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MINIMIZING HARMFUL EFFECT OF SOIL MECHANICAL IMPEDANCE ON SOME SOIL PHYSIO-CHEMICAL PROPERTIES AND GROWTH PARAMETERS FOR MAIZE HYBRID (*Zea mays* L.)

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ABSTRACT

A greenhouse experiment was carried out in soil columns. Surface soil samples (0.0 – 0.2 m depth) were collected from the Faculty of Technology and Development Farm (Clayey soil), and the second one from the Soil, Water and Environment Research Institute, Giza Governorate, Egypt (Clay Loam soil). This study aims to investigate the effect of polyacrylamide (PAM) application on some properties of compacted soil and roots-shoots Maize growth parameters. A nine-soil treatments combined different compaction strengths (CS) (0, 2.5, 4.5kg rammer) and PAM application (0, 0.25, 0.5, and 1 g PAM L^{-1}) in the soils.

Soil compaction led to increasing soil bulk density by 25% and 12% for the CS4.5PAM0 treatment (4.5 kg rammer), compared to the uncompacted treatments in the clayey and clay loam soil, respectively. Some growth parameters of maize were deteriorated due to soil compaction. The application of PAM significantly decreased soil bulk density, penetration resistance, and plasticity index in the tested soils. In addition, there are significant increases in mean and geometric weight diameters, and hydraulic conductivity coefficient. Consequently, the PAM application also improved maize growth parameters and biomass yields. The superior treatment generally was CS2.5PAM0.5 at the application rate of 0.5 g PAM L^{-1} with the second compaction strength (CS; 2.5kg rammer). This treatment achieved the highest effects on soil physical characteristics, increasing maize growth parameters such as stem length, leaf space guide and root length, in addition that the biomass yields increase by 12% in the tested soils, compared to the check treatment without compaction.

***Conclusively,** according to the results, the application of PAM at rate of 0.5 g L^{-1} was recommended as a sustainable amendment.*

Keywords: Soil compaction, Polyacrylamide, Bulk density, Penetration resistance, Maize growth parameters.

INTRODUCTION

Soil compaction is a problem in modern agriculture, impacting soil health and crop productivity (Donde *et al.*, 2024; Majdoubi *et al.*, 2024). Consequences of soil compaction on plants include stunted plant root growth, reduced crop yields up to 50%, and altered soil properties. Researchers continue to explore sustainable approaches for reducing soil compaction. Soil compaction occurs due to many natural causes (*e.g.,* layer thickness, parent material, high clay percentage, environmental conditions and climate, the contraction of soil, and trampling or grazing (Shaheb *et al.,* 2021), and anthropogenic activities (*e.g.*, wheels and tracks, heavy machinery, intensive cropping, unsustainable soil management soil (Donde *et al.*, 2024; Majdoubi *et al.*, 2024; Shaheb *et al*., 2021).

Many factors control soil compaction such as heavy agricultural equipment, soil texture, soil moisture, tillage layer, tire type, and inflation pressure. Most studies have indicated negative impacts of soil compaction (*e.g.,* reduced soil porosity, infiltration rate, increasing surface ponding, runoff, soil erosion, reducing plant available water, and restricting root exploration for uptake of nutrients, while increasing soil compactness, Soil bulk density, penetration resistance, degree of compactness(Obour and Ugarte 2021; Guerin 2022), due to a reduction in soil porosity and permeability, and therefore reducing plant growth and yield**.**

Moreover, there are many studies indicating that soil compaction significantly decreases root growth (Bawa *et al.*, 2019), a notable decrease in the root growth of maize and yield in compacted soil due to different tractor passes (de Moraes *et al.*, 2019), indicated that a substantial decrease in crop yield was observed with higher levels of tractor traffic, reaching up to 50% in certain instances. Several strategies were applied to reduce the negative effect of soil compaction, such as the application of organic matter (Bawa *et al.*, 2019), or other organic wastes, as well as biochar, all of which increased macro-porosity and significantly decreased soil bulk density recently application of PAM.However, the challenge to alleviate soil compaction lies in the need to apply not only large quantities but also frequently due to their high decomposition rates compared to PAM, which serves as a sustainable tool (Ma *et al.* 2020).

Polyacrylamide (PAM) has distinct properties such as a wide range of modulus elasticity (Subramani *et al.*, 2020),amine (NH_2) and carbonyl (C=O) groups, which may form hydrogen bonds with the hydroxyl groups of cellulose(Aventian *et al.*, 2024; Halder *et al.*, 2018; Voronova *et al.*, 2020). In addition, PAM contains very few or no molecules with electric charge, which leads to a negligible impact on soil salinity (Aventian *et al.,* 2024). These properties of PAM improve soil physical, chemical, and biological characteristics such as soil aggregation, structure(Amalia *et al.* 2023; Aventian *et al.* 2024; El Idrissi *et al.* 2024), and soil porosity, adsorption of plant nutrients(Aventian *et al.*, 2024; Zhang *et al.*, 2024).

Therefore, this study aims to investigate the effects of polyacrylamide application on some properties of compacted soils and maize growth parameters.

MATERIALS AND METHODS

1. *The experimental site and treatments*

Soil samples were obtained from the surface layer (0.0 - 0.2m depth) at two different sites, The first location was at the Faculty of Technology and Development Farm latitude, 30°.56'72608"N, longitude, 31°.57'35592"E, and the second one at the Soil, Water and Environment Research Institute latitude, 30°.02'1147"N, longitude 31°.20'9455"E. The experiment zone is carried out at the Soil, Water and Environment Research Institute, greenhouse, Giza Governorate, Egypt (Latitude, 30°.021'9319"N, longitude 31°.210'8546,662"E) The Water and Environment Research Institute, Egypt. To investigate the effect of compaction strengths and various application rates of polyacrylamide on some growth parameters of maize (*Zea mays hybrids TWC-360*) in two investigated 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). The 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 polyacrylamide (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 in three replicates.

2. Compaction strengths and polyacrylamide application

The soil samples were processed, sifted, and filled into polyvinyl chloride columns (PVC) measuring 0.25m in height and 0.10m in 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 piton. Compression was performed at a moisture level of 23% for clayey soil and 16% for clay loam soil, based on the plasticity index. The soil bulk density 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 "Bluwat AA3515” was purchased from Yixing Bluwat Chemicals company, China.

Table (1): Initial characteristics of the two investigated soils.

Soil type	Clayey soil	Clay loam soil
Physical property		
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]	clay	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 property		
pH[2]	7.60	7.10
EC (dS m^{-1})[3]	2.17	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 water suspension (1:2.5); 3; EC was measured in soil paste extract

Sowing was done using maize seeds (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. Two weeks after planting, 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 levels (0-0.05, 0.05-0.1, and 0.1-0.15m). Milling, sieving, and coding soil layers for physical and chemical attributes.

3. Soil physio-chemical analyses and measurements:

Particle size distribution was determined using a hydrometer protocol. We utilized the core and pycnometer protocols to determine the BD, and particle density (PD), respectively (Estefan *et al.*, 2013). The following equations calculated Reference Bulk Density (RFB), and degree of compactness (DC) (Reichert *et al.*, 2009).

$$\mathbf{RFB = -0.00033 \times clay + 1.91655} \qquad \mathbf{Eq.1}$$

$$\mathbf{DC = \frac{Soil\ bulk\ density}{Reference\ bulk\ density} \times 100} \qquad \mathbf{Eq.2}$$

Clay; clay content (g kg^{-1}); RFB (g cm^{-3}).

Penetration resistance, the soil penetration resistance was measured at three varied layers (0.0٠-0.05m), (0.05-0.1٠m), and (0.1٠-0.15m). It was measured at three varied moisture levels (PR^1 at 30%, and 22% = felid capacity; PR^2 at 23%, and 16% = plasticity index; and PR^3 at 19%, and 9% for clayey soil and clay loam soil, respectively). The penetration resistance of the soils was determined using a Japanese cone penetrometer , models SR-2Disk5500 to determine the average soil penetration resistance (PR) according to (Marey *et al.*, 2023).

$$\mathbf{PR = \frac{10 \times F}{A}} \qquad \mathbf{Eq.3}$$

F; denotes the required strength (N), and A; denotes the cone area (cm^2).

Mean Weight Diameter (MWD) and Geometric Weight Diameter (GMD) were calculated below equations (Youker & McGuinness, 1957) and the water stability of large aggregates was calculated as follows.

$$\mathbf{MWD = \left[\frac{\sum_{i=1}^{n}(x_i w_i)}{\sum_{i=1}^{n}(w_i)}\right]} \qquad \mathbf{Eq.4}$$

$$\mathbf{GWD = Exp\left[\frac{\sum_{i=1}^{n}(w_i \ln x_i)}{\sum_{i=1}^{n}(w_i)}\right]} \qquad \mathbf{Eq.5}$$

w_i; weight of the aggregate; n; number of sieves; x_i; the mean diameter of aggregates of each sieve size.

A sensitivity index (SI) was calculated to measure the influence of the PAM application rates on the MWD and GMD in the investigated soil mechanical impedance compared to the check treatment as proposed by (Bolinder *et al.*, 1999).

$$SI = \frac{As}{Ac} \qquad \text{Eq.6}$$

As; The MWD or GMD values of each layer exposed to each aqueous PAM solution, and Ac; the GMD or MWD values of investigated soils in the check treatment.

The plasticity index (PI), and hydraulic conductivity coefficients (HCC). Soil acidity (pH) was measured in water suspension (1:2.5) using a pH meter. Organic matter (OM) was quantified using a wet oxidation technique (H_2CrO_7), and calcium carbonate ($CaCO_3$) was determined using back-titration. The soluble calcium and magnesium (Ca^{2+} and Mg^{2+}) were determined by titrating with $EDTANa_2$. Extractable- Nitrogen (N) was extracted using K_2SO_4 and determined by the Kjeldahl method. Electrical conductivity (EC) was also measured using an EC-meter in soil paste extracts. Soil Olsen-Phosphors (P) were measured using a colorimetric method with 0.5M $NaHCO_3$. Potassium (K) was measured using a flame photometer, whereas the extractable-K from the soil was extracted with 1M NH_4OAc. All aforementioned analytical methods were performed as described (Estefan *et al.*, 2013). It 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, the identification of the most probable phases is carried out using an analytical computer-certified program with the aid of the International Center of Diffraction Database (Imad EL-Ddin 2022).

4. Plant growth parameters and NPK contents

Some growth parameters were measured in maize shoot and root parts, as well as the stem length, stem diameter, and leaf space guide. Moreover, leaf area (LA) was calculated by the below equation (Miralles & Slafer, 1991).

$$LA = LW.835 \qquad \text{Eq.7}$$

L and W represent leaf length and width, respectively. The leaf space guide (LSG) was calculated according to (Coombs et al., 1985). Root length density (RL), specific root length (SRL), and fresh and dry weight, as well as root lengths, were calculated by the Newman method. The total length of the roots can be estimated according to Newman (Fageria, 2012; Newman, 1966). Root length density (RLD), and Specific root length (SRL) can be estimated according to (Fageria, 2012).

Maize samples were dried at 70°C for five days and weighed on a sensitive Metler balance, and dry mass was determined. Also, wet-digested using a mixture of sulfuric acid and hydrogen peroxide at 420°C for chemical analyses. Total-N, P, and K shoots and roots were determined using the Kjeldahl, colorimetric, and flame photometer methods, respectively (Estefan *et al.*, 2013).

5. *Statistical analysis*

A 5% significance level was used to compare means based on the least significant difference (LSD 0.05) using the COSTAT software package.

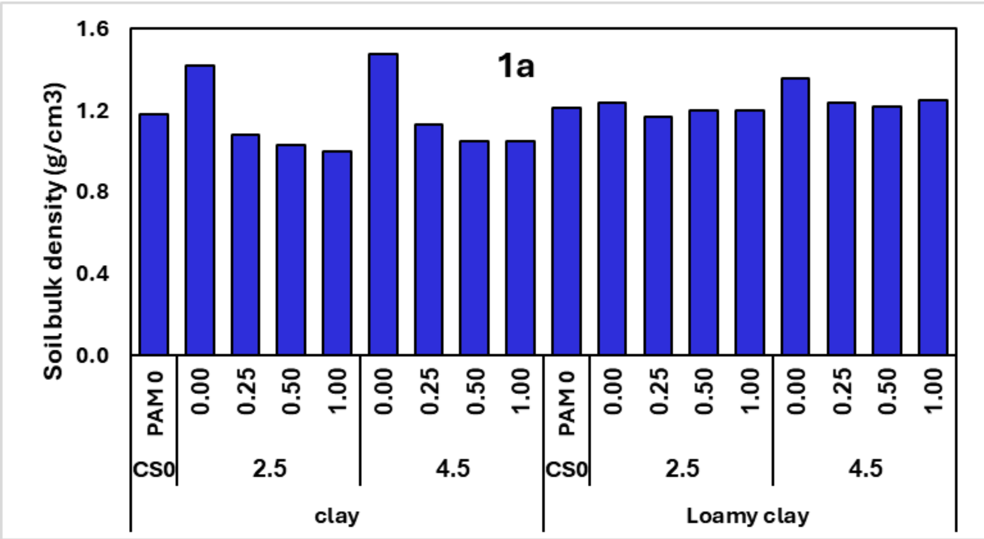
RESULTS AND DISCUSSION

1. *Bulk densities (BD) and degree of compactness (DC)*

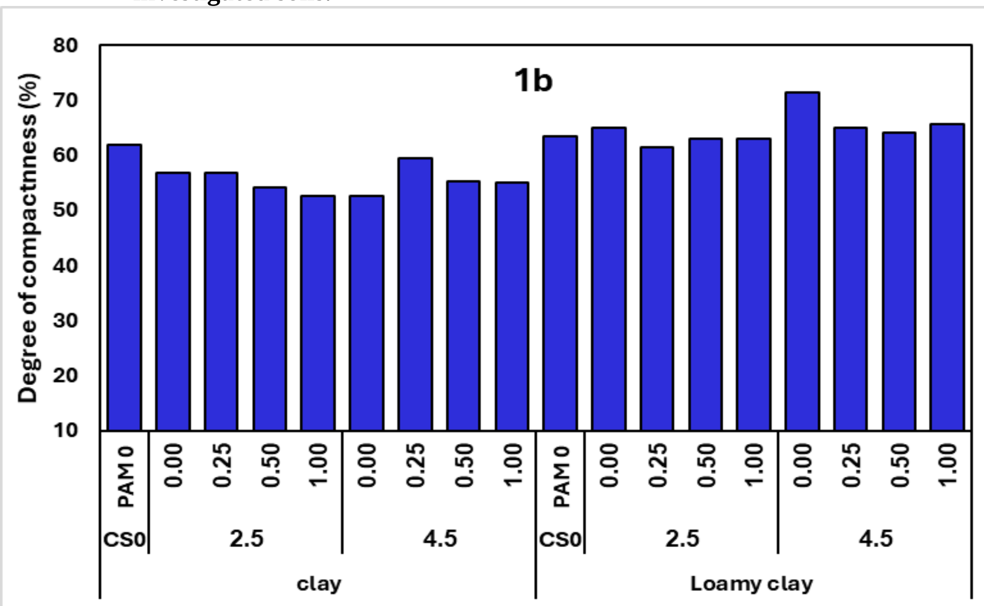
Based on the obtained results, soil bulk densities exhibited an increase due to soil compaction, while the application of polyacrylamide led to a decrease in soil bulk densities (Figure.1a). Soil bulk densities of the initial basic soils were 1.18 and 1.21 g cm^{-3} for clayey and clay loam soils, respectively. There was an increase in soil bulk density due to decreasing porosity. For clayey soil, percentages of increase were 20.34% and 25.42% for the 2.5kg and 4.5kg rammers, respectively. The increases were 2.48% and 12.40% for the 2.5kg and 4.5kg rammers, respectively, compared to the check treatment in clay loam soil. After PAM application, soil bulk densities in clayey soil decreased by -8.47%, -12.71%, and -15.25%, while in clay loam soil, the decreases were -3.31%, -0.83%, -0.83%, and -0.83% for the CS2.5PAM0.25, CS2.5PAM0.5, and CS2.5PAM1 treatments, respectively, compared to the check treatment. This unequivocally demonstrates that soil compaction leads to a decrease in soil porosity and consequently results in higher soil bulk densities in both soils under investigation. However, the introduction of polyacrylamide resulted in enhanced soil bulk densities, particularly at a rate of 1 g L^{-1}. This improvement is attributed to the increased porosity percent caused by an increase in soil aggregates. Based on the results mentioned above, the soil BD increases with the increase in compaction strength, and the porosity of the soil decreases. Therefore, the degree of compaction increases accordingly.

In addition, by applying polyacrylamide, the values of BD in the tested soil generally improved, and the lowest bulk density values were 1gcm^{-3} for 1 g PAM L^{-1} in the clayey soil, while clay loam soil recorded 1.17 g cm^{-3} for 0.25 g PAM L^{-1}. This can be attributed to the PAM application improving soil aggregation, depending on the applied rate, the applied compaction strengths, and the variation in texture of the tested soils. Similar results were obtained by (Nawaz *et al.*, 2023). Concerning polyacrylamide application and their influences on soil BD results, (Figure. 1b) also illustrates that, for different tested soils, the 1 g PAM3 L^{-1} treatment was superior to other treatments for reducing soil BD compared to the check treatment (El-Maslamany *et al.*, 2020). Based on the results, soil bulk densities increased due to soil compaction, whereas applying PAM decreased BD values (Figure. 1a). The soil bulk densities 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 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 (Figure. 1b). 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 (El-Maslamany *et al.*, 2020; Nawaz *et al.*, 2023).



Figure(1a): Effect of polyacrylamide (PAM) application on soil bulk density in the two investigated soils.



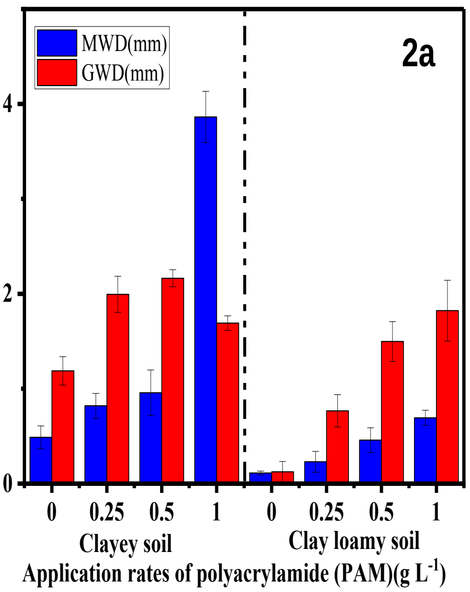
Figure(1b): Effect of polyacrylamide (PAM) application on the degree of compactness in the two investigated soils.

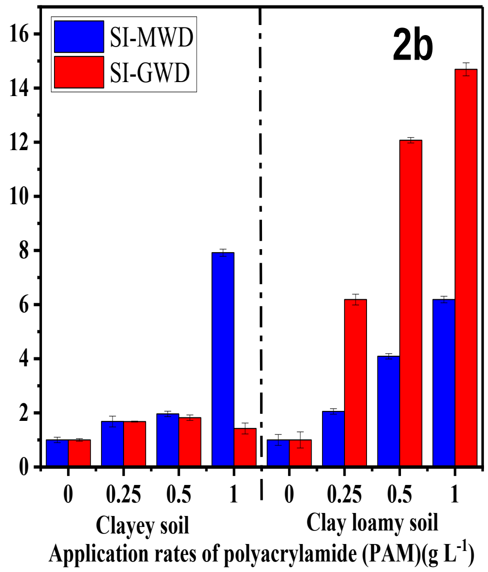
2. Mean weight diameter (MWD), Geometric weight Diameter (GWD), and Sensitivity Index (SI)

Figure 2a illustrates the correlation between PAM application rates and the mean weight diameter (MWD) and geometric weight diameter (GWD) of the soils under investigation. The mean weight diameter (MWD) for clayey soil was 0.49, 0.82, 0.96, and 3.86mm, meanwhile for 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. The GWD values for clayey soil were 1.19, 1.99, 2.16, and 1.69, whereas, for clay loam soil, they were 0.12, 0.77, 1.50, and 1.82, all at the same application rates of PAM.

The sensitivity index (SI) assesses whether the GMD or MWD values of soil treated with PAM vary from those in the check treatment. The results are shown in (Figure. 2b), SI calculated based on MWD and GWD, demonstrate the SI values of the impactful effect of PAM at its applied rates on enhancing the stability of aggregates in the examined soils. When (SI) is more than one, it indicates an enhancement in the aggregate stability of the soil. The SI values in the clayey soil were 1, 1.7, 2, and 7.9, whereas the clay loam soil had PAM values recorded 1, 2.1, 4.1, and 6.2 for PAM application rates of 0.00, 0.25, 0.50, and 1.00g PAM L^{-1}, respectively. There is a similar trend in SI values calculated based on GWD (Figure. 2b). In the clayey soil, values were 1, 1.7, 1.8, and 1.4, whereas in clay loam soil, it was 1, 6.2, 12.1, and 14.7. Additionally, the application of PAM had a beneficial role on the MWD and GWD and a clear effect that is felt in the aggregate stability. In addition, it had a positive effect on maintaining the ability to penetrate resistance to compaction strength in the two investigated soils. Moreover, the highest values of MWD were 3.6, and 0.69 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. We find that the MWD and GWD increase with increasing PAM application rates.

This undoubtedly proves that the application of PAM improves soil aggregation, soil porosity, and ability to adsorb nutrients and reduces the effect of soil compaction(Amalia *et al.* 2023; El Idrissi *et al.* 2024).PAM application contributes to soil improvement by creating a cement-like effect. This occurs when the long-chain PAM molecules attach themselves to soil particles, primarily on the outer surfaces of these particles, which enhances soil aggregate and stability, and hydraulic conductivity (Aventian *et al.*2024) due to the capacity to link soil particles that are widely spaced, hence enhancing the soil aggregate stability, shear strength and aggregates stability.





Figure(2a): Effect of polyacrylamide (PAM) application on Mean weight diameter and Geometric weight diameter (GWD) (MWD) in the two investigated soils.

Figure (2b): Effect of polyacrylamide (PAM) on sensitivity index (SI) calculated based on mean weight diameter and Sensitivity geometric weight diameter in the investigated soils.

3. Penetration resistance (PR)

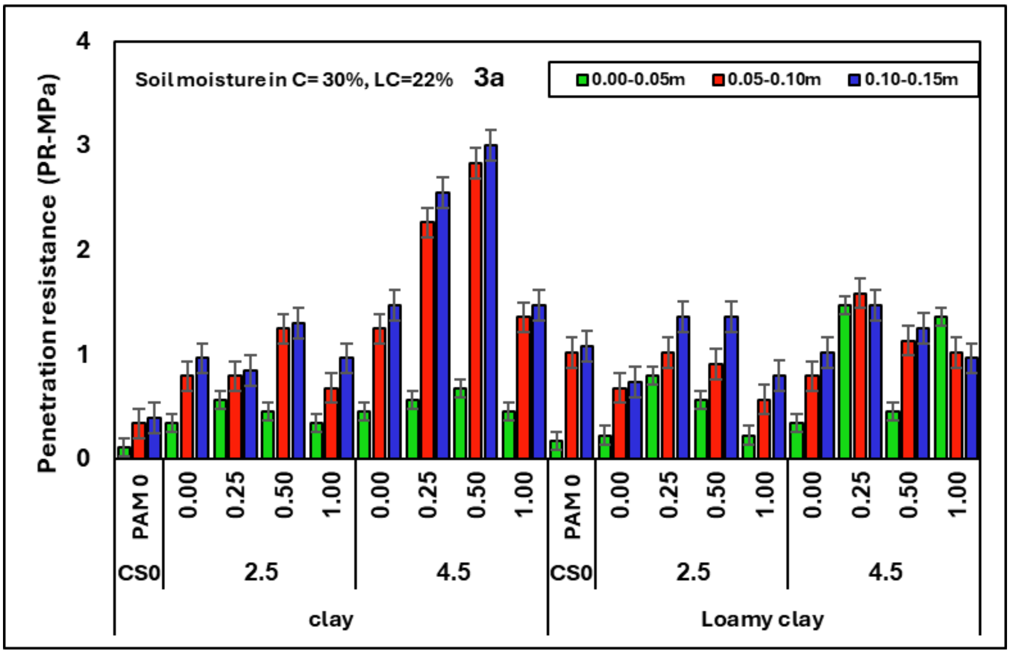
Figures 3a, 3b, and 3c showed PR values. The PR values exhibit an upward trend with increasing compaction strength, whereas they show a downward trend with increasing moisture content in both soils. The PR^1 in the successive clayey soil layers ranged from 0.11 to 0.68, 0.34 to 2.83, and 0.4 to 3.00 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 levels, respectively. In clay loam soil, PR^1 ranged from 0.17 to 1.47, 0.57 to 1.59, and 0.74 to 1.47 MPa in the successive layers, respectively (figure 3a). The PR^1 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 levels. The range of PR^2 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 PR^2 range was 0.68 to 1.81, 1.02 to 2.49, and 1.21 to 3.40MPa, respectively. The PR^3 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 1g PAM L^{-1} rates. In contrast, compaction strengths enhanced PR, especially in the subsurface layer of the soils. Our result found that the PR values exceeded the 3 MPa threshold at soil levels less than 15 cm. A PR value of 2 MPa is often regarded as a key threshold that restricts the development of roots Da Silva *et al.* (1994). Consistent with the results of this investigation, low levels of moisture resulted in greater PR values compared to the often-reported critical values (Botta *et al.*, 2016).In addition, the angle of internal friction in soil increases as the moisture level decreases due to factors such as compression around and beneath the penetrometer tip, which is particularly significant under low moisture contents, and the reliance penetration force on soil density (Botta *et al.*, 2016).

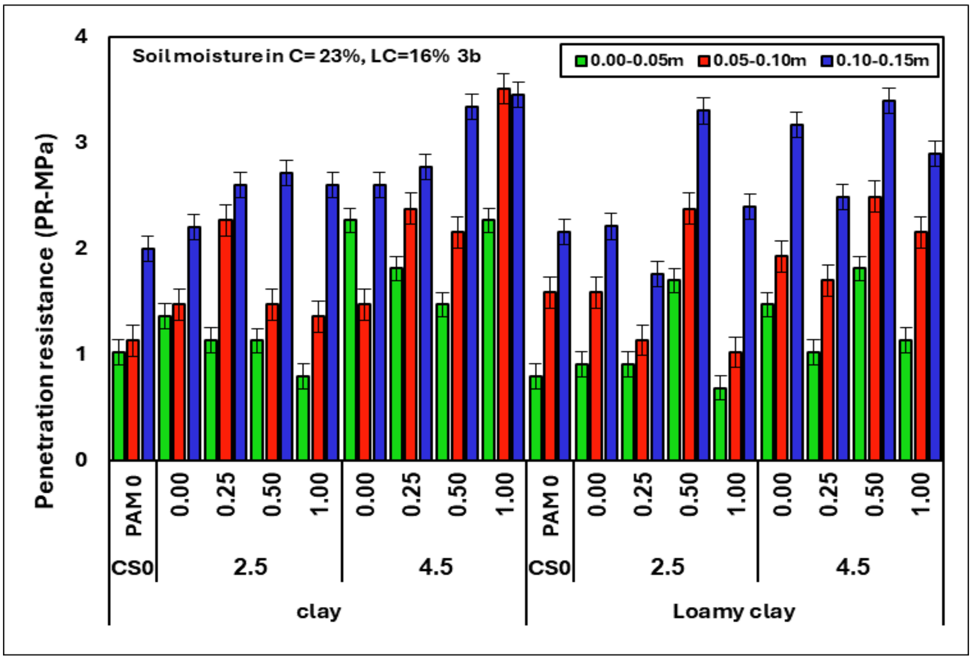
In addition to the significant effects of BD, humidity contents, and types of soil texture, the interaction between soil and cone penetrometer may have an impact on the PR values. Therefore, it is important to not just rely on PR values, especially the often-cited critical value, when assessing the effect on plant development, since the actual harm to plant roots may be lower than what these values indicate. However, delving deeper than only PR values, PR profiles may aid in evaluating the total environmental circumstances in which the root is developing (Nawaz *et al.*, 2023). 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. Correlation analysis generally demonstrated a negative correlation of BD or PR (in 0.10 m layers) with growth parameters and root distribution variables, and these relationships were accentuated for BD and PR in the upper three 0.1m layers, especially 0.1-0.15m layer and these results are consistent with (Nawaz *et al.*, 2023).

Compression-induced changes in bulk density (BD) and penetration resistance (PR) might impede optimal root development (Reichert *et al.*, 2016). The findings of (Reichert *et al.*, 2016) are consistent with our results since they also observed reduced root parameters as a consequence of increased soil bulk density (BD) and penetration resistance (PR). The presence of larger diameter pores is lacking in compacted soil layers, resulting in excessive mechanical impedance and insufficient oxygen supply. This leads to a higher concentration of roots in upper soil layers and reduced rooting in deeper layers. Moreover, the distribution of root length was concentrated in the upper layers, up to a depth of 0.30m. This highlights the importance of avoiding compaction of the topsoil, even if there is no compaction in the subsurface.

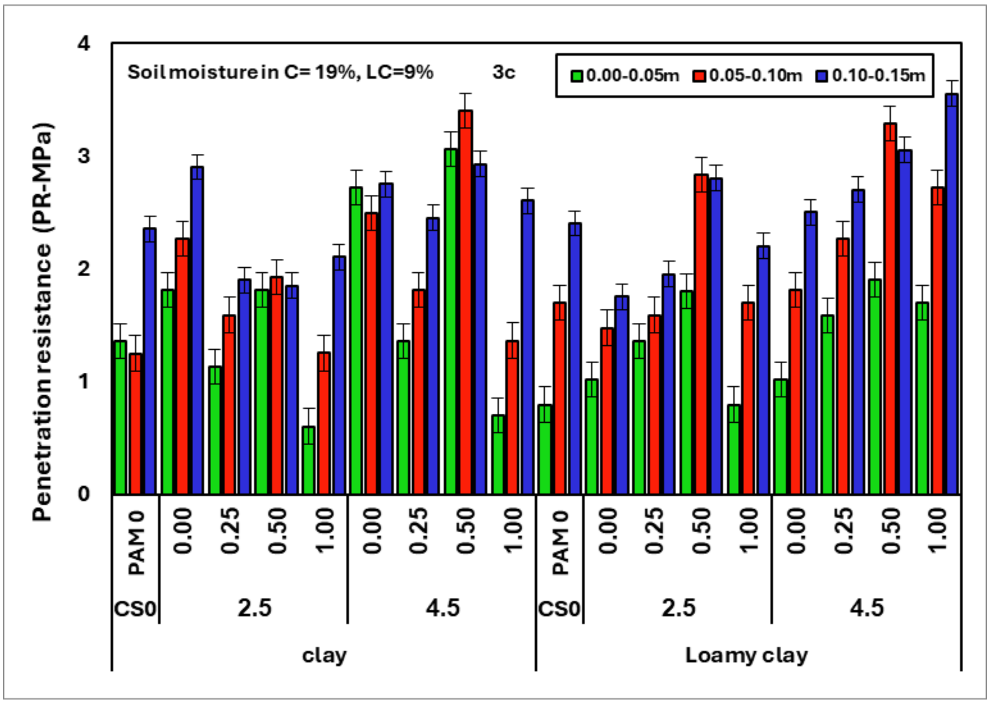
Soil compaction inhibits root development, which in turn negatively impacts shoot growth and crop yield. Furthermore, soil bulk density (BD) in the topsoil and the PR indices showed substantial correlations with a range of plant factors, such as growth parameters and grain production. In addition, the connection between root dry matter, root length, and grain production with bulk density (BD) and penetration resistance (PR) is strongly negative.



Figure(3a): Effect of polyacrylamide (PAM) application and compaction strengths on penetration resistance (PR) at soil moisture in Clay soil = 30%, Loamy Clay soil =22% in the two investigated soils.



Figure(3b): Effect of polyacrylamide (PAM) application and compaction strengths on penetration resistance (PR) at soil moisture in Clay soil = 23%, Loamy Clay soil =16% in the two investigated soils.



Figure(3c): Effect of polyacrylamide (PAM) application and compaction strengths on penetration resistance (PR) at soil moisture in Clay soil = 19%, Loamy Clay soil = 9% in the two investigated soils.

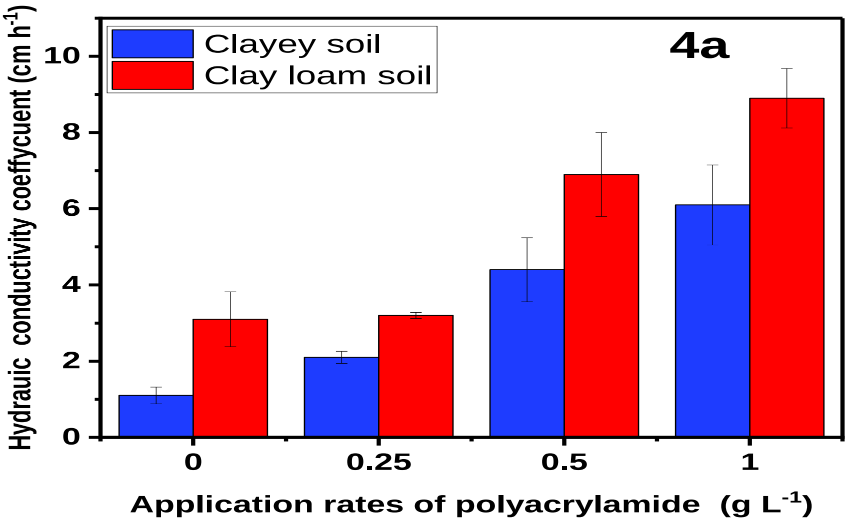
4. *Hydraulic conductivity coefficient (HCC), Plastic Index (PI), Liquidity Limit (LL), Plasticity Limit (PL), and X-Ray analysis*

Application of PAM resulted in an increase in hydraulic conductivity coefficients (HCC) in the tested soils (Figure. 4a). The results demonstrated a direct correlation between the application of PAM and a gradual increase in HCC. The hydraulic conductivity values (HCC) in the clayey soil were 1.1, 2.1, 4.4, and 6.1 cm.h^{-1} for PAM application rates of 0, 0.25, 0.50, and 1.00 g L^{-1}, respectively. Similarly, in clay loam soil, HCC values were 3.1, 3.2, 6.9, and 8.9 cm h^{-1} for the treatments mentioned earlier. The positive impact of PAM application on enhancing the physical characteristics of compacted soils is very clear. This is demonstrated by the decrease in the plastic index (PI), liquidity limit (LL), and plasticity limit (PL)with each incremental addition of PAM to clayey soil. (Figure. 4b) presents obtained results that reveal the physical characteristics of the investigated soils when PAM is applied at rates of 0.00, 0.25, 0.50, and 1.00g PAM L^{-1}. The PI exhibited a decrease of 23, 20, 17, and 15%, respectively, in clayey soil. In contrast, clay loam soil exhibited values of 16, 11, 7, and 5%, respectively, for the rates mentioned above of PAM application. In addition, the application of PAM resulted in a decrease in the LL. For clayey soil, they were 30%, 28%, 25%, and 23%, whereas in clay loam soil, they were 27%, 17%, 18%, and 18%. Moreover, the PL in clayey soil was recorded at 53%, 48%, 42%, and 38%. Throughout clay loam soil, it was recorded at 43%, 28%, 25%, and 23% for the previously mentioned treatment, respectively.

Figure 4c presents the X-ray diffraction patterns of the tested soil samples. Quartz peaks are present in two tested soil samples, whereas albite and calcite peaks are found in varying amounts. The peaks of quartz, albite, calcite, and some other minerals are visible in clay loam soil. Microcline, albite, and some minerals, including illite, feldspar, and smectite, appeared in clayey soil. Many minerals are found in clayey soil i.e., smectite, illite, chlorite, albite, quartz, calcite, microcline, and feldspar. In clay loam soil, quartz, albite, microcline, and calcite were most found in X-ray analysis. In general, clayey soil contains a higher proportion of clay minerals. In addition, the results obtained presented in peaks of X-ray diffraction (Figure. 4c) illustrated some chemical and physical properties of the tested soils.

There were clear differences in soil texture of investigated soil (sand, silt, and clay), where the clayey soil recorded a percentage of 16.4, 37.4, and 42.2%, whereas the clay loam soil recorded 30.3, 35.2, and 34.5%. Clayey soil exceeds the percentage of clay over the clay loam soil by 11%. The difference in the percentage of clay minerals had a clear effect on some chemical and physical properties. These results are very similar to the results of the peaks X-ray chart (Imad EL-Ddin 2022). Therefore, the clayey soil contained more minerals than clay loam soil, and this was reflected in the soil properties and maize growth parameters in the clayey soil compared to the same properties and parameters in the clay loam soil under the influence of all treatments.

In another hand, HCC exhibited greater values in the PAM application compared to the check treatment (CS0PAM0), whereas the plastic index, liquidity limit, and plasticity limit values in the PAM application were smaller than in the check treatment. In addition, these results show that the destruction degree of soil aggregates in the two investigated soils was lower in the plot treated with the PAM application than in the check treatment in terms of dissipation, clay disintegration, and mechanical disturbance, which shows that PAM could increase the stability of soil aggregates and enhance soil anti-erodibility (Wang *et al.*, 2023). The content of water-stable aggregates was increased after the PAM application. This result is also consistent with previous studies (Abu-Hamdeh *et al.*, 2019; Sadeghi *et al.*, 2020) which indicate that PAM improves soil aggregate formation via the cohesion of adjacent particles. Furthermore, the results indicate that the level of soil aggregate destruction was lower in the plot treated with PAM application compared to the check treatment, specifically in terms of dissipation, clay disintegration, and mechanical disturbance. This suggests that PAM has the potential to enhance the stability of soil aggregates and improve soil resistance to erosion (Wang *et al.*, 2023). The presence of water-stable aggregates significantly increased after the application of PAM. This finding aligns with prior research conducted by (Abu-Hamdeh *et al.*, 2019; Sadeghi *et al.*, 2020), which suggests that PAM enhances the development of soil aggregates by promoting the cohesion of



Figure(4a): Effect of polyacrylamide (PAM) application on hydraulic conductivity coefficient (HCC) in the two investigated soils.

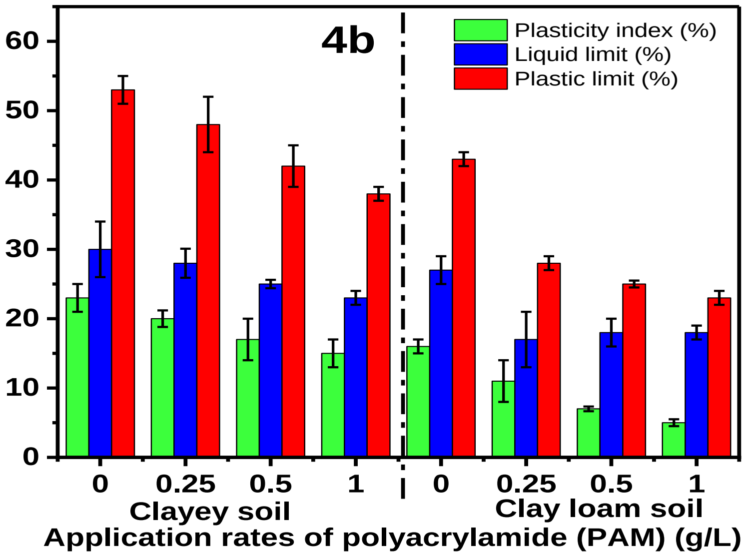


Figure (4b): Effect of polyacrylamide (PAM) application on plasticity index, liquid, and plastic limit in the two investigated soils.

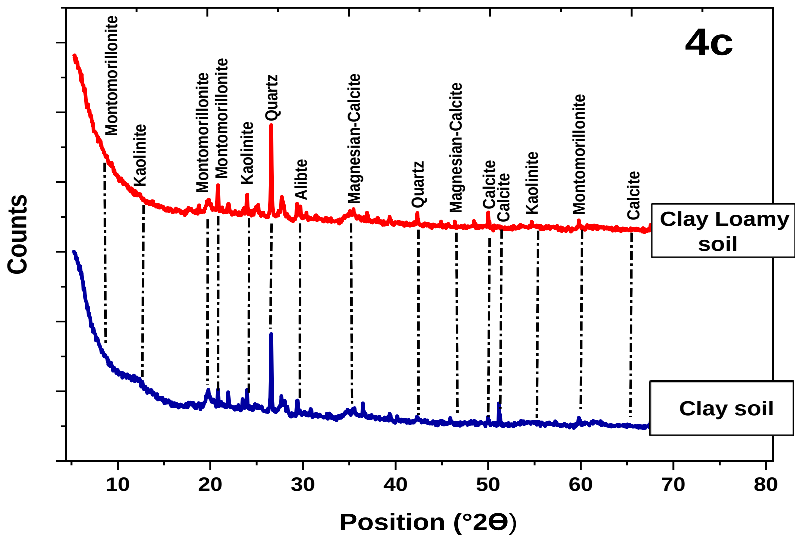


Figure (4c): X-ray pattern of the two investigated soils before polyacrylamide application.

adjacent particles. 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 a result, strong, water-stable aggregates are formed (Albalasmeh *et al.*, 2021).

5. *Some maize growth parameters and N, P, and K contents in maize shoots and roots*

The averages of some maize growth parameters (maize roots and shoots) varied according to the studied factors (polyacrylamide application or compaction strengths) in both tested soils.

In general, results presented in (Table 2) indicate statistically significant differences in germination percentage, maize stem diameter, stem lengths, leaf space guide, root length, and maize biomass (shoot and root weights). The parameters above confirm that the clayey textured soils recorded greater averages than the clay loam soil. Germination percentage significantly varied depending on the soil type. It recorded 86.42% and 77.78% in the clayey soil and clay loam soil, respectively. The CS ٠.٥PAM٢.٥treatment had the highest value in stem length and diameter as well as maize biomass yield, and it recorded 23.17cm, 1.12cm, and 7.35g/pot, respectively. On the other hand, clayey soil generally had the highest values in most measured maize growth

Table (2): Effect of soil compaction with different strengths and polyacrylamide (PAM) application rates on some maize growth parameters in the two tested soils.

Treatments	G (%)	SL (cm)	SD (mm)	LSG	SDW(g)	RDW(g)	RL (cm)	BY(g)
CS0.0PAM0.00	83.33^{ab}	22.33^{a}	1.00^{ab}	2.01^{a}	5.21^{a}	1.35^{b}	17.17^{ab}	6.56^{ab}
CS2.5PAM0.00	83.33^{ab}	18.67^{ab}	0.99^{ab}	1.69^{ab}	4.89^{a}	0.98^{b}	16.75^{ab}	5.89^{bc}
CS2.5PAM0.25	83.33^{ab}	18.67^{ab}	0.98^{ab}	1.63^{ab}	3.03^{b}	1.05^{b}	16.17^{ab}	5.75^{bc}
CS2.5PAM0.50	94.44^{a}	23.17^{a}	1.12^{a}	2.24^{a}	5.89^{a}	1.87^{a}	18.08^{a}	7.35^{a}
CS2.5PAM1.00	66.67^{b}	20.08^{ab}	0.93^{b}	1.89^{ab}	3.88^{b}	1.46^{b}	9.17^{d}	4.08^{d}
CS4.5PAM0.00	77.78^{ab}	15.33^{b}	0.84^{b}	1.06^{b}	3.76^{b}	1.00^{b}	14.67^{b}	4.74^{cd}
CS4.5PAM0.25	83.33^{ab}	19.75^{ab}	0.93^{b}	1.33^{ab}	3.49^{b}	1.32^{b}	14.33^{b}	4.81^{cd}
CS4.5PAM0.50	83.33^{ab}	18.58^{ab}	1.01^{ab}	1.53^{ab}	3.24^{b}	1.36^{b}	14.58^{b}	4.60^{cd}
CS4.5PAM1.00	83.33^{ab}	18.33^{ab}	0.88^{b}	1.75^{ab}	2.92^{b}	1.13^{b}	11.67^{c}	4.05^{d}
LSD 0.05	**16.18**	**3.82**	**0.11**	**0.56**	**0.84**	**0.33**	**1.92**	**0.95**
Soil type								
Clayey soil	86.42^{ns}	24.00^{a}	1.04^{ns}	2.20^{a}	5.22^{a}	1.38^{ns}	16.76^{a}	6.60^{a}
Clay loam soil	77.78^{ns}	14.87^{b}	0.89^{ns}	1.16^{b}	2.84^{b}	1.18^{ns}	12.70^{b}	4.03^{b}
LSD 0.05	**NS**	**4.48**	**0.15**	**0.91**	**0.23**	**NS**	**3.34**	**0.37**
Interaction								
Soil (S)	NS	Sig.	NS	Sig.	Sig.	NS	Sig.	Sig.
Treatments (T)	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
S×T	NS	Sig.	Sig.	NS	Sig.	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). G is germination percentage, SL is stem length, SD is stem diameter, LSG is leaf space guide, SDW is shoot dry weight, RDW is root dry weight, RL is root length, and BY is biomass yield (root+ shoot).

parameters. In contrast, the clay loam soil had the lowest values of the parameters mentioned above.

Maize root growth parameters were generally affected by increasing in polyacrylamide rates. The CS2.5 PAM0.5 treatment recorded the highest values in root dry weight and weight of roots in the first layer, and these values were 1.87 and 4.66g (Tables 2 and 3). In contrast, the CS۰.۵PAM۲.۵ treatment recorded the highest values in the weight of maize root in the second and third layers as well as in root length. These values were 2.09, 1.34g, and 18.08cm, respectively and 13.55%, respectively, calculated based on the check treatment.

In general, the superior treatment was CS2.5PAM0.5 treatment, which resulted in applying polyacrylamide at a rate of 0.5 g L^{-1} with compaction of 2.5kg rammer (Table 3). The increases in root lengths, root lengths in successive layers, total root lengths, root length density, and specific root length ranged from 5.29, 5.51, 4.99, 12.88,7.01, 7.40, 57.09%, respectively, calculated based on the check treatment. It was found that increasing polyacrylamide 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 were the highest values compared to the clay loam soil. The results indicate that PAM is an amendment in soil properties, PAM has a large molecular chain, making it suitable for many applications such as thickening, binding, flocculating, and amending soil (Li *et al.*, 2022).

PR is well-known for evaluating mechanical impedance to root development(De Lima et al. 2016)In our study, PAM application led to enhanced maize growth parameters in the two investigated soils.

In another hand, the N, P, and K contents of maize shoots and roots were affected by increasing soil compaction (Table 3). The N content of shoots and roots ranged from 1.72 to 2.62 and 0.36 to 0.66, respectively. The (CS2.5PAM1) treatment resulted in the highest N content in the shoot component 2.62%whereas the highest value of N content in roots was 0.66% for the (CS2.5PAM0.5) treatment. The P content in maize shoots and roots ranged from 0.10 to 0.14% and 0.09 to 0.07. The highest P content of maize shoots and roots was (CS2.5PAM0.5) treatment. Additionally, the K content in maize shoots and roots ranged from 3.28 to 2.19%, and 3.95 to 1.63%, respectively. The highest K value of maize shoots and roots was (CS2.5PAM0.5) treatment. In general, they were superior in most of the N, P, and K contents of the clay loam soil compared to the clayey texture, without any statistical significance except for the K content of maize shoots in the soils. The N, P, and K contents of maize shoots were always the highest values compared to the root contents for the same nutrients.

The findings demonstrated a notable disparity contingent upon the soil composition. These improvements of the studied soils were significantly improved. These improvements were reflected in the improvement of some maize growth measurements 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}. In another hand, even when there is no lack of nutrients or water, mechanical impedance may impede plant growth. This was shown in studies where root growth was mechanically hampered, resulting in lower leaf elongation. Therefore, we deduce that changes in soil properties caused by traffic have an impact on the growth and distribution of roots, which in turn affects the ability of crops to absorb and use nutrients and water from the soil through their roots. This ultimately leads to a negative effect on the overall growth of crops and the amount of grain produced in fields that experience traffic Based on root dispersion and ocular observations, our research showed that maize developed its roots more fully in deeper soil layers, even when there was only mild soil compaction with PAM application.

Table (3): Effect of soil compaction with different strengths and polyacrylamide (PAM) application rates on some maize root parameters and nutrient N, P, and K contents in shoot and root maize grown in the investigated soils.

Treatments	Root fresh weight (g) First layer	Root fresh weight (g) Second layer	Root fresh weight (g) Third layer	Root length (cm) First layer	Root length (cm) Second layer	Root length (cm) Third Layer	Total root length (cm)	Root length density (cm)	Specific root length ($cm\ g^{-1}$)	N (%)		P (%)		K (%)	
					Calculated based on the Newman method					Shoot	Root	Shoot	Root	Shoot	Root
CS0.0PAM0.00	3.49^{b}	1.86^{ab}	1.18^{ab}	191.33^{ab}	127.10^{a}	106.63^{b}	367.27^{ab}	0.27^{ab}	262.82^{ab}	2.00^{bc}	0.54^{ns}	0.14^{a}	0.07^{ab}	2.78^{b}	3.53^{b}
CS2.5PAM0.00	3.61^{b}	1.96^{ab}	0.72^{bcd}	182.36^{b}	105.04^{b}	83.84^{c}	293.06^{c}	0.26^{b}	283.92^{ab}	2.02^{bc}	0.47^{ns}	0.12^{b}	0.08^{ab}	2.29^{bc}	2.75^{c}
CS2.5PAM0.25	3.16^{bcd}	2.04^{a}	0.60^{cd}	146.56^{cd}	110.40^{b}	81.38^{c}	339.94^{b}	0.25^{b}	286.79^{ab}	2.32^{b}	0.55^{ns}	0.13^{ab}	0.08^{ab}	2.43^{bc}	2.68^{c}
CS2.5PAM0.50	4.66^{a}	2.09^{a}	1.34^{a}	201.88^{a}	133.45^{a}	120.37^{a}	393.03^{a}	0.29^{a}	412.89^{a}	2.07^{bc}	0.66^{ns}	0.14^{a}	0.09^{a}	3.28^{a}	3.95^{a}
CS2.5PAM1.00	2.86^{b}	2.07^{a}	0.47^{de}	151.90^{c}	82.43^{c}	57.70^{d}	354.69^{b}	0.25^{b}	247.83^{b}	2.62^{a}	0.36^{ns}	0.11^{b}	0.07^{b}	2.29^{bc}	3.50^{b}
CS4.5PAM0.00	1.51^{e}	0.96^{d}	1.16^{ab}	130.91^{d}	79.77^{c}	16.88^{e}	269.61^{c}	0.21^{c}	201.17^{b}	1.72^{c}	0.71^{ns}	0.10^{c}	0.06^{b}	2.19^{c}	1.63^{d}
CS4.5PAM0.25	2.64^{d}	1.21^{cd}	1.00^{abc}	154.35^{c}	78.64^{c}	55.36^{d}	288.35^{c}	0.21^{c}	226.48^{b}	2.19^{bc}	0.59^{ns}	0.13^{ab}	0.07^{b}	2.28^{bc}	1.66^{d}
CS4.5PAM0.50	3.31^{bc}	1.46^{bc}	0.82^{bcd}	133.32^{d}	65.12^{c}	65.55^{d}	342.57^{b}	0.20^{c}	280.34^{ab}	2.11^{bc}	0.43^{ns}	0.13^{ab}	0.07^{b}	2.33^{bc}	2.95^{c}
CS4.5PAM1.00	2.55^{d}	1.75^{ab}	0.17^{e}	129.00^{d}	62.20^{c}	56.52^{d}	261.44^{c}	0.19^{c}	345.04^{ab}	2.02^{bc}	0.50^{ns}	0.13^{ab}	0.07^{ab}	2.19^{c}	1.94^{d}
LSD 0.05	**0.46**	**0.37**	**0.33**	**15.17**	**15.64**	**12.12**	**27.26**	**0.02**	**100.92**	**0.29**	**NS**	**0.01**	**0.01**	**0.34**	**0.36**
Soil type															
Clayey soil	3.67^{a}	2.55^{a}	1.30^{a}	196.78^{a}	133.85^{a}	112.05^{a}	442.68^{a}	0.32^{a}	346.64^{ns}	2.19^{ns}	0.48^{ns}	0.13^{ns}	0.07^{b}	2.54^{ns}	2.76^{ns}
Clay loam soil	2.50^{b}	0.88^{b}	0.35^{b}	119.13^{b}	53.74^{b}	31.11^{b}	203.98^{b}	0.15^{b}	219.42^{ns}	2.05^{ns}	0.58^{ns}	0.13^{ns}	0.08^{a}	2.37^{ns}	2.71^{ns}
LSD 0.05	**0.04**	**0.2**	**0.22**	**12.97**	**21.76**	**2.26**	**12.83**	**0.01**	**NS**	**NS**	**NS**	**NS**	**0.01**	**NS**	**NS**
Interaction															
Soil (S)	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	NS	NS	NS	NS	Sig.	NS	NS
Treatments (T)	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	NS	Sig.	Sig.	Sig.	Sig.
S×T	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.

Three compaction forces (CS) CS0(0.9Kg rammer), CS2.5(2.5Kg rammer), CS4.5(4.5Kg rammer),Four polyacrylamide (PAM) levels (0.00,0.25,0.50,1.00g PAM L^{-1}.

Conclusion

In this study, we compared the effects of the different application rates of the PAM amendment on some physio-chemical properties of the investigated-compacted soils and the growth of roots and shoots parameters for maize plants as an indicator. The PAM amendments led to positive impacts on some properties of the investigated soils, such as BD, PR, MWD, GWD, PI, LL, PL, and HCC. Consequently, the PAM application provided better effects for soil mechanical impedance conditions and maize growth that resulted in larger biomass yields than the check treatment.

In addition, the interaction of PAM application and compaction strengths had significant effects on most growth parameters of maize. The 0.5 g L^{-1} application rate (PAM0.5) under the second compaction strength (CS2.5; 2.5kg rammer) (CS2.5PAM0.5) treatment significantly recorded the highest effect of all the amendment treatments on some properties of tested soils and maize biomass yields. Moreover, the PAM amendment not only improved some soil properties but also decreased the harmful effect of compaction, so that maize was successfully grown without impacting crop yields with increased soil compaction levels and lower penetration resistance values after PAM application. Conclusively, because soil compaction due to agricultural machinery is a problem in most soils, the extensive application of the PAM amendment is thus a promising management practice.

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التخفيف من التأثير الضار للمقاومة الميكانيكية للتربة على بعض الخواص الفيزيائية والكيميائية للتربة ومعايير النمو لهجين الذرة الصفراء (*Zea mays L.*).

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تم إجراء تجربة بأعمدة تربة في الصوبة الزجاجية. وجمعت عينات من التربة السطحية (عمق 0.0 - 0.2 متر) من مزرعة كلية التكنولوجيا والتنمية ذات القوام الطينى، والثانية من معهد بحوث الأراضي والمياه والبيئة، مركز البحوث الزراعية، الجيزة، مصر قوامها طينية سلتية. تهدف هذه الدراسة إلى دراسة تأثير إضافة مادة البولي أكريلاميد (PAM) على بعض خصائص التربة المضغوطة وقياسات نمو المجموع الجذري والخضري للذرة الهجين(TWC-360) . عرضت تسع معاملات لكل قوام تربة لدراسة التأثير المشترك بين التضاغط الميكانيكي وإضافة PAM بما فيها أعمدة الكنترول، وكانت قوى ضغط مختلفة (CS) (٠، ٢.٥، ٤.٥ كجم) ومعادلات PAM (٠، ٠.٢٥، ٠.٥، و١ جرام PAM لتر$^{-١}$) في التربة. أدى ضغط التربة إلى زيادة الكثافة الظاهرية للتربة بنسبة ٢٥% و١٢% للمعاملة CS4.5PAM0 (٤.٥ كجم)، مقارنة بالمعاملات غير المضغوطة في التربة الطينية والطينية السلتية، على التوالي. تدهورت بعض قياسات نمو الذرة بسبب انضغاط التربة. أدى إضافة PAM إلى انخفاض ملحوظ في كثافة التربة ومقاومة الاختراق ومؤشر اللدونة في التربة التي تم اختبارها. بالإضافة إلى ذلك، هناك زيادات معنوية في متوسط القطر الوزنى والهندسي ومعامل التوصيل الهيدروليكي. ونتيجة لذلك، أدى تطبيق PAM أيضًا إلى تحسين معايير نمو الذرة وإنتاجية الكتلة الحيوية. أفضل معاملة بشكل عام هي CS2.5PAM0.5 بمعدل ٠.٥ جرام PAM لتر$^{-١}$ مع قوة الضغط الثانية (CS؛ ٢.٥ كجم)، حققت هذه المعاملة أفضل التأثيرات على الخصائص الفيزيائية للتربة،

التوصية: من هذه النتائج أدت إلى زيادة مؤشرات نمو الذرة وإنتاجية الكتلة الحيوية بنسبة ١٢% في التربة التي تم اختبارها، مقارنة بمعاملة الكنترول بدون ضغط. ولذا وتحت نفس الظروف يوصى بتطبيق PAM كتعديل مستدام بمعدل ٠.٥ جم لتر$^{-1}$.