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STATISTICAL MODELING OF MAIZE YIELD VARIABILITY UNDER DIFFERENT SOIL FERTILITY AND TILLAGE CONDITIONS

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Abstract

Soil fertility, tillage, and organic matter management are all factors that affect maize productivity and thus yield. This study aimed to evaluate maize yield variability under different soil fertility and tillage conditions using statistical modeling techniques. Thirty-six experimental observations were used for a quantitative analytical approach: three tillage practices and three organic matter treatments. Treatment differences and relationships between soil characteristics and the maize yield were assessed through descriptive statistics, two-way analysis of variance (ANOVA), Pearson correlation analysis and multiple linear regression. Results showed differences in maize productivity among management treatments, traditional rotary tillage yielding the highest and the lowest yield was from no-till and earthworm bio-till. ANOVA, however, showed that neither tillage nor organic matter treatments nor the combination of tillage and organic matter were significant. Correlation analysis revealed that there was weak non-significant relationship between maize yield and soil fertility indicators. Multiple linear regression indicated a significant positive relationship between traditional rotary tillage and maize yield when compared with earthworm bio-tillage, but the model had not been satisfactory in explaining the phenomena. The results here suggest that the relationship between agriculture management practices and soil properties is complicated and that all these influence maize yield variability. The study highlights the need for integrated soil management and advises for deeper, multi-season studies with a greater statistical weight to promote a better predictive modeling and the sustainable production of maize in different agricultural environments.

Keywords: Maize yield variability; Organic matter management; Soil fertility; Statistical modeling; Tillage practices.

1. Introduction

Maize (Zea mays L.) is among the most important cereal crops, that play a significant role in food security, livestock feed production and agricultural sustainability in the world. The productivity of maize however is complexly affected by soil characteristics, nutrient availability, tillage methods and environmental factors. These factors vary and can result in significant crop performance variation, making it important to find management strategies to help ensure consistent crop productivity. Important factors that influence maize yield such as agricultural management practices (nutrient application, soil preparation etc.) have been identified, and statistical and predictive modelling approaches can be used to assess the relative importance of these factors (Bhat et al., 2024). Conservation management also has shown promise to enhance maize yield stability in diverse agricultural scenarios (Kiboi et al., 2023). Long-term evidence also indicates that conservation agriculture can improve the productivity of maize especially with the management practices adjusted to their local environmental context (Mhlanga et al., 2025).

Maize growth is affected by soil fertility which is a basic factor that determines nutrient availability, root growth and physiological processes. The amount of soil organic carbon, total N, P availability and soil pH affect nutrient cycles and the ability of agricultural soils to sustain soil productivity. Soil organic carbon and nitrogen distribution can be altered by agronomic management practices, which can impact on the productivity of crops and the functioning of soils over time (Bohoussou et al., 2025). The application of nitrogen fertilizers for long duration is correlated with the improvement of soil fertility and the yield potential of the crops in no-tillages (Li et al., 2024). In addition, spatial variability in soil properties may be one of the reasons for the differences in maize productivity in agricultural fields, highlighting the need for quantitative soil assessment (Nyéki et al., 2022). Additionally, the effects of soil fertility due to tillage management on maize yield formation under different planting conditions may also be different (Wang, L. Q., et al., 2025).

Tillage management also constitutes a key factor in sustainable maize production as it affects soil structure, water conservation, nutrients distribution and soil biology. The potential of conservation tillage practices for soil health and efficiency of maize yield production has been studied in the environmentally challenged agricultural areas (Cong et al., 2024). The use of integrated tillage, nitrogen management, and organic amendments can help to enhance maize productivity and soil fertility (Iqbal et al., 2024). Conservation tillage may also affect soil nutrient retention, soil erosion and crop performance under semi-arid conditions over the long-term (Jiang et al., 2024). Likewise, various straw return approaches are able to alter the soil characteristics and maize yield potential (Liu, R. Z., et al., 2024). The plow tillage of straw into the soil might also affect maize productivity, root development, and photosynthetic performance, as well as the soil biology processes.

Despite these discoveries, maize yield associated with the soil fertility and tillage management is still context specific, and thus an integrated statistical assessment is needed. Using machine-learning-assisted assessments, the suitability of tillage practices has been identified to be different among regions, suggesting that the effectiveness of management practices can be different in agricultural environments (Liu, S., et al., 2024). Modelling studies have also shown the importance of soil fertility management in the stability of maize yields in the face of climatic variability (MacCarthy et al., 2023). Meta-analytical evidence also highlights the importance of the optimization of tillage and soil related thresholds for maize yield and water-use efficiency (Xu et al., 2025). However, the relationship between the measured soil fertility parameters, the two different tillage systems, the organic matter inputs and maize yield needs further investigation for each experiment. Since experimental observations were already available, the present study aims to evaluate maize yield variability for the different tillage and organic matter treatments and to identify soil fertility indicators associated with yield performance based on the experimental observations by using statistical modelling.

Research Objectives

- To assess maize yield variability under different tillage practices and organic matter management conditions.
- To examine the relationships between soil fertility indicators, including soil pH, organic carbon, nitrogen, phosphorus, and soil moisture, and maize yield.
- To evaluate the combined associations of soil fertility characteristics and tillage practices with maize yield variability using statistical modeling techniques.

2. Materials and Methods

2.1 Study Design and Data Source

The research used a quantitative method of analysis based on experimental data already collected (Li, 2024). The data consisted of 36 observations and 22 variables relating to maize production, soil fertility, and farming methods. The analysis focused on the connection between soil characteristics, cultivation conditions, addition of organic material, and maize production. There were no other field experiments or laboratory tests carried out.

2.2 Experimental Treatment Structure

The experimental data were collected following 3 x 3 factorial designs in which there were three tillage treatments, namely; no tillage, earthworm bio-tillage, and conventional rotary tillage. There were also three treatments for organic matter, which were; no organic matter, straw addition, and the addition of composted cow manure.

2.3 Study Variables

Maize yield was the main dependent variable. Tillage system, organic matter management, soil pH, soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (Avai_N), Olsen phosphorus (OlsenP), and soil

water content (SWC) were some of the independent variables used. The independent variables were chosen based on their relevance to soil fertility and management and maize yield variability.

2.4 Data Preparation and Quality Assessment
Data analysis for completeness, consistency, and type of variables was carried out. All 36 data points were kept, with none of the values being missing in numbers. The null values that indicated no addition of organic matter in that observation were categorized as controls. The continuous variables remained at their initial units of measurement, whereas the categorical variables were recoded.

2.5 Statistical Analysis
Statistical procedures were designed in Python, where tabular output results would be in format compatible with Microsoft Excel. Descriptive statistics involved mean, standard deviation, minimum and maximum values. Two-way ANOVA was designed to compare the effect of tillage practices and organic matter on maize yield and determine their interaction. Pearson correlation was chosen for analysing associations between indicators of soil fertility and maize yield. Linear regression was used to analyse associations between the selected soil fertility indicators and tillage practices and their combined effect on maize yield. Dummy variables would be created for categorical variables. Predictor selection would involve agronomic considerations and checking for multicollinearity. Model assessment would use regression coefficients, 95% confidence interval, p-value, R^2 and adjusted R^2. Diagnostics would include normality of residuals, homoscedasticity, detection of influential observations and variance inflation factors. The statistical significance level was set at $p < 0.05$. Considering limited sample size, the regression models included only several predictors.

3. Results
In total, the analysis was based on 36 observations in the experiment, which comprised of three tillage systems and three organic matter treatments in combination, where each treatment had four repetitions. Five tables and five figures were created to analyse the variability in maize yield, the effect of treatments, correlation between soil fertility, and the performance of regression models.

3.1 Descriptive Characteristics of Maize Yield and Soil Fertility
The descriptive analysis yielded differences in the maize yields and soil fertility attributes in the experiments conducted. The general mean for the maize yields was 4.288 ± 0.494 with the lowest being 2.671 and the highest being 5.344. The mean value for the soil pH was 6.058 ± 0.477. The mean values for soil organic carbon (SOC) and total nitrogen (TN) were 9.247 ± 1.642 and 0.787 ± 0.121, respectively. Available nitrogen values varied between 26.076 to 54.470 and 58.137 to 106.278 for Olsen phosphorus.

Table 1. Descriptive Statistics of Maize Yield and Soil Fertility Indicators (n = 36)

Variable	Mean	SD	Minimum	Maximum
Maize yield	4.288	0.494	2.671	5.344
Soil pH	6.058	0.477	5.470	7.170
SOC	9.247	1.642	4.105	11.961
TN	0.787	0.121	0.469	1.023
TP	0.857	0.156	0.564	1.276
Available nitrogen	42.734	6.405	26.076	54.470
Olsen phosphorus	80.131	10.726	58.137	106.278
Soil water content	19.791	2.695	13.343	24.538

The distribution of maize yield across all 36 observations is presented in Figure 1, illustrating the variation in yield values recorded under the experimental conditions.

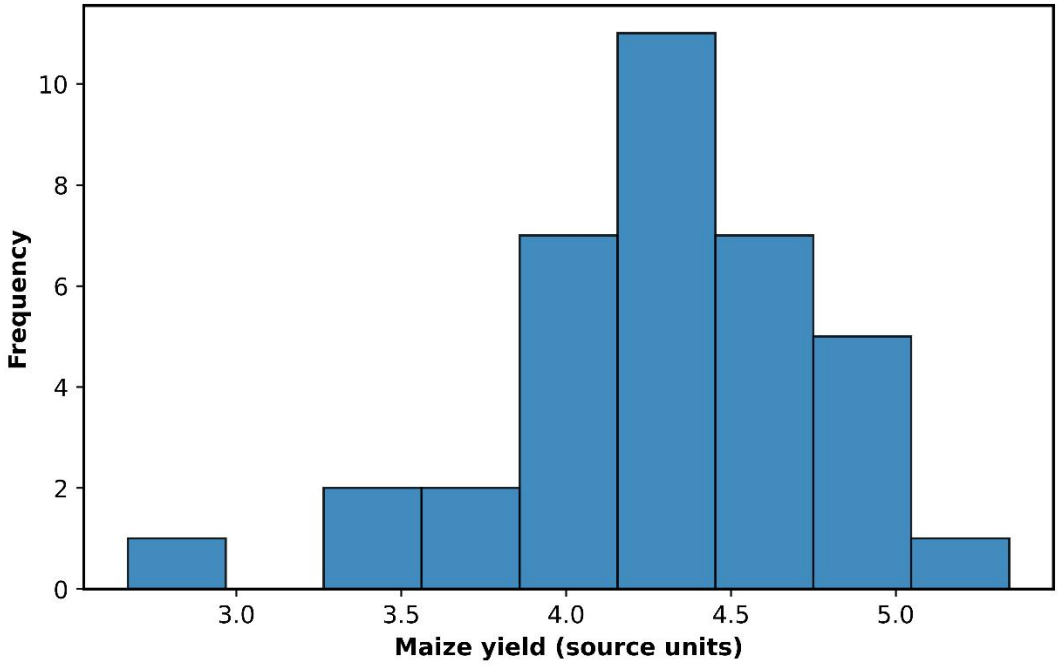


Figure 1. Distribution of Maize Yield Across Experimental Observations

3.2 Maize Yield Variation Across Tillage and Organic Matter Treatments

The mean yield of maize was statistically different between tillage treatments. Traditional rotary tillage had the highest mean yield (4.448 ± 0.363), followed by no tillage (4.390 ± 0.423) and earthworm bio-tillage (4.027 ± 0.594). In the case of organic matter treatments, the highest mean yield (4.554 ± 0.312) was from the control group which did not have any organic matter input, while the mean yields for the straw and composted cow manure were 4.169 and 4.141, respectively. The highest mean yield was obtained when traditional rotary tillage was applied without any organic matter input (4.626), while the lowest mean yield was obtained when earthworm bio-tillage was practiced with composted cow manure (3.775). These treatment-specific differences are summarized in Table 2 and illustrated in Figure 2.

Table 2. Maize Yield Across Tillage and Organic Matter Treatment Combinations

Tillage treatment	Organic matter treatment	n	Mean yield	SD
No tillage	No organic input	4	4.615	0.495
No tillage	Straw	4	4.088	0.156
No tillage	Composted cow manure	4	4.466	0.435
Earthworm bio-tillage	No organic input	4	4.422	0.123
Earthworm bio-tillage	Straw	4	3.883	0.232
Earthworm bio-tillage	Composted cow manure	4	3.775	0.952
Traditional rotary tillage	No organic input	4	4.626	0.250
Traditional rotary tillage	Straw	4	4.537	0.179
Traditional rotary tillage	Composted cow manure	4	4.183	0.492

Two-way ANOVA showed that neither the tillage main effect ($F = 3.185$, $p = 0.057$) nor the organic matter main effect ($F = 3.250$, $p = 0.054$) reached the predefined 0.05 significance threshold. The interaction between tillage and organic matter management was also nonsignificant ($F = 0.904$, $p = 0.476$), indicating insufficient statistical evidence of differential organic matter responses across tillage treatments.

Table 3. Two-Way ANOVA of Maize Yield Across Tillage and Organic Matter Treatments

Source of variation	df	Sum of squares	F-value	p-value
Tillage practice	2	1.253	3.185	0.057
Organic matter treatment	2	1.279	3.250	0.054
Tillage × organic matter	4	0.711	0.904	0.476
Residual	27	5.311	—	—

Note: df = degrees of freedom. No tested effect was statistically significant at $p < 0.05$.
Figure 2 presents the treatment-specific mean yields, allowing visual comparison of the nine management combinations.

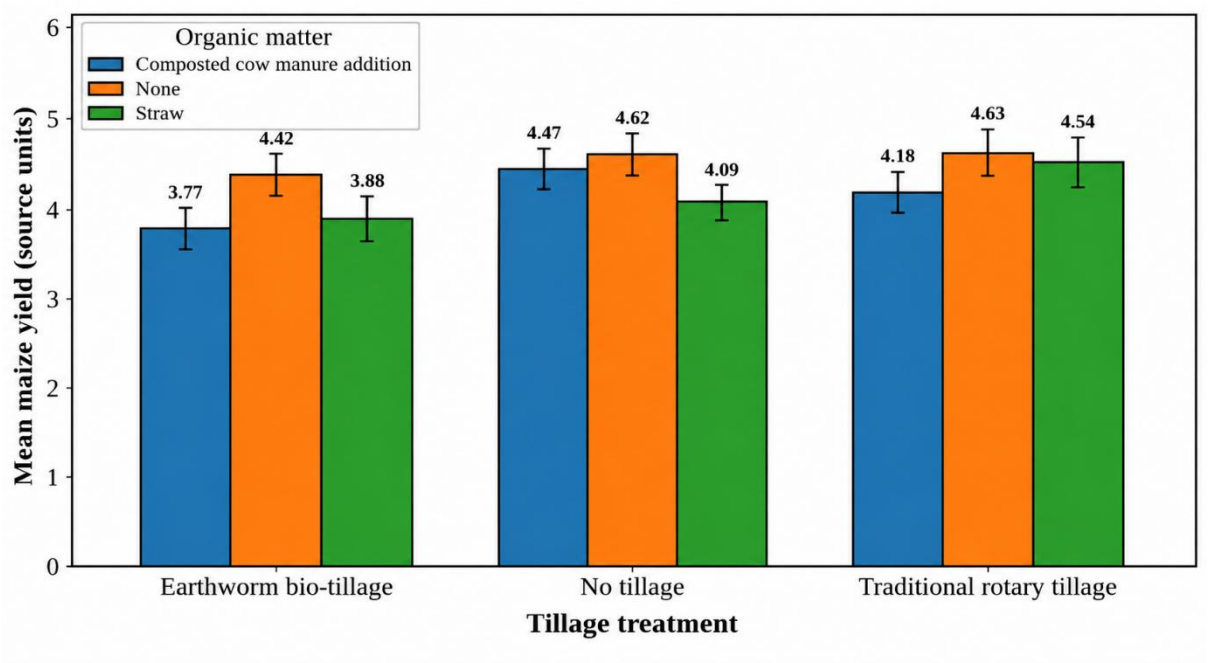


Figure 2. Mean Maize Yield Across Tillage and Organic Matter Treatments

3.3 Relationships Between Soil Fertility Indicators and Maize Yield

The Pearson correlation analysis results showed that there were generally weak correlations between maize production and soil fertility attributes. The soil pH attribute recorded the highest negative correlation ($r = -0.281$, $p = 0.097$) with maize yield, whereas soil moisture content exhibited the strongest positive correlation ($r = 0.231$, $p = 0.176$). The other soil fertility attributes like soil organic carbon, total nitrogen, total phosphorus, available nitrogen, and Olsen phosphorus were positively correlated with maize production. None of these correlations were statistically significant.

Table 4. Pearson Correlation Between Soil Fertility Indicators and Maize Yield

Soil fertility indicator	Pearson r	p-value
Soil pH	−0.281	0.097
SOC	0.061	0.723
TN	0.086	0.620
TP	0.029	0.866
Available nitrogen	0.095	0.580
Olsen phosphorus	0.131	0.448
Soil water content	0.231	0.176

Note: All correlations were calculated using 36 observations. None was statistically significant at $p < 0.05$.
The overall relationships among maize yield and soil fertility indicators are illustrated in Figure 3 through a Pearson correlation matrix.

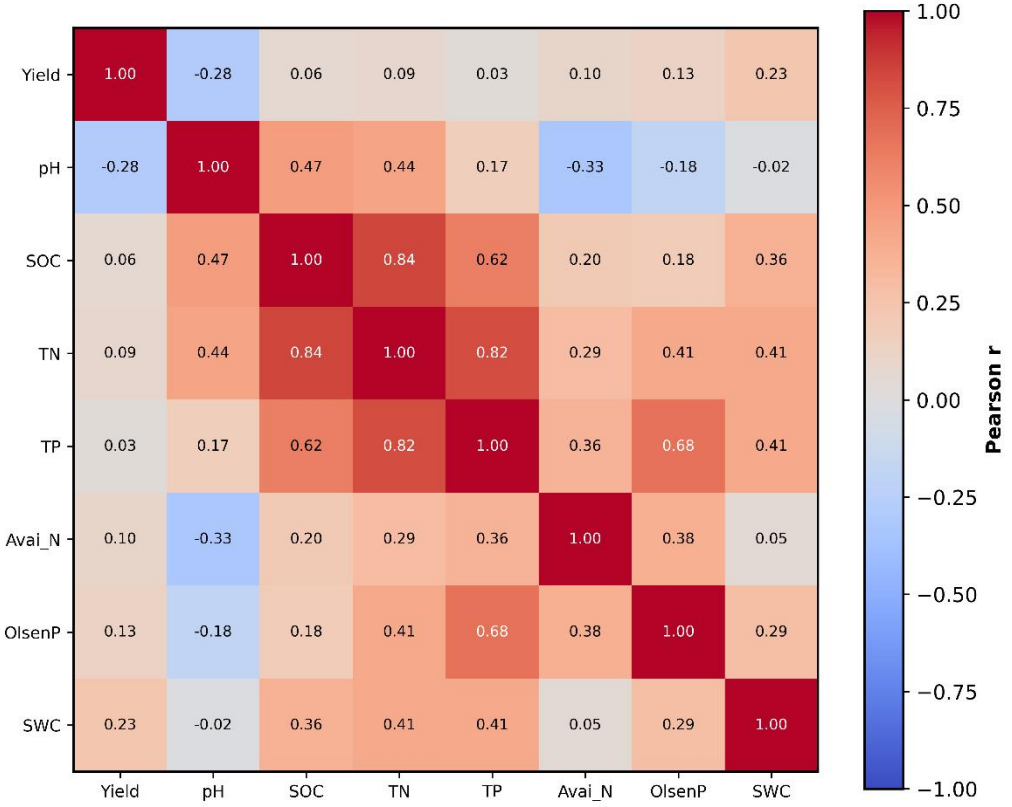


Figure 3. Correlation Matrix of Maize Yield and Soil Fertility Indicators

3.4 Multiple Linear Regression Analysis of Maize Yield

A multiple linear regression was conducted to explore the combined effects of the mentioned tillage practices, application of organic matter, SOC, and Olsen phosphorus on maize yield. Earthworm bio-tillage and composting cow manure were used as the reference groups. The percentage of the variance in maize yield explained by the model was about 31.0% ($R^2 = 0.310$; adjusted $R^2 = 0.167$).

Traditional rotary tillage had a positive effect on maize yield in comparison with earthworm bio-tillage ($\beta = 0.421$, 95% CI: 0.021–0.820, $p = 0.039$). No tillage also had a positive impact on the yield, yet it was insignificant ($p = 0.261$). The lack of organic matter application had a positive effect, but it was also insignificant relative to composted cow manure ($p = 0.059$). There was no significant effect of SOC and Olsen phosphorus on maize yield after accounting for treatment variables.

Table 5. Multiple Linear Regression Analysis of Factors Associated with Maize Yield

Predictor	β coefficient	95% CI	p-value
Intercept	3.433	1.845 to 5.021	<0.001
No tillage	0.308	−0.229 to 0.845	0.261
Traditional rotary tillage	0.421	0.021 to 0.820	0.039
No organic input	0.470	−0.018 to 0.957	0.059
Straw application	0.082	−0.410 to 0.574	0.743
SOC	0.041	−0.122 to 0.205	0.620
Olsen phosphorus	0.001	−0.022 to 0.023	0.959

Note: $R^2 = 0.310$; adjusted $R^2 = 0.167$. Reference categories were earthworm bio-tillage and composted cow manure addition. Confidence intervals and p-values were calculated using HC3 heteroscedasticity-robust standard errors.

The adjusted regression coefficients and corresponding 95% confidence intervals are illustrated in Figure 4.

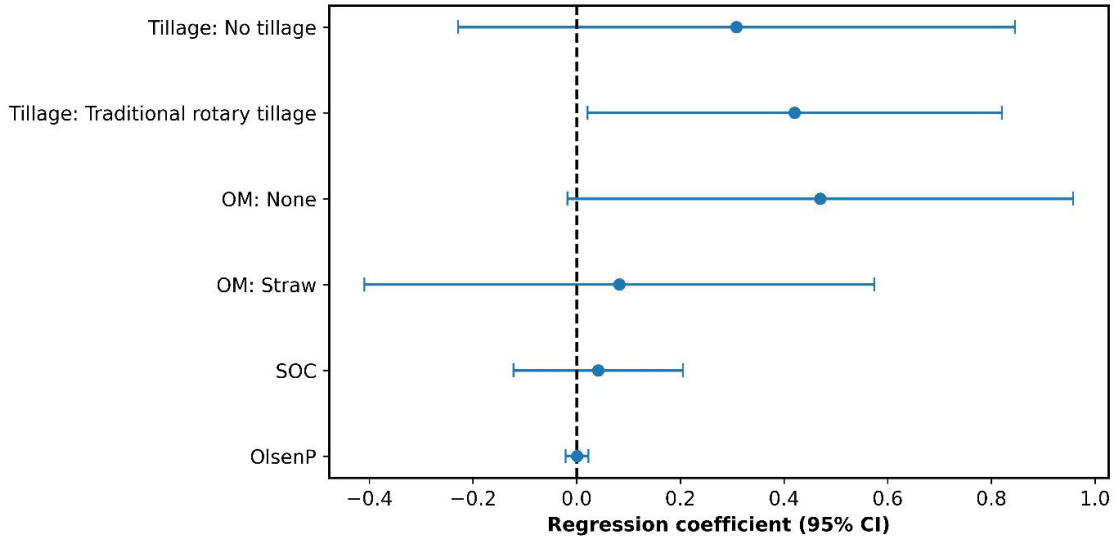


Figure 4. Regression Coefficients of Factors Associated with Maize Yield

3.5 Model Performance and Diagnostic Assessment

Analysis of regression diagnostics was carried out to determine the reliability of the model. There was no evidence of a deviation from the normality of residuals in the Shapiro-Wilk test, as p-value = 0.427. Variance inflation factor values varied between 1.37 and 1.76, meaning there was no multicollinearity in the predictors that were used. The highest Cook's distance value is 0.396, which means at least one observation needed further analysis in terms of its influence. Even though the model accounted for some variance, its relatively low adjusted R^2 shows that it had low explanatory power.

Maize yield differed among treatments for tillage and organic matter management with traditional rotary tillage having the highest mean yield of all. Two-way ANOVA failed to reveal any significance between the treatments or interaction effects. Indicators of soil fertility were poorly correlated with maize yield in a non-significant way. Multiple linear regression found that there was a significant relationship between traditional rotary tillage and maize yield compared with earthworm bio-tillage.

4. Discussion

The present study evaluated maize yield variability under different soil fertility and tillage conditions using statistical modeling. The results showed there were numerical differences in maize yields between tillage and organic matter treatments, but these were not significant. Overall mean yield was the highest in the traditional rotary tillage, followed by no tillage and earthworm bio-tillage with 4.448, 4.390 and 4.027 yield, respectively. These results indicate that tillage management can impact maize productivity, with variation in responses to the treatments due to soil and management conditions. Past studies have shown that integration of tillage and nitrogen management could enhance soil fertility and crop production in cereal based cropping systems (Cui et al., 2023). Likewise, the adoption of conventional tillage along with organic and inorganic fertilizers for maize cultivation has been found to help increase maize yield and soil fertility (Gao, M., et al., 2025).

Differences in soil structure, nutrient distribution and root development might account for the difference in maize yield between tillage treatments. In the adjusted regression model the relationship between earthworm bio-tillages and the maize yield was negative, while the traditional rotary tillage had a positive relationship ($\beta = 0.421$, $p = 0.039$). But this association should be viewed with some care since the overall ANOVA failed to detect a significant tillage effect. The effect of tillage on maize root–shoot development and grain yield can be changed by soil compaction differences (Gao, Z., et al., 2025). Meta-analysis results have also shown that the impact of soil management practices on crop productivity varies between agricultural conditions (Liang et al., 2025). In addition, the use of conservation tillage in conjunction with nitrogen management can impact maize yield as well as nutrient-related environmental impacts (Meng et al., 2025). These results highlight the need to assess tillage systems for their particular soil environments, as opposed to assuming that they are all better.

Numerical differences were also observed in maize productivity as a result of the management of organic matter. The mean yield of treatment without organic matter addition was the highest (4.554) followed by straw addition (4.169) and addition of composted cow manure (4.141). However, the main effect of organic matter was not significant ($p = 0.054$). The long-term effects of tillage and residue management have shown that soil nutrient availability can affect crop productivity over time (Li et al., 2025). In the same way, nutrient uptake and soil fertility have been linked to fertilizer management in crop rotation production systems (Pendke et al., 2025). Maize straw application has been shown in meta-analysis to have the potential to boost soil fertility and crop yields in agricultural regions, with varying responses depending on environmental and management factors (Wang, X., et al., 2025; Xiao et al., 2025).

Correlation analysis showed only weak and nonsignificant relationships between the soil fertility indicators measured and the maize yield. The soil pH exhibited the highest negative correlation ($r = -0.281$) while the soil water content had the highest positive correlation ($r = 0.231$). These results indicate that soil indicators as such accounted for a low level of

variation in the yield of the experimental observations. Soil fertility, nitrogen dynamics and water availability have been identified as key factors influencing crop productivity in previous modeling studies (Kumar et al., 2024). Conservation tillage has also been shown to be a promising solution to stabilize maize yields in the face of climate change through simulation-based research (Liu, H., et al., 2024). Long-term agro hydrological simulations also suggest that the alteration of soil water dynamics due to tillage may affect maize production (Pinheiro & Nunes, 2023). Similar modelling has highlighted the influence of the interplay between tillage and irrigation and soil texture on cereal productivity (Shahadha & Wendroth, 2025).

The model for the regression of maize yield accounted for only about 31.0% of the variability in maize yield, and had an adjusted R^2 of 0.167, a value considered as modest. All of these indicate the complexity by which crops respond and indicate that there might be more environmental and management factors that influence crop yields. More extensive research in agriculture has revealed that tillage systems and fertilization practices can also affect soil carbon sequestration (Ispas et al., 2025) and that there are interactions between climate, crop rotation and tillage on yield responses, as identified by long-term experiments (Ordóñez et al., 2025). The small number of subjects, the limited system of treatments and the absence of independent model validation were limitations of the present study. Future studies should be based on more detailed experimental observations in larger seasons to give greater statistical validity and generality.

5. Conclusion

The present work investigated the variability in maize production under various soil fertility and tillage levels by statistical modelling of experimental observations. Results showed maize yield differences among the different tillage practices and organic matter management treatments. The traditional tillage method (rotary tillage) gave the highest mean maize yield, followed by the no tillage and earthworm bio-tillage methods. But there was no significant tillage, organic matter or tillage x organic matter interaction for maize yield by two-way analysis of variance. With these findings, it was not possible to conclude consistent management effects within the experimental conditions. Weak and statistically non-significant relationships were found between maize yield and individual soil fertility indicators based on the correlation analysis. The soil pH was negatively associated, while soil water content was positively associated with maize productivity. The multiple linear regression indicated that traditional rotary tillage was significantly and positively related to the maize yield with reference to earthworm bio-tillages. However, the model failed to provide a sufficient explanation of the results obtained, indicating that there may be other agricultural and environmental factors that influence yield variation. The results in total indicate that the relationship between soil fertility, tillage management and maize productivity is complex. Sample size and experimental conditions are relatively small, and the results are limited. Future research with larger samples of experiments, more growing seasons and other environmental factors are proposed for better statistical reliability and evidence-based soil management for sustainable maize production.

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