*Gezira J. of Agricultural Science*
*ISSN Linking: 1858-8735*
*http://journals.uofg.edu.sd/index.php/gjas/*

# Linear Relationships of Soil Bulk Density and Total Porosity under Machinery Traffic in a Silty Clay Soil of River Nile State, Sudan

Mohammedahmed. Abdelmowla. Ahmed[1], Imadeldin Abdulla. Farah[1]

Department of Agricultural Engineering, Faculty of Agriculture, Nile Valley University, Atbara, Sudan
Corresponding author: mohmedabdo@nilevalley.edu.sd

***INFORMATION:***

*Submission:*
*6/09/2026*

*Accepted:*
*29/09/2026*

*Publication:*

***ABSTRACT***

Machinery traffic can cause soil compaction and alter soil physical properties in mechanized agriculture. This study evaluated the effects of machinery traffic, tillage, and soil moisture on soil bulk density (BD) and estimated total porosity (TP) in a silty clay soil at Nile Valley University, River Nile State, Sudan, during the 2019/2020 and 2020/2021 growing seasons. A split-split plot experiment with three replications included two tillage treatments, two target gravimetric soil-moisture levels (16% and 25%), and four traffic treatments (0, 1, 3, and 6 tractor passes). Soil samples were collected at depths of 0–15 and 15–30 cm. Bulk density increased from 1.261 to 1.400 g $cm^{-3}$ at 0–15 cm and from 1.279 to 1.376 g $cm^{-3}$ at 15–30 cm as traffic increased from zero to six passes, representing increases of 11.0% and 7.6%, respectively. Machinery traffic significantly affected bulk density at both depths ($P < 0.001$). Linear regression based on individual experimental-unit observations indicated positive relationships between traffic intensity and bulk density, with $R^2$ values of 0.9465 and 0.9363 for the upper and lower layers, respectively. The effects of tillage and soil moisture varied with depth, and significant interactions among management factors were observed, particularly at 15–30 cm. Estimated total porosity declined with increasing traffic, reflecting its mathematical dependence on bulk density. These findings indicate that repeated tractor passes were associated with increased soil compaction under the investigated conditions. Minimizing unnecessary machinery passes may help reduce compaction risk in comparable silty clay soils.

***KEYWORDS:***
.

Keywords: Soil compaction; machinery traffic; bulk density; total soil porosity; soil moisture; tillage.

## 1. Introduction:

Soil compaction caused by agricultural machinery traffic is a major form of soil degradation in mechanized agriculture. Repeated wheel loading can rearrange soil particles, reduce pore space, and increase soil bulk density (BD), adversely affecting water infiltration, soil aeration, root penetration, and soil functioning. Compaction severity depends on several interacting factors, including traffic intensity, wheel and axle loads, tyre inflation pressure, soil texture, moisture content, and initial soil structure (**Obour and Ugarte, 2021; Abagale, 2021; Yang *et al.*, 2022).** These studies emphasize the importance of assessing machinery-induced compaction as a soil-management concern rather than considering field operations solely in terms of operational efficiency.

Soil bulk density is widely used to evaluate compaction because it represents the mass of dry soil per unit volume. Total soil porosity (TP) provides complementary information about pore space and can be estimated from BD and particle density. However, when calculated using an assumed particle density, TP is mathematically dependent on BD and should not be interpreted as an independent measurement. Moreover, BD alone may not fully characterize soil physical quality; complementary indicators, such as penetration resistance and hydraulic properties, can provide additional information when available (**Abukari, A*,et at*,2021;Yang *et al.*, 2022**,).

The effects of machinery traffic may vary with the number of passes and soil depth. Repeated passes along the same wheel tracks can increase cumulative loading, while stress transmission and soil structural properties influence compaction in deeper layers. Regression analysis can quantify empirical relationships between traffic intensity and BD, although such relationships should be interpreted within the tested traffic range and experimental conditions (**Obour and Ugarte, 2021; Zhang et al., 2024**).

Soil moisture and tillage practices may further modify the response to machinery traffic. Moisture influences soil deformation under loading, while tillage alters soil structure and mechanical resistance. Their effects may vary with soil texture, traffic intensity, and initial soil conditions. **Vanderhasselt et al. (2024)** demonstrated that tyre inflation pressure and relatively small differences in soil moisture could influence compaction indicators during seedbed preparation. However, these effects are context-dependent and should not be generalized across all soils and machinery systems. Evaluating traffic intensity alongside tillage and moisture conditions is therefore essential for understanding soil compaction under specific field conditions.

In River Nile State, Sudan, evidence on machinery-induced compaction in fine-textured soils is important for improving agricultural machinery management. The silty clay soil at the research farm of the Faculty of Agriculture, Nile Valley University, provides an opportunity to quantify traffic-associated changes in soil physical properties under local conditions. Such site-specific evidence can support management decisions under comparable soil and operating conditions.

Accordingly, this study evaluated the effects of machinery traffic intensity, tillage condition, and gravimetric soil moisture on BD and calculated TP in a silty clay soil at Darmeli, River Nile State, Sudan. A split-split plot experiment was conducted during the 2019/2020 and 2020/2021 growing seasons, comprising two tillage conditions (plowed and unplowed), two target soil-moisture levels (16% and 25%), and four traffic treatments (0, 1, 3, and 6 tractor passes). Soil samples were collected

at depths of 0–15 and 15–30 cm. The specific objectives were to (i) quantify traffic-associated changes in BD at both depths; (ii) assess whether tillage and soil moisture effects varied with depth and traffic intensity; and (iii) establish empirical linear relationships between tractor passes and BD and calculated TP. The findings provide field-based evidence to support machinery-traffic management under comparable soil and operating conditions.

## 2. Materials and Methods:

### 2.1. Experimental Site:

The field experiment was conducted during two consecutive growing seasons, 2019/2020 and 2020/2021, at the research farm of the Faculty of Agriculture, Nile Valley University, Darmeli, approximately 13 km north of Atbara, River Nile State, Sudan (**Ahmed , *et at*,2022).** The experimental soil was classified as silty clay, comprising 16.60% sand, 41.15% silt, and 42.25% clay. The field had previously been cultivated with alfalfa. The total experimental area was approximately 3,600 m².

### 2.2. Experimental Design and Treatments:

A split-split plot design with three replications was used to investigate the effects of tillage, soil moisture, and machinery traffic on soil bulk density and estimated total soil porosity. Tillage was assigned to the main plots, soil moisture to the subplots, and machinery traffic to the sub-subplots.

Tillage treatments consisted of P1 (plowed to a depth of 0–30 cm) and P2 (unplowed). Each main plot measured 30 × 20 m (600 m²). Each main plot was divided into two moisture subplots of 300 m² each, representing S1 (25% gravimetric soil moisture) and S2 (16%). Each moisture subplot was further divided into four traffic sub-subplots of 75 m² each, representing T0 (0 passes), T1 (1 pass), T3 (3 passes), and T6 (6 passes).

Each replication contained two main plots, four moisture subplots, and 16 traffic-treatment sub-subplots. Across the three replications, the experiment comprised six main plots and 48 traffic-treatment sub-subplots. Treatments were randomly allocated within their respective experimental units. For T1, T3, and T6, successive tractor passes were made along the same wheel tracks to impose cumulative traffic loading, while T0 served as the non-trafficked control.

### 2.3. Tillage and Soil-Moisture Treatments:

The P1 treatment was plowed to a depth of 0–30 cm, whereas P2 was maintained without tillage. Soil-moisture treatments were established at target gravimetric moisture contents of 25% (S1) and 16% (S2). Irrigation was applied as necessary before machinery traffic to establish the designated moisture conditions.

Gravimetric soil moisture was determined using soil samples collected with an auger and oven-dried at 105°C for 24 h or until constant mass. Moisture content was calculated utilizing formula1.

$$SMC(\%) = \frac{\mathbf{Mw-Md}}{\mathbf{Md}} \times 100 \quad \text{..... (1)}$$

Where (GMC) is gravimetric soil-moisture content (%), (M_w) is the mass of moist soil (g), and (M_d) is the mass of oven-dried soil (g).

The measured moisture content was used to assess the soil-moisture condition before the traffic treatments were imposed.

### 2.4. Tractor Specifications and Machinery Traffic:

Machinery traffic was imposed using a Massey Ferguson MF-290 tractor. The same tractor was used throughout the experiment, and operating conditions were maintained as consistently as practicable. The treatments comprised zero, one, three, and six passes. For treatments involving traffic, successive passes were applied along the same wheel tracks.

The principal tractor specifications are presented in **Table 1.** Specifications that depend on tractor configuration, tires, ballast, or operating conditions were distinguished from experimentally measured values. Operating weight, axle loads, and tire inflation pressures were not treated as measured experimental variables unless supported by original field records or verified documentation.

**Table 1: Principal specifications of the Massey Ferguson MF-290 tractor.**

| **Parameter** | **Specification** |
|---|---|
| Manufacturer | Massey Ferguson |
| Model | MF-290 |
| Drive configuration | Two-wheel drive (2WD), subject to confirmation of the experimental tractor |
| Engine | Perkins AD4.248, four-cylinder diesel |
| Rated engine power | Approximately 80 hp (59.7 kW), subject to model configuration |
| Engine displacement | Approximately 4.1 L |
| Fuel tank capacity | Approximately 80 L |
| Rear power take-off speed | 540 rpm |
| Operating weight and axle loads | Report actual measured or verified values only |
| Tire sizes and inflation pressures | Report the actual experimental configuration where documented |

*Note:* Values dependent on the specific tractor configuration should be verified against the tractor identification plate, manufacturer documentation, or original field records. Estimated axle loads and provisional tire pressures should not be presented as experimental measurements.

### 2.5. Soil Sampling and Bulk-Density Determination:

Soil samples were collected at two depth intervals: 0–15 cm and 15–30 cm. These intervals represented the upper and lower portions of the 0–30 cm tillage layer. Soil samples for moisture determination were collected using an auger, while undisturbed samples for bulk-density determination were obtained using cylindrical core samplers.

Bulk density was determined using cores with an internal diameter of 5 cm and a height of 5 cm. The core volume was calculated using equation 2.

$$V=\pi r^2 h \quad \ldots\ldots (2)$$

Where (V) is the core volume ($cm^3$), (r) is the internal radius (cm), and (h) is the internal height (cm).

For a core radius of 2.5 cm and a height of 5 cm:

$$V= \pi (2.5)^2 (5) = 98.17\ cm^3$$

Soil samples were oven-dried at 105°C for 24 h or until constant mass. Bulk density was calculated using formula3.

**BD = Md/V** ……..……. (3)

where (BD) is soil bulk density (g $cm^{-3}$), (M_d) is the oven-dry soil mass (g), and (V) is the core volume ($cm^3$). The core method and drying procedure followed standard soil physical-analysis principles (USDA-NRCS, 2017).

**2.6. Estimation of Total Soil Porosity:**

Total soil porosity (TP) was estimated from bulk density using equation 4.

**TP (%) = (1- BD/PD) 100** ……..…….. (4)

where (TP) is total soil porosity (%), (BD) is bulk density (g $cm^{-3}$), and (PD) is particle density (g $cm^{-3}$). Particle density was assumed to be 2.65 g $cm^{-3}$ for mineral soil.

Because total porosity was calculated directly from bulk density rather than measured independently, it was interpreted as a derived soil physical property. Consequently, the relationships between machinery traffic and porosity were interpreted in consideration of the mathematical dependence between bulk density and calculated porosity.

**2.7. Statistical Analysis:**

Data were analyzed using analysis of variance (ANOVA) appropriate for the split-split plot design. Tillage, soil moisture, and machinery traffic were evaluated using error terms corresponding to their respective randomization levels. The effects of the experimental factors and their relevant interactions were considered.

The two soil-depth intervals, 0–15 cm and 15–30 cm, were analyzed separately because soil responses to machinery traffic may differ with depth. Where treatment effects were statistically significant, means were compared using the least significant difference (LSD) test at the 5% significance level ((P\leq0.05)). Coefficients of variation (CV) were calculated to assess experimental variability. Statistical analyses were performed using R software, version 4.2.0.

Where data from both growing seasons were analyzed jointly, the statistical model accounted for season and the relevant season-by-treatment interactions. The analysis and interpretation were based on the actual experimental randomization and sampling structure rather than treating subsamples as independent replications. The statistical approach followed established procedures for agricultural experiments (Gomez and Gomez, 1984).

**2.8. Linear Regression Analysis:**

Simple linear regression was used to evaluate the relationships between machinery-traffic intensity and soil bulk density (BD) and estimated total soil porosity (TP) at each sampling depth. The number of tractor passes (0, 1, 3, and 6) was treated as the explanatory variable, while BD or estimated TP was treated as the response variable. Regression analyses were based on individual experimental-unit observations rather than treatment means.

The regression model was expressed using formula 5.

**Y=a+ bX+ varepsilon** ……..…… (5)

Where (Y) represents BD or estimated TP, (a) is the intercept, (b) is the regression coefficient, (X) is the number of tractor passes, and (varepsilon) is the random error term. Model fit was assessed using the coefficient of determination (($\mathbf{R^2}$)), and the statistical significance of the regression coefficient was evaluated at the 5% significance level.

Because the experiment involved a split-split plot design with repeated treatment levels across tillage, soil-moisture, and replication conditions, the independence of observations was considered when interpreting the regression results. The regression equations were interpreted as empirical relationships within the tested traffic range and experimental conditions rather than as independently validated predictive models. Estimated total porosity was derived from BD using an assumed particle density of 2.65 g $cm^{-3}$; therefore, the regression results for these two variables were not considered independent evidence of soil physical responses.

### 2.9. Experimental Quality Control:

The same core dimensions, oven-drying procedure, soil-sampling depths, and assumed particle density were used throughout the study. Soil moisture was assessed before machinery traffic, and repeated passes were applied along the same wheel tracks. Tractor specifications and operating conditions were reported according to the available documentation, with estimated values distinguished from measured observations.

Methodological limitations, including the derived nature of total porosity and the limited number of traffic-treatment means used in regression, were considered when interpreting the results and drawing conclusions.

## 3. Results and Discussion:

### 3.1. Effect of Machinery Traffic on Soil Bulk Density:

Machinery traffic was associated with a progressive increase in soil bulk density (BD) at both sampling depths (**Figure** 1 ). At 0–15 cm, mean BD increased from 1.261 g $cm^{-3}$ under T0 (no passage) to 1.305, 1.358, and 1.400 g $cm^{-3}$ under T1, T3, and T6, respectively. At 15–30 cm, the corresponding means were 1.279, 1.308, 1.350, and 1.376 g $cm^{-3}$.

From T0 to T6, BD increased by approximately 11.0% at 0–15 cm and 7.6% at 15–30 cm. These percentages are descriptive comparisons of the reported treatment means; they do not by themselves establish a statistically significant difference between depths. The larger proportional increase in the upper layer is consistent with the concentration of wheel-induced stress near the soil surface, while the increase at 15–30 cm indicates that the response was not confined to the uppermost layer.

This pattern agrees with broader evidence that field traffic can increase BD and soil mechanical strength while reducing pore space and altering pore geometry (**Elaoud, R *et at*,. 2015; Obour and Ugarte, 2021; Zhang et al., 2024**). The magnitude and depth distribution of compaction depend not only on the number of passes but also on wheel load, tyre inflation pressure, soil water status, texture, and pre-existing soil structure. Because these factors were not independently varied in the present experiment, the observed changes should be attributed to the tested traffic treatments under the study conditions rather than to pass number alone as a universal causal predictor.

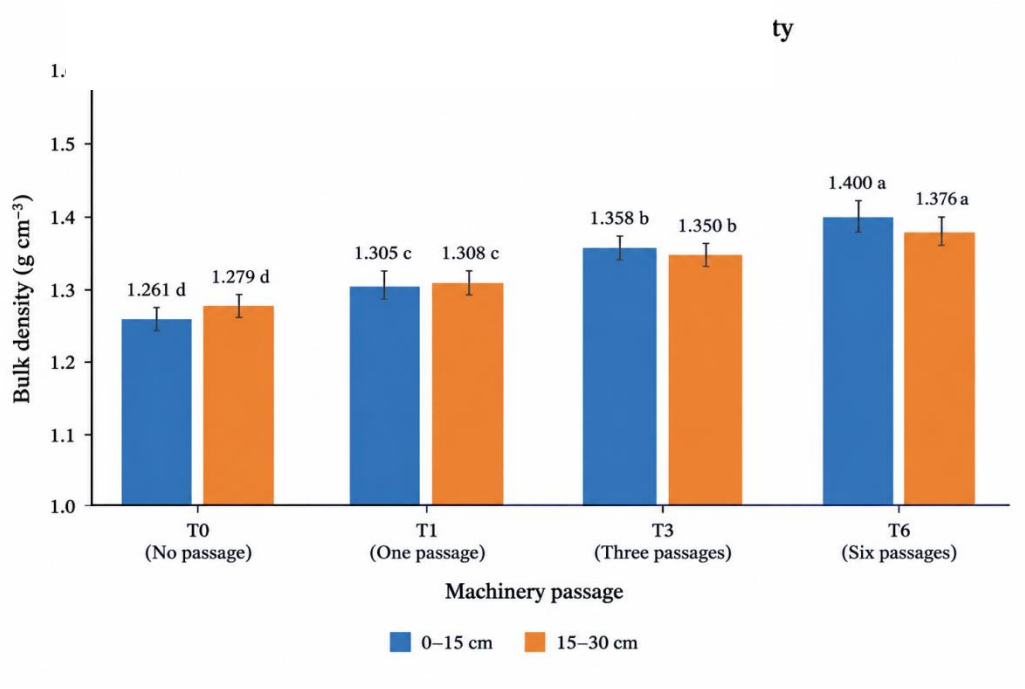



**Figure 1: Effect of Machinery Passage on Soil Bulk Density at Two Soil Depths**

Means followed by different letters within a column differ significantly according to the LSD test at $P \leq 0.05$.

### 3.2. Linear Relationship between Machinery Traffic and Soil Bulk Density:

Linear regression analysis using individual experimental-unit observations showed a positive relationship between machinery-traffic intensity and soil bulk density (BD) at both sampling depths (**Table 2**). The fitted equations were:

$$\mathbf{BD}_{\mathbf{0–15\ cm}} = 1.2752 + 0.0223T$$
$$\mathbf{BD}_{\mathbf{15–30\ cm}} = 1.2888 + 0.0158T$$

Where BD is soil bulk density (g $cm^{-3}$) and T is the number of machinery passes. The coefficients of determination ($\mathbf{R^2}$) were 0.9465 and 0.9363, respectively, indicating that the linear models explained a high proportion of the variation in BD within the experimental dataset.

The steeper slope in the surface layer indicates a greater estimated increase in BD per additional pass than in the deeper layer. This finding is consistent with **Obour and Ugarte (2021),** who reported that agricultural traffic can increase soil compaction, although the magnitude of the response depends on soil texture, moisture conditions, and mechanical loading. Repeated traffic may increase soil density through particle rearrangement and the reduction of pore space; however, these mechanisms were not directly measured in the present study.

Despite the high $\mathbf{R^2}$values, the equations should be interpreted within the range of traffic levels and experimental conditions investigated. High $\mathbf{R^2}$values alone do not demonstrate predictive accuracy under independent conditions

**Table 2: Linear regression statistics describing the relationship between machinery traffic and soil bulk density**

| Soil depth | Regression equation | Slope | SE | t | P | $R^2$ |
|---|---|---|---|---|---|---|
| 0–15 cm | BD = 1.2752 + 0.0223T | 0.02233 | 0.00375 | 5.950 | 0.0271 | 0.9465 |
| 15–30 cm | BD = 1.2888 + 0.0158T | 0.01579 | 0.00291 | 5.424 | 0.0324 | 0.9363 |

### 3.3. Effect of Plowing on Soil Bulk Density:

The effect of plowing on soil bulk density (BD) varied with sampling depth **(Table 3).** At 0–15 cm, mean BD was comparable between plowed and unplowed treatments (1.332 and 1.330 g $cm^{-3}$, respectively), with no statistically significant difference ($P$ = 0.6438). In contrast, at 15–30 cm, BD was significantly higher in plowed soil (1.338 g $cm^{-3}$) than in unplowed soil (1.318 g $cm^{-3}$; $P$ < 0.001), representing an absolute difference of 0.020 g $cm^{-3}$ (approximately 1.5% relative to the unplowed treatment).

The depth-dependent response suggests that the association between plowing and BD was not uniform throughout the sampled soil profile. Previous research has shown that the effects of tillage and agricultural traffic on soil physical properties depend on soil texture, moisture status, mechanical loading, and pre-existing soil structure (**Obour and Ugarte, 2021; Keller et al., 2022**). Nevertheless, the present results do not establish the mechanism responsible for the higher BD in the 15–30 cm layer. Because plowing extended to a depth of 30 cm, this layer was within the cultivated zone; therefore, the observed difference should not be interpreted as evidence of compaction below the plowed layer. Further interpretation would require supporting measurements, such as soil penetration resistance, pre-tillage BD, or changes in soil structure.

**Table 3: Effect of plowing condition on soil bulk density at two soil depths**

| Tillage condition | 0–15 cm (g $cm^{-3}$) | 15–30 cm (g $cm^{-3}$) |
|---|---|---|
| Plowed | 1.332 | 1.338 a |
| Unplowed | 1.330 | 1.318 b |
| CV (%) | 2.131 | 1.300 |
| LSD | 0.0115 | 0.0079 |

*Means followed by different letters within a column differ significantly at $P \leq 0.05$.*

### 3.4. Effect of Soil Moisture on Soil Bulk Density:

Soil bulk density (BD) differed significantly between the two soil-moisture treatments at both sampling depths (**Table 4**). At 0–15 cm, mean BD was 1.322 g $cm^{-3}$ under the 25% gravimetric moisture treatment, compared with 1.340 g $cm^{-3}$ under the 16% treatment (F = 9.29, P = 0.0031). Similarly, at 15–30 cm, BD was 1.318 g $cm^{-3}$ at 25% moisture and 1.339 g $cm^{-3}$ at 16% moisture (F = 35.647, P < 0.001). Thus, the 16% moisture treatment was associated with higher mean BD by 0.018 g $cm^{-3}$ in the upper layer and 0.021 g $cm^{-3}$ in the lower layer, equivalent to approximately 1.4% and 1.6%, respectively, relative to the corresponding means at 25% moisture. These differences describe the observed treatment means; the reported significance levels should be verified against the original ANOVA output, with particular attention to the appropriate error term for the split-split plot design.

The higher BD observed at 16% than at 25% gravimetric moisture should be interpreted in the context of the experimental conditions rather than as evidence that drier soil is inherently more susceptible to compaction. Soil water content influences soil deformation and mechanical behaviour, but the resulting response depends on soil texture, structural condition, applied wheel load, tyre

inflation pressure, and the range of water contents considered. Consequently, the relationship between moisture content and compaction is not necessarily linear or uniform across soils and operating conditions.

This interpretation is consistent with the meta-analysis by **Obour and Ugarte (2021)**, which synthesized evidence from 51 published studies and demonstrated that the effects of machinery traffic on soil physical properties vary with soil texture, traffic-related loading factors, and sampling depth. More recently, (**Jebur, H. Aet at,. 2017;Vanderhasselt et al. 2024)** investigated tyre inflation pressure and small differences in soil moisture during seedbed preparation. Their findings indicated that using field-recommended tyre pressure and operating under slightly drier conditions could reduce traffic-induced compaction under the conditions they studied. However, these findings should not be interpreted as establishing a universal moisture threshold because the response depends on the soil and field operation.

In the present study, the lower BD under the 25% moisture treatment may reflect differences in soil mechanical behaviour under the specific experimental conditions; however, the available results do not establish the mechanism responsible for this pattern. In addition, because soil moisture was evaluated at two treatment levels, the experiment cannot establish the shape of the moisture–compaction relationship or identify an optimum moisture content for machinery traffic. The findings should therefore be restricted to the two moisture treatments and the conditions of this study. Future experiments incorporating a wider range of measured soil-water contents, together with penetration resistance, wheel load, and tyre inflation pressure, would help clarify how moisture conditions influence traffic-induced changes in soil bulk density.

**Table 4: Effect of soil moisture on soil bulk density at two soil depths**

| **Soil moisture** | **0–15 cm (g cm$^{-3}$)** | **15–30 cm (g cm$^{-3}$)** |
|---|---|---|
| 25% | 1.322 | 1.318 |
| 16% | 1.340 | 1.339 |
| Statistical significance | **P = 0.0031** | **P < 0.001** |

The statistical analysis indicated significant moisture effects at both 0–15 cm (**F = 9.29, P = 0.0031**) and 15–30 cm (**F = 35.647, P < 0.001**).

### 3.5. Interaction Effects on Soil Bulk Density:

The analysis of variance showed that the effects of machinery traffic, tillage, and soil moisture on soil bulk density (BD) varied with sampling depth (**Tables 5 and 6**). At 0–15 cm, machinery traffic and soil moisture had significant main effects, whereas tillage and season were not significant. The significant traffic × tillage interaction (P<0.001P<0.001P<0.001) indicated that the response of BD to machinery traffic differed between plowed and unplowed soil. The other reported interactions were not significant at this depth.

At 15–30 cm, machinery traffic, tillage, and soil moisture had significant main effects, and both two-way and three-way interactions were significant. This indicates that BD at the lower depth depended on the combined effects of traffic intensity, tillage, and soil moisture. These findings highlight the importance of considering interactions among management factors when assessing subsurface compaction.

These results agree with **Obour and Ugarte (2021),** who reported that machinery traffic generally increases soil BD and mechanical strength, with responses varying according to soil texture, loading conditions, and sampling depth. **Zhang *et al*. (2024**) similarly emphasized the effects of agricultural

machinery on soil physical properties. Repeated wheel loading can rearrange soil particles and reduce pore space, while soil moisture and tillage conditions may influence the extent of compaction.

Overall, the results demonstrate that the effects of machinery traffic on BD were depth-dependent. The significant interactions, particularly at 15–30 cm, emphasize the need to evaluate traffic in relation to tillage and soil moisture.

**Table 5: ANOVA for soil bulk density at 0–15 cm**

| Source | df | F-value | P-value |
|---|---|---|---|
| Machinery passage | 3 | 109.510 | <0.001*** |
| Plowing | 1 | 0.220 | 0.6438 |
| Moisture | 1 | 9.290 | 0.0031** |
| Season | 1 | 3.070 | 0.0836 |
| Passage × plowing | 3 | 12.480 | <0.001*** |
| Passage × moisture | 3 | 0.480 | 0.6952 |
| Plowing × moisture | 1 | 3.620 | 0.0606 |
| Passage × plowing × moisture | 3 | 0.250 | 0.8611 |
| Residual | 79 | — | — |

**Table 6: ANOVA for soil bulk density at 15–30 cm**

| Source | df | F-value | P-value |
|---|---|---|---|
| Machinery passage | 3 | 152.335 | <0.001*** |
| Plowing | 1 | 32.880 | <0.001*** |
| Moisture | 1 | 35.647 | <0.001*** |
| Season | 1 | 3.358 | 0.0706 |
| Passage × plowing | 3 | 14.904 | <0.001*** |
| Passage × moisture | 3 | 5.557 | 0.0016** |
| Plowing × moisture | 1 | 7.076 | 0.0095** |
| Passage × plowing × moisture | 3 | 7.365 | 0.0002*** |
| Residual | 79 | — | — |

### 3.6. Effect of Machinery Traffic on Calculated Total Soil Porosity:

Calculated total soil porosity (TP) decreased progressively with increasing machinery traffic at both soil depths (0–15 and 15–30 cm) **Figure 2.** Based on the reported BD means and an assumed particle density of 2.65 g $cm^{-3}$, TP declined from 52.42% to 47.17% at 0–15 cm and from 51.74% to 48.08% at 15–30 cm between T0 and T6. These changes correspond to decreases of 5.25 and 3.66 percentage points, respectively.

The decline in calculated TP reflects the increase in BD associated with repeated machinery passes. Wheel loading can rearrange soil particles and reduce pore space, thereby increasing soil compaction. Similar effects of agricultural machinery traffic on soil physical properties have been reported by **Obour and Ugarte (2021) and Zhang et al. (2024).**

However, TP in this study was calculated from BD using a fixed particle density rather than measured independently. Therefore, the decline in TP is mathematically linked to the increase in BD and should be interpreted as a derived indicator of soil compaction, not as independent evidence of changes in soil porosity.

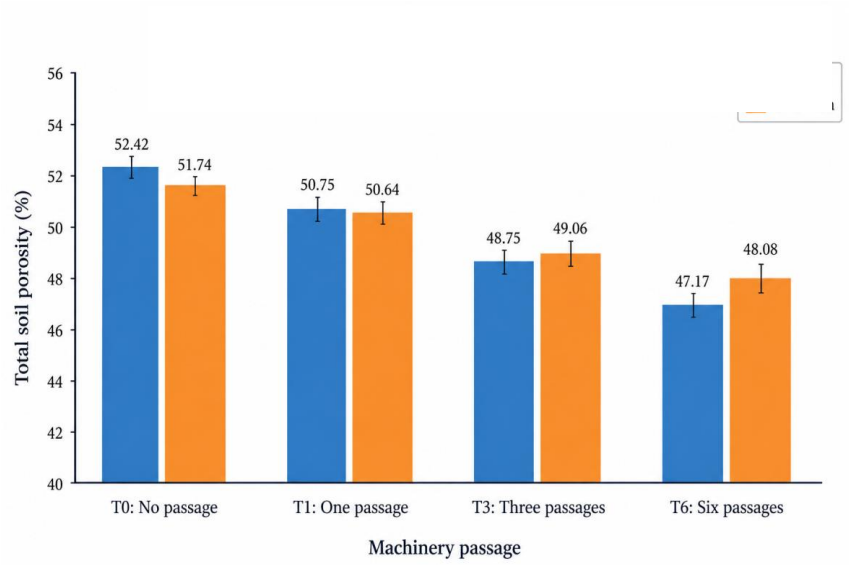



**Figure 2: Effect of Machinery Traffic on Calculated Total Soil Porosity at Two Soil Depths (0–15 and 15–30 cm).**

### 3.7. Integrated Discussion and Practical Implications:

The results demonstrated a consistent increase in soil bulk density (BD) with increasing machinery traffic at both investigated depths. The proportional increase was greater in the 0–15 cm layer, although the increase observed at 15–30 cm indicates that traffic-induced compaction also affected the subsurface layer. This pattern is consistent with previous syntheses reporting that machinery traffic can increase soil bulk density and mechanical strength, with the extent and depth of compaction depending on wheel load, contact stress, soil moisture, and soil physical properties (**Shaheb, M. R., *et at,*. 2021; Keller *et al*., 2022; Zhang *et al*., 2024**).

In the present experiment, mean BD was higher under the 16% gravimetric moisture treatment than under the 25% treatment. However, this finding should be interpreted within the specific soil and experimental conditions rather than used to establish a general recommendation for machinery traffic at a particular moisture content. Gravimetric water content alone does not fully characterize the mechanical state of soil, and the tested moisture levels may not correspond to equivalent matric potentials or trafficability conditions across different soils. Moreover, the effects of tyre inflation pressure and variations in soil water content may depend on tyre characteristics and operating conditions (**Khemis, *et al*,. 2022; Vanderhasselt *et al*., 2024**).

From a practical perspective, the findings support minimizing unnecessary machinery passes to reduce the risk of soil compaction. Controlled traffic management and appropriate tyre-pressure adjustment are potential strategies for further investigation under local field conditions. Previous meta-analysis has indicated that controlled traffic can improve soil and crop outcomes, although the magnitude of these effects varies among farming systems and environmental conditions (Yang *et a*l., 2022). Because the present study did not directly evaluate controlled traffic, tyre-pressure optimization, crop yield, fuel consumption, or economic performance, these strategies should be regarded as potential management options rather than demonstrated outcomes of this experiment.

An important limitation is that BD and calculated total porosity (TP) do not independently capture all dimensions of soil physical quality. In particular, because TP was calculated from BD using an assumed particle density, it represents a derived indicator rather than an independent measurement of

soil porosity. Future studies should therefore combine BD measurements with complementary indicators, including penetration resistance measured at standardized soil water status, infiltration rate or hydraulic conductivity, air-filled porosity, and crop response. In addition, detailed reporting of plot dimensions and experimental units, replication, statistical model error terms, treatment-combination means, wheel and axle loads, tyre inflation pressure, and traffic conditions would improve reproducibility and facilitate the interpretation and transferability of the findings to other agricultural settings.

**4. Conclusions**:

Machinery traffic was associated with a progressive increase in soil bulk density at both investigated depths, with increases of 11.0% at 0–15 cm and 7.6% at 15–30 cm between zero and six tractor passes. Regression analysis of individual experimental-unit observations indicated positive linear relationships between traffic intensity and bulk density. The effects of tillage and soil moisture varied with depth, with significant interactions among experimental factors, particularly in the 15–30 cm layer. Estimated total porosity decreased with increasing traffic but was derived mathematically from bulk density. Overall, the findings support minimizing unnecessary tractor passes to reduce soil compaction risk under comparable field conditions. Further research should incorporate complementary soil physical measurements and verified wheel-load and tyre-pressure data to strengthen interpretation and practical recommendations.

## 5. References:

**Abagale, F. K. (2021**). Effect of agricultural machinery on physical and hydraulic properties of agricultural soils. Journal of Soil Science and Environmental Management, 12(2), 58–65.

**Abukari, A., Christian, D., and** Ochire-Boadu, K. (2021). Bulk density and porosity of soils influenced by skidding operations in the Nkrankwanta Off-Forest Reserve of Ghana. Advances in Forestry Sciences, 8(2), 1409–1415.

**Ahmed, M. A. Elmowla**, and Abu Bakr, A. (2022). Effect of forward speed and soil type in tractor Massey Ferguson Tractor (Model 290) performance. Diyala Agricultural Sciences Journal, 14(2), 33–42.

**Elaoud, R., Elaoud, A**., Chehaibi, S., and Abrougui, K. (2015). Effect of the passage for different tractors on the soil compaction. International Journal of Current Engineering and Technology, 5(1), 527–533.

https://doi.org/10.1016/j.still.2024.106109

**Jebur, H. A., and Alsayyah**, Y. A. A. (2017). Study of the soil moisture content and the tractor speed on the performance efficiency of the machinery unit. IOSR Journal of Agriculture and Veterinary Science, 10(5), 65–70. https://doi.org/10.9790/2380-1005016570

**Keller, T., Lamandé, M., Naderi-Boldaji**, M., and de Lima, R. P. (2022). Soil compaction due to agricultural field traffic: An overview of current knowledge and techniques for compaction quantification and mapping. In E. Saljnikov, L. Mueller, A. Lavrishchev, and F. Eulenstein (Eds.), Advances in Understanding Soil Degradation (pp. 287–312). Springer. https://doi.org/10.1007/978-3-030-85682-3_13

**Khemis, C., Abrougui, K., Gabsi**, K., Amami, R., Geofrey, W., Mutuku, E., Cornelis, W., and Chehaibi, S. (2022). Effects of tractor forward velocity on soil compaction under different soil water contents in Tunisia. African Journal of Agricultural Research, 18(5), 288–294. https://doi.org/10.5897/AJAR2019.14395

**Obour, P. B., and Ugarte, C. M**. (2021). A meta-analysis of the impact of traffic-induced compaction on soil physical properties and grain yield. Soil and Tillage Research, 211, 105019. https://doi.org/10.1016/j.still.2021.105019

**Shaheb, M. R., Venkatesh, R.,** and Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. Journal of Biosystems Engineering, 46(4), 417–439. https://doi.org/10.1007/s42853-021-00083-9

**Vanderhasselt, A., D'Hose**, T., Sneyders, M., and Cornelis, W. (2024). Effects of road- vs. field-recommended tyre inflation pressures and small variations in soil moisture content on traffic-induced soil compaction during seedbed preparation. Soil and Tillage Research, 241, 106109.

**Yang, P., Dong, W., Heinen**, M., Qin, W., and Oenema, O. (2022). Soil compaction prevention, amelioration and alleviation measures are effective in mechanized and smallholder agriculture: A meta-analysis. Land, 11(5), 645. https://doi.org/10.3390/land11050645