extract N from lower soil layers and store it within plant tissues. When these plants are incorporated back into the soil, they decompose and release N compounds near the surface, thereby enhancing soil fertility (Lee, 2021) [52]. In salty soils, green manure contributes to the supplementation of potassium and phosphorus. Common crops are typically unable to absorb P and

K from mineral and fixed soil pools, while green manure plants can. These nutrients are released into the soil in more soluble and plant-accessible forms after integration and decomposition, increasing the amounts of available P and K. Additionally, rhizosphere activity linked to the growth of green manure facilitates the solubilization and transformation of non-labile nutrient forms through increased microbial interactions and root exudates. The total fertility and nutrient availability of salt-affected soils are improved by this biological activation (Ma et al., 2021) [53].

3.5. Soil Bulk Density (SBD)

The difference in SBD among the treatments with Ca ameliorants and the control was insignificant ($p < 0.05$). The results of this indicator in the soils of treatments three and two are presented in Table 5. The SBD in the treatments with deep plowing and green manure (treatment three) or manuring without DP (treatment two) differed significantly between these two treatments ($p < 0.05$). The SBD varied from 0.98–1.16 g/cm³ in the treatment with the integrated application of DP and GM, and from 1.20–1.131 g/cm³ for the treatment of a single GM application (Table 5) [43].

Table 5. The soil bulk density (SBD) of ordinary chernozem in treatments with or without deep plowing (DP) [43].

Deep Plowing (for 75 cm) + GM, 100 t/ha (Treatments 3)		GM, 100 t/ha (Treatment 2)	
Genetic Horizons, cm	SBD, g/cm ³	Genetic Horizons, cm	SBD, g/cm
Upper arable layer of soil after deep plowing, 0–25	0.98 ± 0.02	Upper arable layer, 0–20	1.20 ± 0.02
Transitional plowing, 25–50	1.12 ± 0.03	Transitional, 20–45	1.24 ± 0.02
Lower transitional horizon, 50–75	1.16 ± 0.03	Lower transitional, 45–80	1.31 ± 0.03
LSD ₀₅		0.08	

4. Discussion

This research was conducted with the objective of determining the impact of DP along with GM on the physicochemical characteristics of soils affected by salinity in Ukraine. The findings indicated that these practices, when combined, have a significant positive impact on soil structure, nutrition, and its overall quality, leading to higher productivity for crops grown under such conditions.

4.1. Effect on Soil Physicochemical Properties

There were remarkable changes in soil properties, such as soil salinity, SBD, and organic matter, after the application of deep plowing with green manure. The soils under deep plowing and green manure had low EC values due to the reduced amount of soil salinity. More precisely, there was a reduction of 32% in EC content within the 0–30 cm depth of the soil when compared with control soils that had not been treated, and this is very essential in enhancing plant growth in salty conditions [54]. Additionally, the soil's pH was modified from acidic to neutral. Deep plowing and green manure enhance plant growth in saline soils. A differentiated complex of measures for the amelioration of salt-affected soils was developed in Ukraine, encompassing three main groups: (I) installation of drainage systems, hydro-technical measures, and soil leaching to remove excess salts; (II) agricultural measures, including fertilization strategies, soil tillage methods, and the implementation of crop rotation systems, including ameliorative deep plowing; and (III) chemical measures, such as the application of chemical amendments to irrigation water (local pond) and soils [55].

Drozd et al. (2015) [56] demonstrated the effect of ameliorative plant age plowing on enhancing natural saline dark-chestnut soils and chestnuts.

The DP technique uses a plantation plow to a depth exceeding the layer that effervesces with 10% HCl by 10 cm to 15 cm. This operation transfers Ca salt reserves from the transitional horizon to the surface, serving as a self-reclamation technique for salt-affected soils with high electrical conductivity. At the same time, the upper humus layer is moved downward into the transitional horizons. Therefore, in the initial years following plowing, the humus content in the topsoil reduces, while deeper layers exhibit a build-up of organic matter. This approach has a long-term ameliorative effect due to the gradual dissolution of calcium compounds [55]. In variant 3, decompaction of the soil, improvement in the water's physical properties, and improvement in the humus horizon were observed. In the management of salinity-affected soils, the amount of calcium carbonate accumulation can improve the fertility [56,57]. Figure 6 shows the dispersion of CaCO_3 in the soil across the different variants. Both of the irrigated soil's physicochemical characteristics were positively impacted by variation 3's higher CaCO_3 content. The direction of soil-forming processes, as well as the biological and physicochemical characteristics of irrigated soils and their agro-ecological conditions, is significantly influenced by the quality of irrigation water. Salt deposition occurred within the soil profile of the control version that was irrigated with saline water; the concentration of hazardous salts in the 0–50 cm layer rose to 0.11%, indicating that the soil was slightly saline. Over-deep plowing has been shown to have a reclamation effect that promotes soil desalinization. Toxic salt levels eventually stabilized and attained equilibrium levels similar to the control [58]. The soil in the control group had a medium level of alkalinity. However, in the variant with plantation plowing, the proportion of absorbed alkaline cations dropped to 4.3–5.2% of total absorbed cations, resulting in low soil alkalinity. The increase in the cationic composition of the soil-absorbing complex in variant 3 was beneficial to the physicochemical characteristics of the ordinary chernozem soil. The microbiological activity in the soil also increased in the above variant. The ameliorative over-deep plowing variant was beneficial in reducing the degradation of the soil [59]. The focus of this study is on long-term fertilizer treatments, the impact on active calcium carbonate/ CaCO_3 in the soil, and the impact on the pH-buffering capacity of the soil. It does not directly discuss the reduction in sodium absorption [60]. The contents of exchangeable calcium in the soils subjected to over-deep plowing were always more than those of the control soils during the entire period of the eight-year study. However, the percentage content of exchangeable Na^+ and K^+ ions was found to be less in the soils subjected to over-deep plowing, ranging from 4.3 to 5.2%, as compared to the control, where they ranged from 6.6 to 7.0%.

It was also noted that crops used as green manure, such as alfalfa and clover, were able to increase the amount of organic material in the soil, improving the CEC so that more nutrients could be retained and taken up by the plants. Addition of green manure led to an increase in the SOC due to the recorded increase of 15–20% for the SOC in deep plowing and green manure treatment fields when compared to control fields [61,62]. There was a reduction in the SBD, showing good soil aeration and structure, leading to increased root growth and availability of nutrients [63,64]. Alcántara et al. (2016) [25] studied deep plowing to a depth of 55 cm to 90 cm and reported an increase in SOC stocks by 67% relative to the reference subsoil, even after 36–48 years. In addition, it has been associated with substantially lower GHS greenhouse gas emissions than both CT and NT systems. In the present case, deep plowing combined with green manure application at 100 t/ha loosened the soil structure compared with the control treatment. SBD declined by 0.22 g/cm³ in the 0 to 25 cm layer and by 0.12 g/cm³ in the 25 to 45(50) cm layer. These changes enhanced the physical properties of water in ordinary chernozem, as no surface crust formed after irrigation or rainfall. Water-soluble salts were more effectively leached into

deeper layers by downward water movement, resulting in lower salt concentrations in the root zone. Compared with the control and treatments using chemical ameliorants, deep plowing also improved soil moisture build-up during the winter–spring period, which supported better seedling emergence and early crop growth. Chen et al. (2020) [65] reported that deep plowing combined with the incorporation of maize residues in non-saline soils decreased SBD by 0.1 g/cm³ down to a depth of 40 cm, increased organic carbon content in the 0 to 40 cm soil layer, and deepened the root-active zone. As a result, winter wheat yield increased by 5.9–20.2%. Meng et al. (2016) [20] examined green manure and DP on the physicochemical properties of saline soil and the effect on corn yield. Their outcomes showed that this treatment reduced soil bulk density by 0.1 g/cm³, significantly enhanced soil organic matter content, reduced exchangeable sodium, and increased corn yield by up to 43% over a 2-year period. Xong et al. (2011) [23] proved that deep plowing to the subsoil (C horizon), along with the gypsum application, enhanced the properties of sodic soils. The pH values in all fields decreased from around 10 to approximately 9, while the electrical conductivity values dropped from about 8 dS.m^{−1} to approximately 2 dS.m^{−1}. Matosic et al. (2018) [27] also proved that the application of organic amendments combined with strategic tillage plays a crucial role in alleviating the negative impacts of soil salinity and sodicity. Tillage enhances soil aeration and decreases compaction, while organic matter promotes the formation of stable soil aggregates. Together, these practices boost soil structure, improve hydraulic properties, and aid in the restoration of degraded saline–sodic soils. Ding et al. (2021) [66] reported that while deep tillage alone can reduce topsoil organic carbon, this loss is more than offset by the vermicompost. In their study, the integration of vermicompost with deep tillage significantly increased soil organic carbon while simultaneously dropping sodicity and soil salinity compared to untreated no-tillage plots. These outcomes align with the long-term effects observed in our study, where the synergistic one-time application of deep plowing and green manure produced sustained improvements in soil properties throughout the eight-year experimental period. This enduring positive impact underscores the lasting benefit of combined physical and organic interventions, a conclusion further supported by other long-term agricultural experiments.

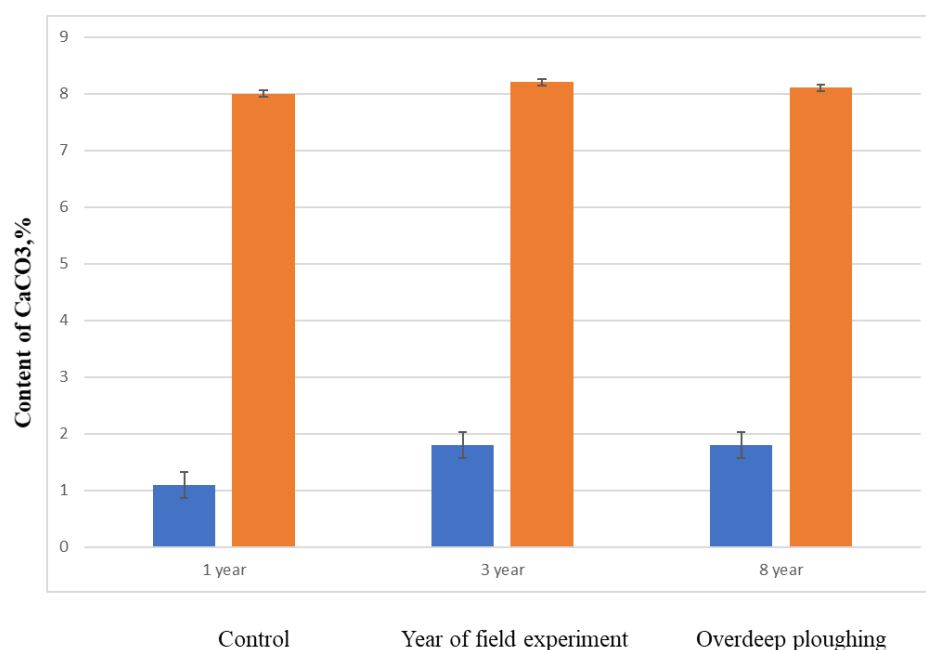


Figure 6. Content of Ca carbonate in the soil of the field experiment (0–50 cm) [37]. Statistical analysis: The values have been expressed in terms of mean ± standard error (SE) obtained through rep-

licate experiments. The significance of the differences was tested by ANOVA, with a p -value < 0.05 . The control treatment contained very low levels of CaCO_3 (1.6–2.0%), while the plowed treatment (variation 3) contained high levels (8.3–8.7%) in the topsoil layer of 0–50 cm.

4.2. Impact on Crop Growth and Yield

The growth of crops in the deep-plowed and green manure soils showed better results than in the control soils. The plants grown in the deep-plowed and green manure soils showed improved growth of roots, biomass production, and photosynthesis levels. This observation was noted mainly in barley and wheat, which were sensitive to salinity. Improved plant health was facilitated by the benefits of improved soil structure and nutrient content. The yields for wheat under deep plowing and green manure treatment were 22% higher than the control, and the yield for barley was 30% higher [67–70].

Moreover, the use of deep plowing and green manure contributed towards making crops more salt-tolerant due to better water and nutrient retention in soil, along with a diminished negative influence from the saline environment. As was stated in the research, there was an improvement in terms of decreasing the toxicity of sodium ions (Na^+), since ESP decreased by 18% while K^+ and Ca^{2+} stayed unchanged or grew. The improved soil conditions created by deep plowing and green manure not only alleviated salt stress but also facilitated better nutrient uptake, allowing crops to flourish under otherwise challenging conditions. This mechanical inversion also enhances soil aeration and increases the depth available for root penetration, thereby supporting better plant establishment. However, deep plowing alone may provide only short-term benefits because salts can later return to the surface through capillary rise under dry conditions. Incorporating green manure with deep plowing strengthens reclamation by adding organic matter that enhances the water-holding capacity and soil structure [71].

4.3. Biological Effects and Microbial Activity

The combination of deep plowing and green manure had a profound effect on the microbial community of the soil. Soil microbial biomass and microbial activity were significantly higher in the deep plowing and green manure treatments. Specifically, the microbial respiration rate increased by 35%, indicating improved microbial activity, which is essential for nutrient cycling in soil. Moreover, the diversity of microbial species was enhanced, with a greater population of beneficial microbes, such as phosphate-solubilizing and nitrogen-fixing bacteria. This contributed to enhanced nutrient cycling and overall soil fertility, reinforcing the beneficial effects of green manure in saline soils [72,73].

The combined deep plowing and green manure approach leads to better crop performance by providing a more favorable root environment and improved nutrient availability.

To alleviate secondary salinization and soil sodification, the replacement of exchangeable Na^+ with Ca is suggested, followed by the application of organic substances to improve the soil structure [74]. The positive influence of sodic soil-amelioration measures using Ca ameliorants (apart from irrigation and cultivation measures) on the soil, physicochemical properties, and the growth and yield of crops [75,76] was proven for the DP improvement of a crop's yield by 20 to 25% under non-irrigated conditions and by up to 40% under irrigation. Deep plowing enhanced biological and physicochemical soil properties, as well as hydro-physical characteristics [6]. Gashi et al. (2025) [77] emphasized the role of gypsum and tillage practices in alleviating salinity stress and facilitating beneficial microbial communities. The combination of tillage practices and gypsum has been shown to be highly effective in improving soil health, providing valuable insights for sustainable soil management in saline settings.

5. Conclusions

Long-term field studies demonstrate that over-deep plantation plowing, combined with the incorporation of green manure (100 t/ha), is a highly effective and sustainable technique for reclaiming salt-affected ordinary chernozem, a process termed self-amelioration. The inversion of soil horizons during deep plowing brought the underlying carbonate-rich layer to the surface. This significantly altered the topsoil's chemical composition, increasing calcium carbonate (CaCO_3) content in the 0 to 50 cm layer from 1.6 to 2.0% (control) to 8.3 to 8.7%. The resultant enrichment of calcium (Ca^{2+}) in the soil-absorbing complex directly displaced exchangeable sodium (Na^+) and potassium (K^+), reducing their proportion from 6.6 to 7.0% to 4.3 to 5.2% of total cations. This shift mitigated soil alkalization and improved the soil's structural and buffer properties.

The treatment (variant 3) led to significant soil decompaction, a reduction in bulk density, and enhanced hydro-physical properties. The humus horizon deepened as surface organic matter was incorporated downward, creating a more favorable root environment.

The combined deep plowing and green manure treatment effectively decreased soil salinity and sodicity. A single intervention produced a reclamation after-effect that persisted throughout the entire eighth year of study, far exceeding the typical 1–5-year longevity of chemical ameliorants. This sustained improvement in soil health directly translated to a 21–38% increase in crop yields compared to the control. The incorporation of green manure complemented deep plowing by enhancing total nitrogen, SOC, and available K^+ and P levels. This biological input supported nutrient cycling and contributed to long-term fertility restoration.

5.1. Future Perspectives

Future studies need to expand past brief field observations and assess the long-term effects of integrating deep plowing with green manure on the restoration and sustainability of salt-affected soils in Ukraine. Given that salt-affected soils are significantly impacted by changes in groundwater levels, rainfall, and irrigation methods, continuous monitoring is crucial to assess whether the enhancements in soil structure, reduction in salinity, and availability of nutrients can be sustained in the long term. Additional research should also explore the biological aspect of soil recovery under deep plowing and green manure practices. While advancements in physicochemical properties are significant, a more thorough investigation into the reactions of enzyme activity, soil microbial biomass, organic carbon dynamics, and rhizosphere interactions is necessary. Comprehending these biological processes would clarify how green manure aids in enhancing soil resilience and nutrient cycling in restored saline areas. Moreover, subsequent research ought to assess various green manure species and combinations to determine the most biomass-efficient and salt-tolerant alternatives suitable for Ukrainian agro-ecological conditions. A crucial aspect is the optimization of deep plowing depth, timing, and frequency based on soil texture, compaction degree, and salinity level. Over-tilling can increase production expenses and disrupt soil composition if mishandled. Consequently, upcoming studies should concentrate on creating tailored management approaches that enhance agricultural advantages while reducing energy consumption and ecological impact. Combining deep plowing and green manure with additional sustainable reclamation strategies, such as gypsum application, controlled drainage, conservation irrigation, and precision nutrient management, might offer a more holistic approach for lands affected by salt. Economic and ecological evaluations are both essential. Future research needs to measure the cost-effectiveness of deep plowing and green manure methods, taking into account labor, fuel use, biomass output, and crop yield returns. Concurrently, their function in carbon capture, soil organic matter rejuvenation, and climate resilience needs to be assessed. These

integrated assessments would facilitate the practical implementation of these techniques by agriculturalists and decision-makers in areas impacted by soil salinization.

5.2. Recommendations

Considering the noted advantages of merging deep plowing with green manure, this combined approach is suggested as an effective soil enhancement method for salt-affected land in Ukraine. Deep plowing must be conducted with caution to disrupt compacted layers, enhance water infiltration, and promote salt leaching, whereas green manure needs to be added to boost organic matter levels, nutrient availability, and aggregate stability. Utilizing both practices together seems to be more effective than depending on just one reclamation method. Farmers are advised to choose green manure crops that are suitably adapted to saline and semi-arid settings, exhibiting high biomass yields and robust root systems. Leguminous and salt-resistant species can be especially beneficial due to their role in enhancing biological nitrogen input and improving soil cover. Selecting species must align with the local soil characteristics, agricultural practices, and seasonal precipitation trends. Deep plowing should not be applied indiscriminately to all salt-affected lands in field implementation. Rather, its use must be directed by soil assessment, which encompasses salinity level, sodicity condition, bulk density, and depth of compaction layers. In highly degraded soils, drainage enhancement and suitable soil amendments should be combined with deep plowing and green manure to hasten reclamation. It is advisable to conduct regular soil testing to track alterations in pH, electrical conductivity, organic carbon in the soil, and nutrient levels following treatment. At the policy and extension level, it is advised that agricultural advisory services increase awareness of integrated soil reclamation methods and assist farmers with technical advice, demonstration projects, and region-specific recommendations. Ukrainian government and research organizations need to enhance their partnership to create reclamation strategies that are effective for agriculture and viable economically in specific regions. This would aid in reviving the productivity of salt-affected soils and enhance sustainable agricultural land management in at-risk areas.

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