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Impact of soil mechanical impedance and polyacrylamide on physical and chemical root- soil interactions for maize hybrids (*Zea mays* L.)

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Abstract

Soil compaction negatively impacts soil properties, especially physical properties, thus reducing soil productivity and plant growth. This study aimed to investigate the role of polyacrylamide (PAM) (0, 0.25, 0.5, and 1.0 g L^{-1}) in improving the properties of compacted soil (0, 2.5, and 4.5 kg rammer) and maize growth in clayey and clay loam soils. Some soil properties deteriorated (e.g., bulk density, porosity, mean weight diameter, geometric weight diameter, structure, penetration resistance, and hydraulic conductivity) due to soil compaction, especially at a compaction strength of 4.5 kg rammer in both tested soils. Soil compaction also led to reduced maize growth (maize shoot and root parameters). On the contrary, soil properties and maize growth parameters were improved with the PAM application, especially at a rate of 0.5 g L^{-1}. This treatment also achieved an increase in root parameters and biomass yield by 27% compared to the compacted soil treatment. In addition, the growth parameters of maize roots also improved due to the decrease of penetration resistance and bulk density, and the increase in mean weight diameter, geometric weight diameter, and porosity. According to these results, PAM application has a positive role in improving the properties of compacted soil and plant growth.

Keywords: Compacted soil; Polyacrylamide; Bulk density; Penetration resistance; Maize growth parameters.

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1. Introduction

Soil compaction is a problem in modern agriculture. Soil is affected by its ability to withstand agricultural machinery and heavy tools, which limits soil characteristics and plant root growth, thus reducing crop production [1,2]. Researchers are pursuing sustainable mechanized practices that provide a favorable soil-root environment for improved plant growth, yields, and profits. However, Extensive application of machines causes soil compaction that deteriorates the bio-physical-mechanical properties of the maize-cropped soil-root ecosystem [3,4]. In addition, soil compaction ensues when soil loading stresses from machinery exceed the elastic limit [5]. The natural causes of soil compaction encompass various factors, such as the thickness of the soil layer, properties of parent materials, clay percentage, environmental conditions, and climate, drying, trampling, and grazing [6]. In addition, soil compaction also may result from several anthropogenic activities, including the use of wheels and tracks on equipment and soil-engaging tools, heavy machinery, the practices of intensive agriculture, and the implementation of unwise soil management techniques [1,2,6].

Additionally, the severity of soil compaction is controlled by several factors, such as agricultural equipment's compaction strength, soil texture, soil moisture, tillage layer, tire type, inflation pressure, and frequency of traffic passes [6]. Most studies have indicated that soil compaction reduces soil porosity, hydraulic conductivity, and infiltration rate [7,10], and increases soil bulk density (BD), penetration resistance (PR), and degree of compactness (DC) [6,11]. There are negative impacts of soil compaction on soil characteristics and root growth such as degradation of soil properties, and crop production [12]. Several studies also have shown that soil compaction leads to many negative impacts, such as decreasing soil porosity, infiltration rate, increasing surface ponding, runoff, soil erosion, reducing plant available water, and restricted root exploration for nutrient uptake [13,15]. These negative impacts generally deteriorate these soil properties and reduce most crop yield [3,16]. In addition, subsoil compaction significantly decreased the root growth of some plants such as maize and soybean [17]. There is a notable decrease in the root growth of maize and yield in compacted soil due to different tractor passes [18]. Shaheb et al. indicated that a substantial decrease in crop yield was observed with higher levels of tractor traffic, reaching up to 50% in certain instances [6].

On the other hand, several strategies have been applied to reduce the negative effect of soil compaction, such as organic agricultural matter [17], other organic wastes, and biochar, which increased macro-porosity and significantly decreased BD [19] and recently PAM application. It was observed that the bulk density (BD) of subsoil increased to 1.80 g cm-3 for conventionally tilled croplands compared to grasslands (1.76 g cm-3), and wild forest areas (1.44 g cm^{-3}) [20]. However, the challenge to alleviating soil compaction lies in the need to apply large quantities of organic matter frequently due to their high decomposition rates, versus PAM application, which is considered a sustainable alternative [21,22].

Polyacrylamide (PAM) has distinct properties that set it apart from other types of amendments, and it may be synthesized using either a traditional or a crosslinked approach [23]. The characteristics of PAM are categorized into four types: elastic, chemical, mechanical, and electro-kinetic [23]. According to Voronova et al. [24], the PAM application exhibits a range of modulus elasticity from 4.53 kPa to 0.26 kPa, depending on its concentration. Furthermore, the swelling characteristics of PAM use are contingent on the concentration, with the swelling ratio escalating from 21.6 to 133%. Additionally, Young's modulus experiences a reduction of 33% at the lowest concentration. In addition, PAM molecules include amine (NH_2) and carbonyl (C=O) groups, which may form hydrogen bonds with the hydroxyl groups of cellulose [23,24]. Polyacrylamide (PAM) also expands when it comes in contact with a strong base, but it takes on a coiled or partly stretched shape when it comes in contact with a strong or weak acid [24,25]. According to Bakker et al. [21], PAM is a synthetic polymer that exhibits resistance to microbial degradation. In addition, PAM contains very few or no molecules with electric charge, which leads to a little or negligible impact on soil salinity [23]. According to recent studies, PAM improves soil's physical, chemical, and biological characteristics. It enhances soil aggregation, maintains soil structure in cold regions [23,26,27,28], increases porosity, and aids in the control of some diseases [29]. In addition to its capacity for plant nutrient absorption, it has several functional groups that differ according to the method of manufacture [23,29]. Applying PAM to compacted soil can reduce the negative effect of compaction in arid and semi-arid regions under Egyptian soil conditions. The application of PAM to enhance the properties of Egyptian soil remains a research question. Therefore, this study hypothesizes that application of PAM improves properties of some compacted clayey and clay loam soils and enhances the growth of maize plants.

2. Materials and Methods

2.1. The experimental site and treatments

Soil samples were collocated from the top layer (0.0 - 0.2m) at two sites (The first location; latitude, 30°.56'72608"N, longitude, 31°.57'35592"E; The Faculty of Technology and Development Farm, and the second one latitude, 30°.02'1147"N, longitude 31°.20'9455"E; The Soil, Water and Environment Research Institute (SWERI). The experiment zone is located at the SWERI, Egypt (Latitude, 30°.021'9319"N, longitude 31°.210'8546,662"E, The Water and Environment Research Institute, Giza City, Egypt. To explore the effect of PAM application, a column experiment was conducted on May 3, 2023, using maize (*Zea mays* CV. SC-176) in two compacted soils (Table 1). The experimental design was a split-plot design with two factors, and the first one was soil type (clayey and clay loam soils). In contrast, second factor was nine combined treatments between three compaction strengths (CS) (CS0; 0kg rammer, CS1; 2.5 kg rammer, CS2; 4.5kg rammer), and four PAM (PAM) application rates (PAM0; 0.00g PAM L^{-1}, PAM0.25; 0.25 g PAM L^{-1}, PAM0.5; 0.50g PAM L^{-1}, and PAM1; 1.00g PAM L^{-1}), the treatments were arranged as CS0PAM0 (check treatment), CS2.5PAM0, CS2.5PAM0.25, CS2.5PAM0.5, CS2.5PAM1, CS4.5PAM0, CS4.5PAM0.25, CS4.5PAM0.5, and CS4. 5PAM1.All treatments were duplicated three times.

2.2. Compaction strengths and polyacrylamide application

The soil samples were processed, sifted, and filled into polyvinyl chloride columns measuring 0.20m in height and 0.10m internal diameter. The soil was densified by repeatedly hitting it with a column compaction rammer (weighing 0.0, 2.50, and 4.50 kg) three times, from a height of 0.3m, into the top plate of the piston. Based on the plasticity index, soil Compaction was performed at a moisture level of 23% for clayey soil and 16% for clay loam soil. The soil BD was assessed by measuring the weight of the soil after it was dried in an oven and the volume of the soil column after it was compacted. Furthermore, the applied PAM was imported from Yixing Bluwat Chemicals, LTD, China (Bluwat AA3515).

Sowing was done using three seeds/column and covered by a 0.02m uncompacted layer. The soil water content was maintained by weighing each column every two days and irrigation with tap water to meet field capacity. After two weeks from sowing, each column had two seedlings. Maize samples were taken 50 days after seeding. Maize shoots, stems, and roots were sampled, and growth characteristics were recorded. Separate, dried, milled, and coded samples were also used for measuring and analyzing. Soil columns were meticulously collected and divided into three layers (First (0-0.05m), second (0.05-0.1m), and third (0.1-0.15m) layers). Milling, sieving, and coding of soil layers for physical and chemical attributes.

Table 1: Initial characteristics of the two investigated soils

Soil type	Clayey soil	Clay loam soil
Physical properties		
Coarse Sand (%)	5.60	10.80
Fine Sand (%)	14.80	19.50
Silt (%)	37.40	35.20
Clay (%)	42.20	34.50
Textural Class[1]	clayey	clay loam
Particle density (g cm^{-3})	2.61	2.67
Bulk density (g cm^{-3})	1.24	1.32
Porosity (%)	52.49	50.56
Hydraulic Conductivity (cm h^{-1})	1.10	3.10
Mean weight diameter (mm)	0.49	0.11
Field capacity (%)	30	22
Plasticity Index (%)	23	16
Chemical properties		
pH[2]	7.60	7.10
EC (dS m^{-1})[3]	1.17	1.89
Ca^{+2} (meq L^{-1})	3.12	4.9
Mg^{+2} (meq L^{-1})	3.34	2.4
Na^{+} (meq L^{-1})	14.21	9.8
K^{+} (meq L^{-1})	1.03	1.8
CO_3^{-2} (meq L^{-1})	–	–
HCO_3^{-}(meq L^{-1})	0.5	0.3
Cl^{-} (meq L^{-1})	15.5	11.8
SO_4^{-2} (meq L^{-1})	5.7	6.8
K_2SO_4-N (mg Kg^{-1})	25.3	18.4
$NaHCO_3$-P (mg Kg^{-1})	27.1	24.8
NaOAc-K (mg Kg^{-1})	0.5	0.4
Organic matter (g Kg^{-1})	4.40	3.20
$CaCO_3$(g Kg^{-1})	4.60	29.00

1; Soil texture was determined using USDA textural tringle; 2; pH was measured in in soil paste; 3; EC was measured in soil paste extract

2.3. Laboratory analyses and measurements

2.3.1. Soil analysis

Particle size distribution was determined using a hydrometer protocol. We used the core and pycnometer protocols to determine the bulk density (BD) and particle density (PA), respectively. Reference bulk density, and degree of compactness (DC) before and after all treatments were calculated by [30,31]. The soil PR was measured at three layers using a Japanese cone penetrometer (SR-2 Dik 5500) to determine the average soil PR [30] at three moisture levels (Table 2). Mean weight diameters (MWD) and geometric weight diameters (GWD) were calculated by [32], and a sensitivity index (SI) was calculated according to [33], as well as hydraulic conductivity coefficient (HCC), and water -holding capacity (WHC) were determined according to [34]. Additionally, Organic matter, calcium carbonate, soluble calcium, and magnesium, K_2SO_4- Nitrogen, Na-HCO_3-Phosphors, soluble and NH_4OAc-Potassium were determined according to determined according to [34].

Mineralogical analysis was performed by X-ray diffractometer (X' Pert Pro, Analytical, Netherland) using Cu

Kα anode (λ = 1.5406 Å) as a radiation source over the 2θ range of 10°–50° at 293 K. In addition, identifying the most probable phases is carried out using an analytical computer-certified program with the International Center of Diffraction Database [35,36,37,38].

2.3.2. Some plant growth parameters and contents of some nutrients

Some growth parameters were measured in maize shoot and root parts and the stem length, stem diameter, and leaf space guide. Moreover, leaf area and leaf space guide were calculated using the equation proposed by [39,40], respectively. The root in each section was separated to estimate the weight and length of each layer, calculate root length density, specific root length, and fresh and dry weight, and calculate root lengths using the Newman method for each layer. The total length of the roots, root length density specific root length (RLD), and specific root length (SRL) were estimated using equations suggested by [41,42]. In addition, all maize samples were dried and weighed, and the dry mass was determined and wet-digested using a mixture of sulfuric acid and hydrogen peroxide, according to [43]. Total-N, P, and K of shoots and roots were determined using the Kjeldahl, colorimetric, and flame photometer methods [34].

2.4. Statistical analysis

A 5% significance level was used to compare means based on the least significant difference (LSD 0.05). The statistical analyses were performed using the SPSS (V. 26) software package. Graphs were made with the software of origin (V. 9).

3. Results

3.1 Effect of polyacrylamide (PAM) application on some properties of compacted soil

Based on the results, soil bulk densities increased due to soil compaction, whereas applying PAM decreased BD values (Table 2). The soil bulk densities (BD) of the initial basic soils were 1.18 and 1.21 g cm^{-3} for clayey and clay loam soils, respectively. There was an increase in BD and degree of compactness (DC) due to decreasing total volume and soil porosity. Soil BD generally improved, and the lowest BD values were 1g cm^{-3} with 1 g PAM L^{-1} in the clayey soil, whereas clay loam soil recorded 1.17 g cm^{-3} for 0.25 g PAM L^{-1}. The means of DC were 62.02 and 63.51% in clayey and clay loam soils, respectively. There was an increase in DC due to increasing soil BD. The increases in DC were 74.63% and 77.78% for the 2.5kg and 4.5kg rammers, respectively, in clayey soil. In clay loam soil, the increases were 65.09% and 71.38% for the 2.5kg and 4.5kg rammers, respectively, compared to the check treatment. The values of DC in the tested soil generally improved, and the lowest DC values were 55.19% for 0.50 and 1 g PAM L^{-1} in the clayey soil, whereas clay loam soil recorded 64.04% for 0.50 g PAM L^{-1} after PAM application. Our results are similar to those of [44,45], which took the same trend as our results.

Table 2: Effect of polyacrylamide (PAM) application rates on the bulk density (BD - g cm-3), degree compactness (DC - %), and penetration resistance (PR - Mpa) (at three levels of soil moisture) in the investigated soils

Soil type	Compaction strengths (CS)	PAM application rates (g L^{-1})	BD (g cm^{-3})	DC (%)	PR^1 (Mpa)			PR^2 (Mpa)			PR^3 (Mpa)		
					First layer	Second layer	Third layer	First layer	Second layer	Third layer	First layer	Second layer	Third layer
Clayey soil	CS0	PAM0.00	1.18	62.02	0.11	0.34	0.40	1.02	1.13	2.00	1.36	1.25	2.35
	CS2.5	PAM0.00	1.42	74.63	0.57	1.25	1.30	1.36	2.26	2.72	1.81	2.26	2.90
		PAM0.25	1.08	56.76	0.45	0.79	0.96	1.13	1.47	2.60	1.80	1.95	2.10
		PAM0.50	1.03	54.14	0.34	0.76	0.94	1.10	1.44	2.58	1.13	1.59	1.90
		PAM1.00	1.00	52.56	0.32	0.68	0.85	0.79	1.36	2.20	0.60	1.25	1.85
	CS4.5	PAM0.00	1.48	77.78	0.68	2.83	3.00	2.26	3.51	3.45	3.06	3.40	2.92
		PAM0.25	1.13	59.39	0.57	2.26	2.55	2.24	2.38	3.34	2.72	2.49	2.75
		PAM0.50	1.05	55.19	0.45	1.36	1.47	1.81	2.15	2.77	1.36	1.81	2.60
		PAM1.00	1.05	55.19	0.42	1.25	1.45	1.47	1.47	2.60	0.70	1.36	2.56
Clay loam soil	CS0	PAM0.00	1.21	63.51	0.17	0.68	0.74	0.79	1.13	2.15	0.79	1.47	1.75
	CS2.5	PAM0.00	1.24	65.09	0.79	1.02	1.36	1.70	2.38	3.30	1.36	2.83	2.80
		PAM0.25	1.17	61.41	0.57	0.91	1.34	0.91	1.59	2.40	1.02	1.70	2.40
		PAM0.50	1.20	62.99	0.23	0.79	1.02	0.91	1.56	1.76	1.01	1.68	2.20
		PAM1.00	1.20	62.99	0.20	0.57	0.79	0.68	1.02	1.21	0.79	1.59	1.95
		PAM0.00	1.36	71.38	1.47	1.59	1.47	1.81	2.49	3.40	1.90	3.28	3.55
		PAM0.25	1.24	65.09	1.36	1.13	1.25	1.47	2.15	3.17	1.80	2.72	3.05
		PAM0.50	1.22	64.04	0.45	1.02	1.05	1.13	1.92	2.90	1.70	2.26	2.70
		PAM1.00	1.25	65.61	0.34	1.02	0.96	1.02	1.70	2.49	1.59	1.81	2.50

Three compaction forces (CS) CS0 (0kg rammer), CS2.5 (2.5 kg rammer), CS4.5 (4.5kg rammer). Four polyacrylamide (PAM) levels (0.00, 0.25, 0.50, and 1.00 g PAM L-1). PR1 (at 30% moisture for clayey soil, and 22% for clay loam soil = felid capacity), PR2 (at 23% moisture for clayey soil, and 16% for clay loam soil = plasticity index), PR3 (at 19% moisture for clayey soil, and 9% for clay loam soil).

On the other hand, (Figure 1a) illustrates the mean MWD and GWD of the soils under investigation after PAM application. In clayey soil, MWD was 0.49, 0.82, 0.96, and 3.86mm, whereas, in clay loam soil, it was 0.11, 0.23, 0.46, and 0.69mm for the 0.00, 0.25, 0.50, and 1.00g PAM L^{-1} treatments, respectively. In clayey soil, GWDs were 1.19, 1.99, 2.16, and 1.69mm, whereas, in clay loam soil, they were 0.12, 0.77, 1.50, and 1.82mm, for the same PAM application rates. The highest values of MWD were 3.86, and 0.69mm in the clayey and clay loam soils, respectively, for the 1g PAM L^{-1} rate, whereas GWD were 1.69, 1.82mm in the clayey and clay loam soils for the same treatment. Moreover, SI assesses whether the GMD or MWD values when a value of SI greater than one indicates an increase in aggregation (Figure 1b). Figure 1b. demonstrates the SI values of the effect of PAM at its applied rates on enhancing the stability of aggregates in the examined soils. The SI values ranged from 1 to 7.9 in clayey soil and 1 to 6.2 in clay loam soil for 0 and 1g PAM L^{-1}, respectively, and there is a similar trend in SI values calculated based on GWD.

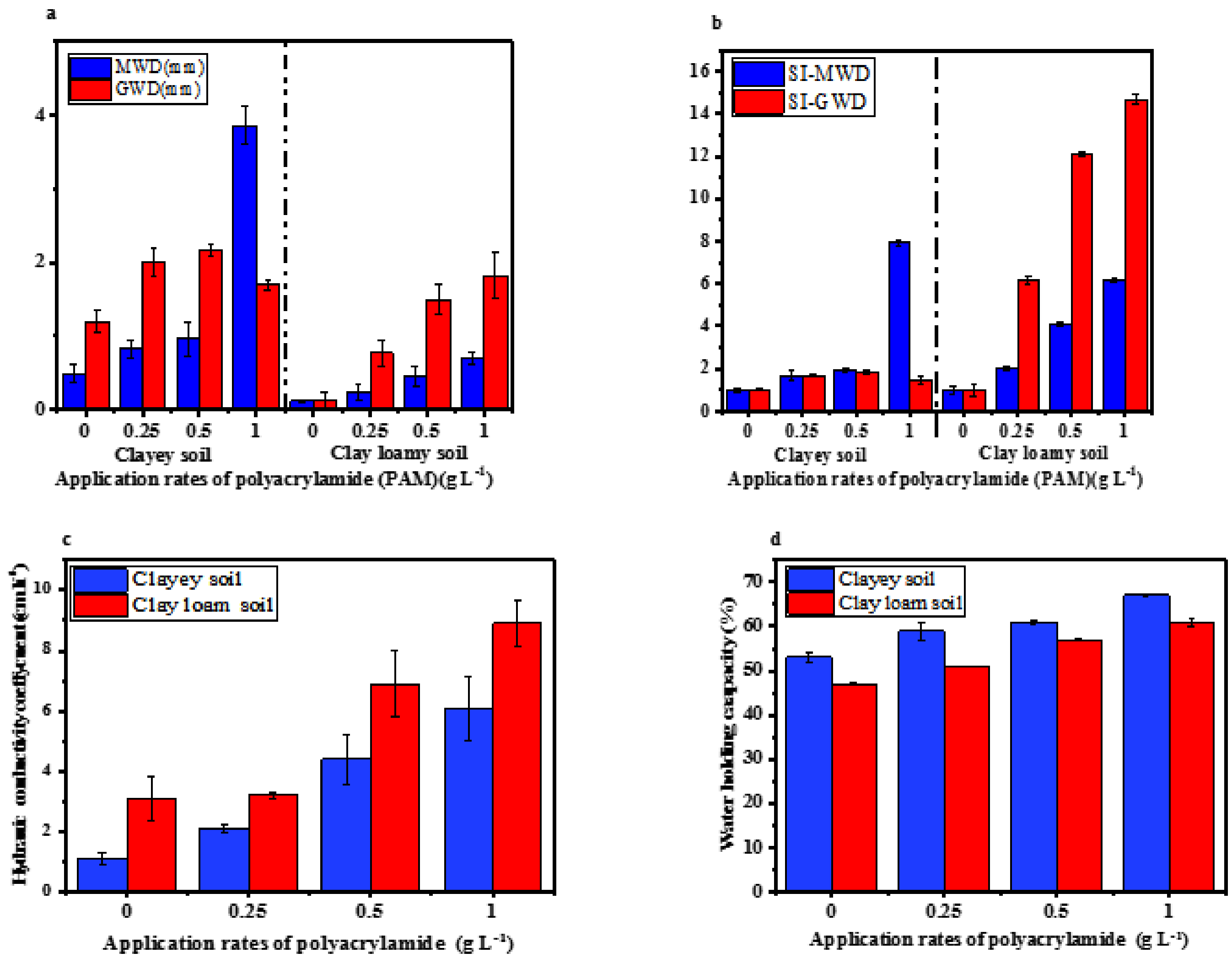

Fig. 1: Effect of polyacrylamide (PAM) application rates on the mean weight diameter and geometric weight diameter (a), on the sensitivity index (SI) calculated based on the mean weight diameter (SI – MWD) and geometric weight diameter (SI – GWD) (b), hydraulic conductivity coefficient (c), and water holding capacity (d) in the two investigated soils.

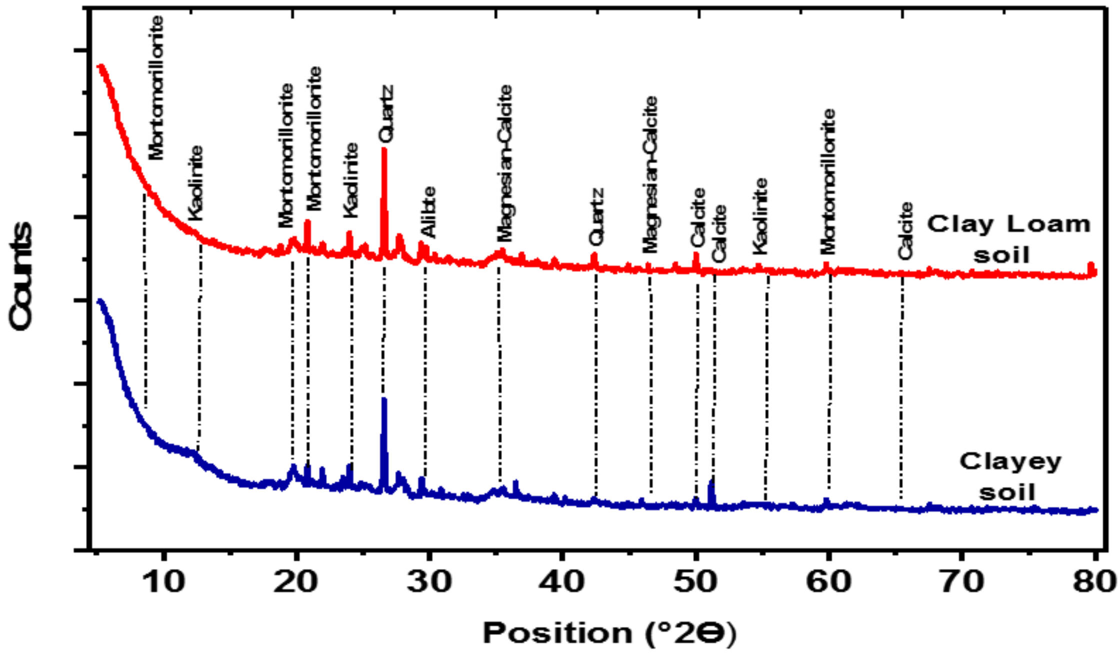

Fig. 2: X-ray pattern of the two investigated soils

Additionally, (Table 2) showed PR values at three varied moisture levels (PR1 at 30%, and 22% = felid capacity; PR2 at 23%, and 16% = plasticity index; PR3 at 19%, and 9% for clayey soil and clay loam soil, respectively). The PR values exhibit an upward trend with increasing compaction strength, whereas they show a downward trend with increasing moisture content in both soils. The PR1 in the successive clayey soil layers ranged from 0.11 to 0.68, 0.34 to 2.83, and 0.4 to 3.00 MPa, respectively. After soil compaction, PR increased by 418%, 518% and 33.33%, 121.57% and 33.09%, 125% in the successive layers for the 2.5 and 4.5kg rammer at 30%, 23%, and 19% moisture, respectively. In clay loam soil, PR1 ranged from 0.17 to 1.47, 0.57 to 1.59, and 0.74 to 1.47 MPa in the successive layers, respectively. The PR increased as the first layer increased, ranging from 2.48 to 12.40, 50.00 to 133.83, and 110.02 to 120.35% for the same compaction treatments at 22%, 16%, and 9% moisture. The range of PR2 varied from 0.79 to 2.26, 1.13 to 3.51, and 2.00 to 3.45MPa in the successive layers. In clay loam soil, the PR2 range was 0.68 to 1.81, 1.02 to 2.49, and 1.21 to 3.40MPa, respectively. The PR3 ranged from 0.60 to 3.06, 1.25 to 3.40, and 1.85 to 2.92MPa in successive clayey soil layers, respectively. In clay loam soil, the PR values for the same layers ranged from 0.79 to 1.90, 1.47 to 3.28, and 1.75 to 3.55 MPa, respectively. Increasing soil moisture decreased PR value with PAM treatments, particularly at 0.5, and 1 g PAM L^{-1} rates. In contrast, compaction strengths enhanced PR, especially in the subsurface layer of the soils. On the other hand, PAM application increased HCC and WHC in the soils, as shown in (Figures 1c and 1d). There is a direct correlation between PAM application and HCC or WHC. Means of HCC in the clayey soil were 1.10, 2.10, 4.40, and 6.10 cm.h-1 for PAM application rates of 0, 0.25, 0.50, and 1.00 g L^{-1}, respectively. In clay loam soil, HCC values were 3.10, 3.20, 6.90, and 8.90 cm h-1 for the same treatments. In addition, WHC of soils improved by 26.41% and 29.79% for clayey and clay loam soils, respectively.

For mineralogical analysis, there were apparent differences in soil texture of investigated soil, where percentages of clay in clayey and clay loam soils were 42.2% and 34.5%, respectively. In addition, (Figure 2) indicates the X-ray pattern of the two soils, which included numerous minerals. However, clay soils have more clay minerals, and the peaks of the X-ray pattern are very similar to those of several studies [38,46, 47].

3.2 Effect of polyacrylamide (PAM) application on some growth parameters of maize and contents of NPK

Maize growth parameters varied according to applied compaction strengths and PAM application in the tested soils. Results from (Tables 3 and 4) indicate statistically significant differences in germination percentage, maize stem diameter, stem lengths, leaf space guide, root length, and weights of maize biomass by PAM application. Most parameters confirm that the clayey texture soils recorded more excellent averages than the clay loam soil. Germination percentages were recorded at 90.12% and 71.60% in the clayey soil and clay loam soil, respectively. Most maize growth parameters decreased due to strong soil compaction, especially at the compaction strength of 4.5 kg rammer. After the PAM application, these parameters significantly improved, especially in the CS2.5PAM0.5 treatments, which generally outperformed and achieved the highest values compared to the other treatments. On the contrary, the CS4.5PAM0 treatment typically achieved the lowest values. Percentages of increases of CS2.5PAM0.5 treatment reached 14, 67, 31, 40, 159, 113, 121, and 87% for the parameters mentioned in (Table 3), respectively, calculated based on the CS4.5PAM0 treatment. In addition, the increases were 176, 95, 705, 136, 162, 38, 59, 60, and 101%, respectively (Table 4). This proves that applying PAM reduces the negative impact of soil compaction, especially at the level of compaction force of 2.5 kg Rammer. The CS2.5PAM0 treatment had the highest value in stem length and diameter as well as maize biomass yield, and it recorded 25.75cm, 1.15cm, and 6.24g/column, respectively. In addition, clayey soil generally had the highest values in most measured maize growth parameters. Maize root growth parameters were generally affected by increasing in PAM rates. The CS2.5PAM0.5 treatment recorded the highest values in root dry weight and weight of roots in the first layer, which were 1.43 and 3.97g (Tables 3 and 4). In addition, the CS2.5PAM0.5 treatment recorded the highest values in the weight of maize root in the second and third layers and root length. The best treatment was CS2.5PAM0.5, which applied PAM at a rate of 0.5 g L^{-1} with a compaction of 2.5kg rammer. It was found that increasing PAM application rates improved maize root growth parameters. There was a clear significance between clayey and clay loam soils in most parameters of roots and shoots of maize. For tested soils, averages of clayey soil had the highest values compared to clay loam soil. Additionally, PAM application enhanced maize growth parameters in the two investigated soils. Contents of N, P, and K of maize shoots and roots were affected by increasing soil compaction (Table 5). The N content of shoots and roots ranged from 1.76 to 3.05% and 0.32 to 0.79%, respectively. The (CS2.5PAM1) treatment resulted in the highest N content in the shoot component (49.5%), whereas the highest value of N content in roots was 0.79 for the (CS2.5PAM0.5) treatment, and the increasing percentage was 46.29%. On the other hand, the P content in maize shoots and roots ranged from 0.14 to 0.19% and 0.07 to 0.14%. The highest P content of maize shoots and roots was (CS2.5PAM0.5) treatment and the increasing percentage was 35.71% and 40% in maize shoots and roots, respectively, whereas the lowest value was in the check treatment. Additionally, the K content in maize shoots and roots ranged from 2.23 to 2.99% and 1.66 to 3.37%, respectively. The highest K value of maize shoots and roots was (CS2.5PAM0.5) treatment; the increasing percentage was 34.08, 98.40% in maize shoots and roots. Improvements due to the application of PAM led to an improvement in the penetration ability of roots and improved N, P, and K contents in maize shoots and roots, especially at an application rate of 0.5 g PAM L^{-1}.

4. Discussion

According to the results presented, it confirms that soil compaction causes many negative effects on soil properties and quality. Soil compaction clearly affects the spread of maize roots in compacted soils and thus reduces the maize biomass yield. Due to soil compaction, the values of BD, BR, and DC increased, while porosity, aeration, MWD, and GWD decreased. Most growth parameters of roots and shoots, and their content of NPK, decreased. In contrast, all these parameters improved following the application of PAM, specifically at a rate of 0.5 g PAM L^{-1}. Compaction also decreases soil porosity and increases BD in both soils. In addition, PAM decreased soil bulk densities, especially at 1 g L^{-1} (Table 2). PAM also improved aggregate stability according to the value of MWD and GWD. The MWD and GWD improve with higher PAM application rates. The different mineral compositions in tested soils, as shown by XRD (Figure 2) mineralogy analysis, explain the disparity. PAM enhances soil aggregation, depending on the pace, compaction intensities, and soil texture, which improves BD and DC [6]. Therefore, clayey soil contained more clay minerals than clay loam soil, which was reflected in clayey soil's soil properties and maize growth parameters compared to the other soil. This proves that the clayey soil was better at stabilizing the aggregates because the clayey soil's MWD and GWD values were higher than the clay loam soil. The PAM application causes an increase in MWD and GWD values. This proves that applying PAM improves soil aggregation, soil porosity, WHC, and the ability to adsorb nutrients and reduces soil compaction effects [23,26,27,28]. PAM increased soil structure, water retention, and cement-like effect. Long-chain PAM molecules adhere to soil particles, particularly on their exterior surfaces [48], improving soil aggregation and stability more than other amendments [49,50]. In addition, when PAM encounters water, the hydrogen group in the molecular chain attracts the soil clay particles, causing the molecules to intertwine and form a chain bridge. This results in the soil particles dispersing and interweaving with each other, leading to the gradual formation of larger aggregates as well as causing strong, water-stable aggregates to be formed [51]. PAM reduces PR and the value of PR of 2 MPa is frequently considered a crucial barrier that limits root growth according to [52,53]. Nevertheless, numerous studies have challenged this assertion by considering various crucial thresholds [54,56]. Consistent with this investigation's results, low moisture levels resulted in greater PR values compared to the often-reported critical values [52,57]. The results indicate that soil compaction not only decreased the dry matter and length of plant roots but also had a more significant impact on the structure and distribution of roots. Results generally demonstrated a negative correlation of BD or PR with growth parameters and root distribution variables. These relationships were accentuated by BD and PR, and these results are consistent with [44]. Compression-induced changes in BD and PR might impede optimal root development [58]. The findings of [58,59] are consistent with our results. This leads to a higher penetration of roots in upper soil layers and reduced rooting in deeper layers [60–62]. In addition, the results align with the findings of Uyeda et al. [63], who observed a decrease in the HCC values of soils affected by compaction strengths. Furthermore, the results indicate that the level of soil aggregate destruction was lower in the plot treated with PAM application, specifically in terms of dissipation, clay disintegration, and mechanical disturbance. Moreover, compacted soil inhibits plant root development, and mechanical impedance may slow plant growth even with enough nutrients and water. Studies that manually impeded root development showed reduced leaf elongation [60,64]. Traffic modifies soil characteristics, which impacts root development and distribution, which affects crops' capacity to absorb and utilize nutrients and water from the soil. This reduces crop growth and grain production in trafficked fields.

Table 3: Effect of soil compaction with different strengths and polyacrylamide (PAM) application rates on some maize growth parameters in the two tested soils

Treatments	Germina-tion(%)	Stem length(cm)	Stem diam.(mm)	Leaf space guide	Shoot dry weight(g)	Root dry weight(g)	Root length(cm)	Biomass yield(g)
CS0.0PAM0.00	83.33[ns]	19.83[bc]	0.97[b]	1.75[ab]	3.66[ab]	1.25[ns]	15.75[b]	4.91[ab]
CS2.5PAM0.00	83.33[ns]	21.33[b]	0.95[b]	2.13[a]	3.63[ab]	1.00[ns]	13.00[b]	4.63[ab]
CS2.5PAM0.25	77.78[ns]	16.25[cd]	0.88[b]	1.51[abc]	3.62[ab]	0.92[ns]	11.13[b]	4.54[ab]
CS2.5PAM0.50	77.78[ns]	25.75[a]	1.15[a]	1.92[ab]	4.93[a]	1.31[ns]	21.17[a]	6.24[a]
CS2.5PAM1.00	83.33[ns]	16.58[cd]	0.88[b]	1.54[abc]	2.77[ab]	1.35[ns]	14.92[b]	4.12[ab]
CS4.5PAM0.00	88.89[ns]	17.58[bcd]	0.93[b]	1.73[ab]	3.38[ab]	0.98[ns]	14.67[b]	4.35[ab]
CS4.5PAM0.25	77.78[ns]	15.42[d]	0.89[b]	1.04[c]	1.90[b]	1.43[ns]	9.58[b]	3.33[b]
CS4.5PAM0.50	77.78[ns]	20.42[bc]	0.95[b]	1.37[bc]	3.76[ab]	0.67[ns]	12.08[b]	4.43[ab]
CS4.5PAM1.00	77.78[ns]	18.42[bcd]	0.93[b]	1.51[abc]	3.46[ab]	1.27[ns]	13.75[b]	4.73[ab]
LSD 0.05	NS	2.85	0.11	0.41	1.44	NS	4.47	1.70
Soil type								
Clayey soil	90.12[a]	23.30[a]	1.02[a]	2.12[a]	4.65[a]	1.57[ns]	16.02[a]	6.20[a]
Clay loam soil	71.60[b]	14.83[b]	0.88[b]	1.11[b]	2.26[b]	0.71[ns]	11.99[b]	2.97[b]
LSD 0.05	9.19	1.07	0.02	0.47	1.03	NS	3.76	1.77
Interaction								
Soil (S)	Sig.	Sig.	Sig.	Sig.	Sig.	NS	Sig.	Sig.
Treatments (T)	NS	Sig.	Sig.	Sig.	Sig.	NS	Sig.	NS
S×T	NS	Sig.	Sig.	Sig.	Sig.	NS	Sig.	Sig.

Three compaction forces (CS) CS0 (0kg rammer), CS2.5 (2.5 kg rammer), CS4.5 (4.5kg rammer). Four polyacrylamide (PAM) levels (0.00, 0.25, 0.50, and 1.00 g PAM L-1).

Table 4: Effect of soil compaction with different strengths and polyacrylamide (PAM) application rates on some maize root parameters in the tested soils

Treatments	Root fresh weight (g)			Root length (cm)			Total root length (cm)	Root length density (cm)	Specific root length (cm g^{-1})
	First layer	Second layer	Third layer	First layer	Second layer	Third layer			
				Calculated based on the Newman method					
CS0.0PAM0.00	1.84[ab]	1.11[ns]	1.00[ns]	109.25[bc]	65.68[ns]	61.75[ns]	236.68[ns]	0.17[ns]	193.23[ns]
CS2.5PAM0.00	1.44[b]	1.17[ns]	0.79[ns]	76.80[c]	77.98[ns]	48.93[ns]	203.71[ns]	0.15[ns]	388.12[ns]
CS2.5PAM0.25	2.82[ab]	0.86[ns]	0.32[ns]	147.45[ab]	34.93[ns]	25.25[ns]	207.63[ns]	0.15[ns]	260.55[ns]
CS2.5PAM0.50	3.80[a]	1.68[ns]	1.61[ns]	137.64[abc]	91.35[ns]	94.85[ns]	323.84[ns]	0.24[ns]	253.51[ns]
CS2.5PAM1.00	3.97[a]	1.63[ns]	0.52[ns]	169.56[ab]	61.49[ns]	38.47[ns]	269.52[ns]	0.20[ns]	221.72[ns]
CS4.5PAM0.00	2.43[ab]	1.22[ns]	0.73[ns]	127.56a[bc]	76.54[ns]	68.69[ns]	272.79[ns]	0.20[ns]	298.85[ns]
CS4.5PAM0.25	3.51[a]	0.96[ns]	0.25[ns]	181.34[a]	66.33[ns]	37.81[ns]	285.48[ns]	0.21[ns]	227.66[ns]
CS4.5PAM0.50	2.71[ab]	1.41[ns]	0.20[ns]	136.07[abc]	44.75[ns]	22.90[ns]	203.71[ns]	0.15[ns]	339.91[ns]
CS4.5PAM1.00	3.97[a]	1.18[ns]	0.23[ns]	159.75[ab]	58.09[ns]	18.06[ns]	235.89[ns]	0.17[ns]	253.22[ns]
LSD 0.05	1.35	NS	NS	42.34	NS	NS	NS	NS	NS
Soil type									
Clayey soil	3.79[a]	1.98[a]	1.01[ns]	178.20[a]	91.55[a]	73.03[a]	342.78[a]	0.25[a]	250.15[ns]
Clay loam soil	2.09[b]	0.52[b]	0.25[ns]	98.56[b]	36.70[b]	19.57[b]	154.83[b]	0.11[b]	291.36[ns]
LSD 0.05	0.83	0.62	NS	9.97	33.75	51.91	56.34	0.04	NS
Interaction									
Soil (S)	Sig.	Sig.	NS	Sig.	Sig.	Sig.	Sig.	Sig.	NS
Treatments (T)	Sig.	NS	NS	Sig.	NS	NS	NS	NS	NS
S×T	NS	NS	Sig.	NS	NS	NS	NS	NS	Sig.

Three compaction forces (CS) CS0 (0kg rammer), CS2.5 (2.5 kg rammer), CS4.5 (4.5kg rammer). Four polyacrylamide (PAM) levels (0.00, 0.25, 0.50, and 1.00 g PAM L-1).

Table 5: Effect of soil compaction with different strengths and polyacrylamide (PAM) application rates on nutrient N, P, and K content in shoot and root maize grown in the investigated soils

Treatments	N (%)		P (%)		K (%)	
	Shoot	Root	Shoot	Root	Shoot	Root
CS0.0PAM0.00	2.04^{ns}	0.54^{b}	0.14^{b}	0.10^{bc}	2.99^{a}	1.88^{cd}
CS2.5PAM0.00	2.07^{ns}	0.46^{b}	0.19^{ab}	0.10^{bc}	2.64^{ab}	2.50^{bcd}
CS2.5PAM0.25	1.76^{ns}	0.46^{b}	0.14^{b}	0.09^{c}	2.29^{b}	2.95^{abc}
CS2.5PAM0.50	2.05^{ns}	0.79^{a}	0.19^{a}	0.14^{a}	2.25^{b}	3.73^{a}
CS2.5PAM1.00	3.05^{ns}	0.32^{b}	0.18^{ab}	0.09^{c}	2.52^{b}	1.98^{cd}
CS4.5PAM0.00	2.36^{ns}	0.42^{b}	0.16^{ab}	0.13^{ab}	2.46^{b}	2.98^{abc}
CS4.5PAM0.25	2.28^{ns}	0.34^{b}	0.18^{ab}	0.09^{c}	2.23^{b}	3.25^{ab}
CS4.5PAM0.50	1.95^{ns}	0.48^{b}	0.15^{ab}	0.10^{bc}	2.48^{b}	1.66^{d}
CS4.5PAM1.00	2.17^{ns}	0.38^{b}	0.16^{ab}	0.07^{c}	2.67^{ab}	1.82^{cd}
LSD 0.05	NS	0.171	0.025	0.016	0.32	0.839
Soil type						
Clayey soil	2.11^{ns}	0.47^{ns}	0.12^{ns}	0.08^{ns}	2.26^{b}	2.77^{ns}
Clay loam soil	2.28^{ns}	0.47^{ns}	0.14^{ns}	0.08^{ns}	2.74^{a}	2.29^{ns}
LSD 0.05	NS	NS	NS	NS	0.25	NS
Interaction						
Soil (S)	NS	NS	NS	NS	Sig.	NS
Treatments (T)	NS	Sig.	Sig.	Sig.	Sig.	Sig.
S×T	NS	Sig.	NS	Sig.	Sig.	Sig.

Three compaction forces (CS) CS0 (0kg rammer), CS2.5 (2.5 kg rammer), CS4.5 (4.5kg rammer). Four polyacrylamide (PAM) levels (0.00, 0.25, 0.50, and 1.00 g PAM L-1).

5. Conclusions

We studied the impact of various PAM amendment rates on compacted soil characteristics and maize plant development as an indicator. PAM application improved BD, PR, MWD, GWD, WHC, and HCC in the tested soils. Thus, the PAM improved compaction-affected soil conditions and maize development, yielding more biomass than the other treatments. The CS2.5PAM0.5 treatments significantly impacted soil properties and maize biomass yields. The PAM amendment also enhanced soil characteristics and reduced compaction, allowing maize to be cultivated without affecting crop yields with higher soil compaction and lower PR values. Finally, broad PAM amendment application is promising since agricultural equipment compacts most soils.

Supplementary Materials

Author Contributions: Conceptualization, A.F., K.A.M, A.E. Methodology, Formal analysis, Investigation, M.H.G, M.A.; Writing – original draft preparation, Writing – review and editing. H.E.A, H.A.R, and A.A.A., contributed to the software, editing, funding and validation processes. All authors have read and agreed to the published version of the manuscript.

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