

# Optimizing organic waste and tillage for post-mining soil rehabilitation with response surface methodology

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**Abstract.** Zainudin, Roeswitawati D, Sutanto A, Ikhwan A, Kesumaningwati R. 2025. *Optimizing organic waste and tillage for post-mining soil rehabilitation with response surface methodology*. *Asian J Agric* 9: 739-753. Rapid urban population growth has significantly increased Municipal Organic Waste (MOW) generation, creating ecological challenges but also opportunities for sustainable land rehabilitation. In Samarinda, East Kalimantan, Indonesia, post mining degradation is a critical environmental issue that requires innovative restoration strategies. This study examined the application of MOW as a soil amendment, combined with Soil Tillage (ST), to improve chemical properties of degraded post-mining soils. A Box-Behnken design under Response Surface Methodology (RSM) was used to evaluate the effect of tillage depth (5-15 cm), Incubation Time (IT) (60-120 days) and waste dosage (20-60 t ha<sup>-1</sup>), resulting in 17 treatment combinations. The MOW included food scraps, vegetable residues, and fruit waste, excluding fish and shrimp residues. Soil analysis covered pH, Organic Carbon (OC), Total Nitrogen (TN), C/N ratio, available phosphorous (P), potassium (K), Cation Exchange Capacity (CEC), and Base Saturation (BS). The optimal condition was identified at 15 cm tillage depth, 103.48 days incubation, and 36.48 t ha<sup>-1</sup> waste, resulting in improvements in the characteristics of post-coal mining soil (pH: 7.43; OC: 1.26%; TN: 0.17%; C/N: 7.58; P: 36.34 ppm; K: 168.73 ppm; CEC: 15.54 me 100<sup>-1</sup> g; BISA: 96.61).

**Keywords:** Organic municipal waste, post mining land rehabilitation, response surface methodology, soil chemical properties

## INTRODUCTION

Coal mining has significantly contributed to Indonesia's economic development, particularly in resource-abundant provinces such as East Kalimantan. However, the rapid expansion of extractive industries has resulted in extensive environmental degradation. One of the most critical challenges is the deterioration of post-mining soils, especially in urban centers such as Samarinda. These soils typically suffer from reduced fertility, altered physical structure, loss of organic matter, and contamination with heavy metals, leading to the disruption of ecological functions and severely limiting the land's potential for agricultural or forestry use (Zhang et al. 2021). Such degradation is commonly associated with low pH, poor nutrient status, and limited microbial activity, all of which inhibit natural regeneration (Ansahar et al. 2022; Sunarto et al. 2023).

On a global scale, soil degradation caused by mining operations is a pressing concern. It not only results in the loss of productive land but also poses risks to biodiversity, water quality, and human health due to the mobilization of toxic elements. In tropical regions, the recovery of degraded soils is particularly challenging due to high rainfall, intense leaching, and the presence of Fe and Al-oxides, which immobilize essential nutrients such as P (Prasetya et al. 2024). Moreover, mining-induced soil

compaction and erosion further diminish the soil's physical integrity, making restoration efforts more complex. These challenges underscore the urgent need for sustainable and scientifically sound rehabilitation strategies that can effectively restore soil quality and function.

In Indonesia, post-mining land reclamation is not only an environmental necessity but also a legal and socioeconomic obligation. Following the expiration of mining permits companies are required to rehabilitate former mining sites. Increasingly, reclamation efforts are expected to go beyond ecological restoration and aim to transform degraded landscapes into productive lands that support local livelihoods, food security, and climate resilience. Consequently, the development of cost-effective, environmentally friendly, and scalable soil amendment technologies is of paramount importance.

One promising approach to rehabilitating degraded mining soils is the application of organic waste. Municipal and agricultural residues, especially from households, markets, and agro-industries—remain underutilized in many urban areas, including Samarinda. When properly composted, these wastes can improve soil structure, increase organic matter, enhance microbial activity, and boost nutrient availability (O'Connor et al. 2021; Cao et al. 2023). This practice also aligns with circular economic goals by reducing landfill waste and promoting carbon sequestration. Additionally, the effective selection of

organic materials and management practices is crucial for sustaining soil organic carbon levels and ensuring long-term soil health (Navarro-Pedreño et al. 2021; Abbey et al. 2022). Despite its potential, the effectiveness of organic waste application depends on several interacting variables, such as application rate, application frequency, compost maturity, tillage depth, and incubation period (Voltr et al. 2021). These factors collectively influence key soil chemical processes, including the mobilization and retention of macronutrients like nitrogen and phosphorus—both critical for plant growth (Novair et al. 2024). However, many previous studies have examined these variables independently, which limits understanding of their synergistic effects under tropical conditions and in highly degraded post-mining soils.

To address this gap, the present study employs RSM, a statistical technique designed for modeling and optimizing complex systems involving multiple interacting variables. Using a Box–Behnken design, this research systematically investigates the effects of organic waste dosage, tillage depth, and incubation time on the chemical properties of degraded mining soils. RSM is particularly advantageous over traditional trial-and-error or single-variable experimental approaches because it enables the development of predictive models, quantifies variable interactions, and identifies optimal conditions for specific outcomes (Veza et al. 2023). While methods such as Analysis of Variance (ANOVA) are effective for determining statistical significance, RSM offers a more comprehensive framework for optimization and decision-making in complex environmental systems (Breig and Luti 2021; Chelladurai et al. 2020).

Despite RSM's growing application in environmental research, few studies have explored its potential for simultaneously optimizing the combined effects of OW, ST, and IT—particularly in tropical post-mining soils. This study seeks to address this gap by applying RSM to identify optimal combinations of these variables for improving key soil chemical properties. We hypothesized that RSM can determine effective combinations of organic waste application, tillage depth, and incubation time to enhance post-mining soil quality. Key indicators evaluated include pH, Organic Carbon (OC), total-N, available P, K, exchangeable-Cation Exchange Capacity (CEC), and Base Saturation (BS). By integrating sustainable waste management practices with data-driven optimization, this research aims to provide a practical and scalable framework for rehabilitating tropical post-coal mining landscapes.

## MATERIALS AND METHODS

### Experimental design and materials

The study was conducted at a post coal mining site in Samarinda City, East Kalimantan, Indonesia (coordinates: 00°29'34" S; 117°10'80" E). The experimental site represents a degraded landscape characterized by low soil fertility and poor soil structure, typical of post-mining areas. This research employed the Response Surface Methodology (RSM) using a Box–Behnken Design (BBD)

to optimize post-mining soil rehabilitation by evaluating the effect of three independent variables: soil tillage depth, incubation time, and municipal organic waste dosage.

The experiment was carried out under field conditions with two replications for each treatment combination to ensure data reliability and minimize experimental error. The experimental design consisted of 17 treatment combinations, as shown in Tables 1 and 2. The ranges and levels of the independent variables are presented below. The experimental design and data analysis were conducted and validated using Design Expert version 13 software to assess model accuracy and optimize the response variables.

These variables were selected based on agronomic relevance: Tillage depth (5-15 cm): Represents shallow to moderate tillage to improve structure and root penetration without excessive disturbance. Incubation time (60-120 days): Captures early to mid-term effects of soil amendment under tropical conditions. Organic waste dosage (20-60 t ha<sup>-1</sup>): Chosen based on prior studies and field practices promoting soil fertility improvement.

### Soil and organic waste preparation

Post-coal mining soil was collected from a degraded site and manually homogenized before being placed into raised beds (1×2 m) with 30 cm spacing between units to ensure aeration. The soil was tilled according to the designated depths of 5 cm, 10 cm, and 15 cm as per the treatment combinations.

**Table 1.** The ranges and the level of the independent variables

Factor	Symbol	Levels	Unit
Soil tillage depth	A	5-10-15	cm
Incubation time	B	60-90-120	days
Municipal organic waste dosage	C	20-40-60	tons ha <sup>-1</sup>

**Table 2.** Experimental design for organic waste application in post-coal mining land using Response Surface Methodology (RSM) Box–Behnken

Run	Factor A: ST (cm)	Factor B: IT (days)	Factor C: MOW (t ha <sup>-1</sup> )
1	10	60	60
2	15	90	20
3	10	120	60
4	10	90	40
5	10	90	40
6	10	90	40
7	5	120	40
8	15	120	40
9	15	60	40
10	10	60	20
11	10	120	20
12	10	90	40
13	10	90	40
14	15	90	60
15	5	90	60
16	5	60	40

Note: ST: Soil Tillage, IT: Incubation Time, MOW: Municipal Organic Waste

Raw municipal organic waste was collected from Temporary Disposal Sites (TPS) in Samarinda City, consisting primarily of food scraps, vegetable residues, and fruit waste, with the exclusion of fish and shrimp remains. The waste was selected for its high nutrient content and local availability. After collection, the waste was directly incorporated into the pre-tilled soil and mixed thoroughly according to the specified dosages. The amended soil was then subjected to incubation periods of 60, 90, and 120 days, in line with the RSM matrix.

### Soil chemical and biological analysis

Soil analysis comprised both baseline (pre-treatment) and post-treatment assessments following the application of organic waste. The initial soil analysis included the following parameters. Each treatment was replicated three times to ensure statistical reliability. Microbiological data obtained from the same experimental setup are presented in a separate publication and are not included in this article (Zainudin et al. 2025) (Tables 3 and 4).

### Soil sampling and analysis

At the end of each incubation period, composite soil samples were collected from each treatment plot. Samples were air dried, sieved (2 mm), and analyzed for key chemical properties: pH (measured using a pH meter in H<sub>2</sub>O 1:2.5 suspension), organic-C (Walkley-Black method), total-N (Kjeldahl digestion), C/N ratio, available-P (Bray I method), available-K (ammonium acetate extraction), CEC, and BS.

### Data analysis and model evaluation

The dataset was analyzed using ANOVA in Design-Expert v13 to evaluate the significance of model terms. Model performance was assessed based on: Coefficient of Determination (R<sup>2</sup>), Adjusted R<sup>2</sup> and Predicted R<sup>2</sup>, and Lack of fit test. These statistics were used to confirm model adequacy and predictive reliability.

### Response surface visualization and optimization

The relationships and interactions among the independent variables were visualized through 3D response surface plots. These visual tools facilitated the identification of optimal conditions for improving soil chemical properties. The model predictions were validated

through confirmatory trials, ensuring the robustness and practical applicability of the findings.

## RESULTS AND DISCUSSION

### Response surface analysis on soil physicochemical properties

The reliability of the experimental results was assessed using F-and p-value from ANOVA. Generally, a high F-value combined with a low p-value ( $\leq 0.05$ ) indicates a robust model. For soil pH, the model yielded an F-value of 2.68 and a p-value of 0.1040, indicating that the overall model was not statistically significant, as the p-value exceeded the conventional threshold of 0.05 and the F-value was not sufficiently high to demonstrate a strong model fit. This outcome underscores the preliminary nature of the study and suggests the need for further refinement through increased sample size, expanded variable selection, or alternative modeling approaches (Sae-Tun et al. 2025). Despite the lack of overall model significance, ST was identified as a significant factor affecting soil pH ( $p=0.0466$ ). This suggests that tillage practices may contribute to increasing soil pH in post-mining soils, likely through enhanced aeration and redistribution of organic matter. Different results were reported by Sadiq et al. (2021) through a three-year study, which stated that soil pH was not affected by tillage depth or differences in tillage systems, although it tended to be lower under conservation tillage practices compared with conventional tillage. Incubation time ( $p=0.1245$ ) and municipal organic waste application ( $p=0.1022$ ) did not reach statistical significance; however, both factors exhibited trends approaching the significance threshold, indicating the need for further investigation under broader experimental conditions (Figure 1). Consistent with these findings, previous research employing municipal solid waste compost at application rates of 20, 40, and 60 t ha<sup>-1</sup> also reported no significant changes in soil pH (Oueriemmi et al. 2021). Regarding base saturation (BS), the model was also not significant overall; however, organic waste application showed a statistically significant positive effect on BS. This indicates potential for organic waste to improve specific soil chemical properties within the scope of this short-term experiment.

**Table 3.** Nutrient content of raw municipal organic waste

pH	OC	C/N	Total of N	Total of P	Total of K	Standard (Indonesian Minister of Agriculture 2019)
9.50	51.20	29.7	1.72	4.13	4.23	The soil pH (>9) and C/N ratio (>25) do not meet the standard, whereas organic carbon (>15%) and nutrient elements (N + P <sub>2</sub> O <sub>5</sub> + K <sub>2</sub> O >2%) comply with the standard.

**Table 4.** Characteristics of post-mining soil before the application of raw municipal organic waste

Location	pH	OC %	N (L)	C/N (M)	P available (mg kg <sup>-1</sup> ) (VL)	K (VH)	Al	Fe mg kg <sup>-1</sup>	Mn	BS (%) (VH)	CEC (meq 100 g <sup>-1</sup> ) (L)

Note: SA: Slightly Acidic, L: Low, M: Moderate, VL: Very Low, VH: Very High (Agency for Agricultural Development and Modernization 2023), CEC: Cation Exchange Capacity, BS: Base Saturation, OC: Organic Carbon

Other soil chemical properties—namely soil organic carbon, total nitrogen, C/N ratio, available phosphorus, available potassium, and Cation Exchange Capacity (CEC)—did not exhibit statistically significant responses to the tested variables. Nevertheless, preliminary trends indicated that incubation time may influence total nitrogen and available potassium, while organic waste appeared to have potential effects on CEC. These preliminary indications should be interpreted with caution due to the limited duration of the experiment (120 days) and the relatively small sample size in this preliminary study. According to Mahapatra et al. (2022), the application of organic materials is more beneficial when they are in a matured and stabilized form, such as well-decomposed compost. Furthermore, Roy et al. (2024) emphasized that while biochar, vermicompost, and duckweed amendments hold significant potential for improving soil quality and mitigating heavy metal contamination, long-term field trials are essential to validate their efficacy under diverse agricultural conditions. Additional statistical diagnostics are provided in Table 5, which summarizes fit statistics across the measured responses. The coefficient of variation (C.V.%) highlights high relative variability in some responses, particularly P (60.53%) and base saturation (92.97%), reflecting spatial and compositional heterogeneity typical of post-mining soils. While  $R^2$  values ranged from moderate (0.5813 for P) to strong (0.7965 for CEC), indicating how well the models fit the data, adjusted  $R^2$  values were substantially lower in most cases (e.g., 0.0471 for OC), revealing that the inclusion of non-significant terms likely reduced overall model efficiency.

Of particular concern are the negative predicted  $R^2$  values for nearly all responses (e.g., -3.0922 for TN, -3.3842 for K), which suggest that the models have limited predictive capacity outside the experimental dataset. This may result from overfitting, insufficient replication, or an inadequate range of treatments. Nevertheless, adequate precision values exceeded the minimum threshold of 4 for pH (5.96), TN (4.82), C/N (4.46), and BS (6.18), indicating that despite low predictive power, the models still maintained acceptable signal-to-noise ratios for certain variables.

The Box–Behnken design used in this study efficiently explored interaction effects between factors, but did not consistently yield statistically strong or predictive models. These statistical limitations may stem from narrow treatment levels, the short duration of soil incubation, and the high natural variability of tropical post-mining soils. The absence of significant changes in organic carbon is consistent with previous short-term studies and may also reflect microbial priming effects—where added labile organic matter accelerates decomposition of native organic matter—leading to net carbon loss (Zhu et al. 2021). Similarly, tillage did not significantly affect total-P or K, aligning with Wang et al. (2022). The lack of significant response in P to organic inputs concurs with Noor et al. (2023), who also observed minimal P increases in short-term manure application trials.

Importantly, this study was conducted under controlled laboratory conditions and does not fully represent field conditions, where climatic and biological variability play a critical role in soil response. As such, these findings should be viewed as exploratory. This study is best understood as a pilot investigation designed to test a methodological framework using RSM in tropical post-mining soils—a context that remains underexplored. The novelty of this work lies primarily in the application of the experimental design and modeling approach rather than in the statistical significance of the findings. Future research should include longer-term, field-based experiments with expanded replication and treatment levels to better capture treatment effects and validate the proposed framework for practical soil rehabilitation strategies.

Figure 2 illustrates the interaction effects of the variables on soil pH. Panel A shows that soil pH increased with longer IT and greater tillage depth. Panel B indicates that soil pH increased with higher MOW dosages, although the effect of ST was less pronounced. Panel C shows that while pH increased with longer IT, the dosage of organic waste had a limited effect on soil pH.

$$\text{pH} = 7.27 + 0.4925A + 0.3563B - 0.3838C - 0.2450AB - 0.1250AC - 0.5525BC - 0.5123A^2 + 0.0852B^2 - 0.5197C^2$$

Figure 3 illustrates the interaction effects of the variables on soil BS. Panel A shows that BS increased with increasing tillage depth (ST) and incubation time (IT). The lowest BS values were observed under shallow tillage and short incubation periods, whereas the highest BS values were achieved at greater tillage depths combined with moderate to long incubation times. Panel B indicates that BS increased with increasing tillage depth (ST) and organic waste application rate (OW). Lower BS values were observed under shallow tillage and low OW rates, whereas higher BS values were achieved at greater tillage depths combined with moderate to high OW application rates, indicating a synergistic effect of soil tillage and organic waste addition on BS improvement. Panel C shows that BS increased with longer incubation time (IT) and higher organic waste application rates (OW). Lower BS values were observed at shorter incubation periods and lower OW rates, whereas higher BS values were achieved under longer incubation times combined with moderate to high OW applications, indicating that prolonged incubation enhances the effectiveness of organic waste in improving BS.

$$\text{BS (\%)} = 98.67 + 1.90A + 1.01B - 8.35C - 1.48AB + 0.2600AC - 7.45BC - 5.99A^2 + 2.49B^2 - 8.61C^2$$

Where:

A: Soil tillage

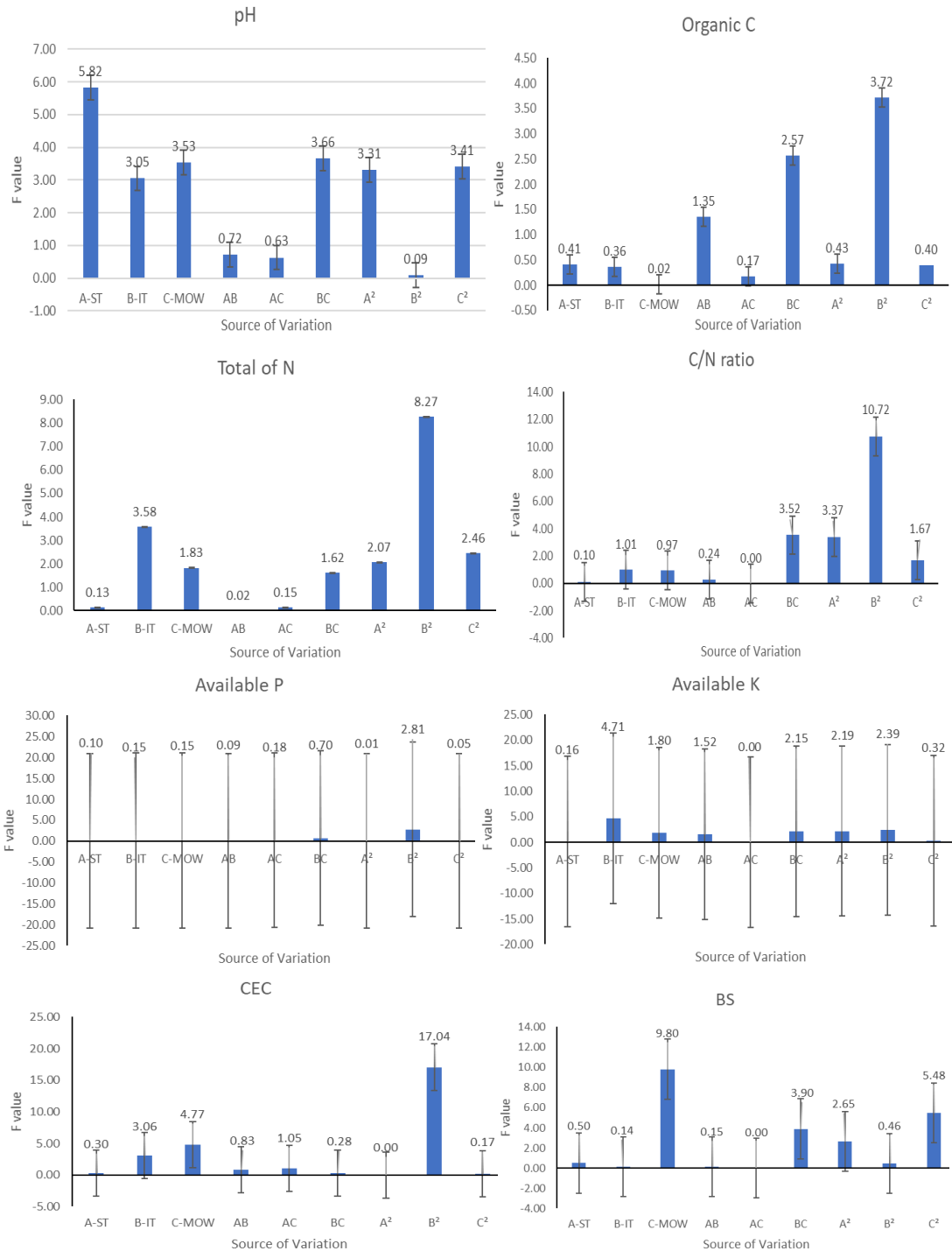
B: Incubation time

C: Municipal organic waste dosage

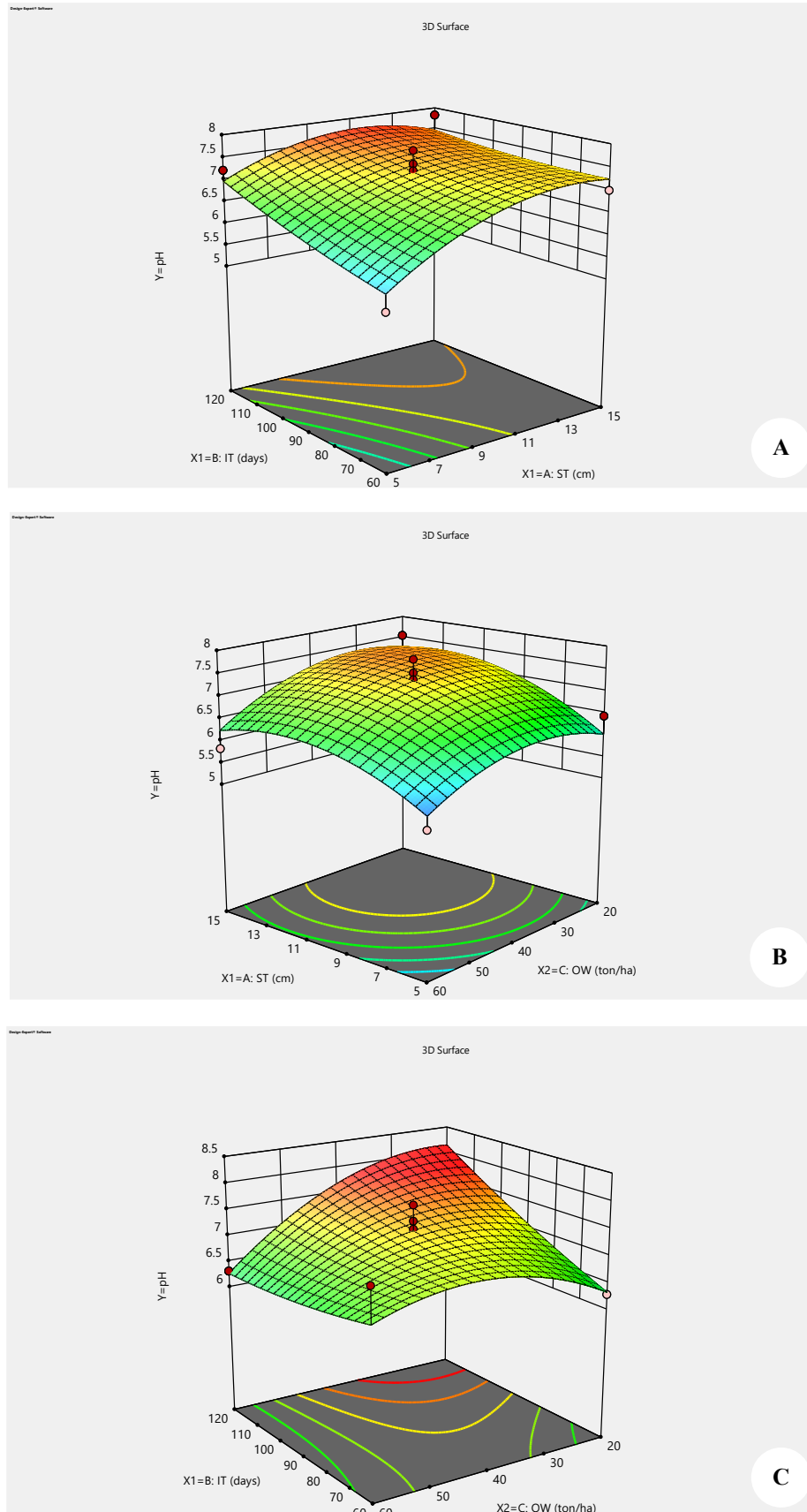
**Table 5.** Fit statistics

	pH	OC	N	C/N	P	K	CEC	BS
Std. Dev.	0.57	0.19	0.03	2.08	17.71	33.74	2.87	7.55
Mean	6.83	1.23	0.15	8.77	29.26	164.80	14.18	92.97
C.V. %	8.46	15.67	25.36	23.69	60.53	20.47	20.23	8.12
R <sup>2</sup>	0.77	0.58	0.73	0.75	0.38	0.68	0.79	0.76
Adjusted R <sup>2</sup>	0.48	0.04	0.40	0.44	-0.41	0.28	0.53	0.47
Predicted R <sup>2</sup>	-1.83	-2.39	-3.09	-1.97	-1.82	-3.38	0.46	-2.40
Adeq Precision	5.96	2.88	4.81	4.46	1.84	4.62	6.46	6.18

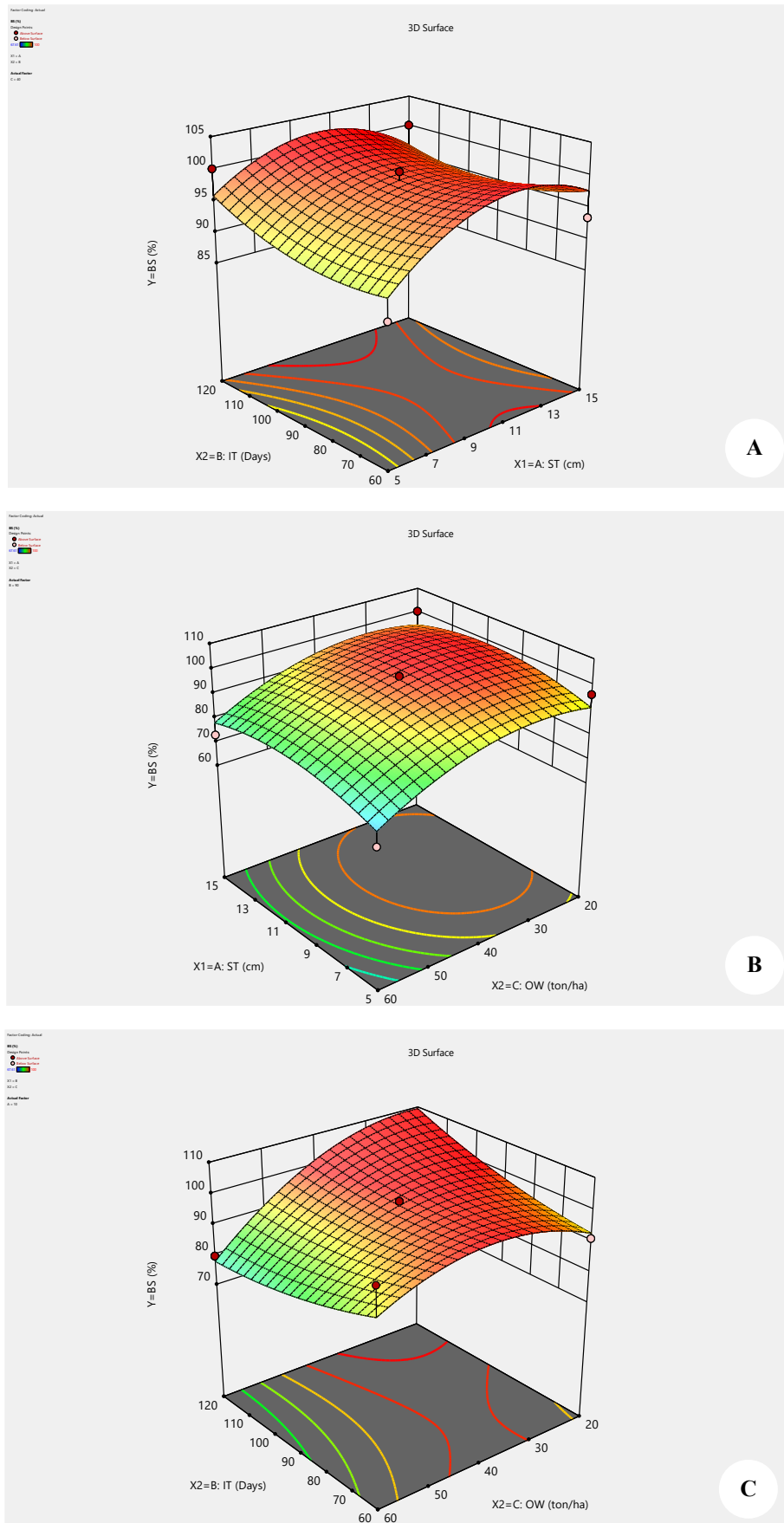
Note: CEC: Cation Exchange Capacity, BS: Base Saturation, OC: Organic Carbon



**Figure 1.** F-value analysis showing the effects of different factors and their interactions on pH, organic C, total N, C/N ratio, available P, available K, CEC, and BS responses. CEC: Cation Exchange Capacity and BS: Base Saturation



**Figure 2.** Response surface plots showing the effect of variable interactions on soil pH. A. Interaction between ST depth and IT, B. ST and MOW dosage, and C. IT and MOW dosage. Each plot illustrates how the combination of two factors influences soil pH, with the third factor held constant. Axes are labeled with corresponding units to facilitate interpretation



**Figure 3.** Response surface plots showing the effect of variable interactions on Base Saturation (BS) of soil. A. Interaction between ST depth and IT, B. ST depth and MOW dosage, and C. IT and MOW dosage. Each plot illustrates how the combination of two factors influences soil BS, with the third factor held constant. Axes are labeled with corresponding units to facilitate interpretation

The results of the analysis of the effects of ST, IT, and MOW dosage on the characteristics of post-coal mining soil are presented in Table 6. The bootstrap distribution of organic carbon means exhibits a near-normal shape centered around 1.25 ton/ha, as shown by the histogram of 1,000 bootstrap resamples and its smooth probability density curve. This confirms the stability and reliability of the sample means (Figure 4). Ordinary Least Squares (OLS) regression results indicate no significant effects of ST, IT, or MOW on organic-C, supported by high p-values ( $>0.05$ ) and low  $R^2$  (0.047). Diagnostic tests show no major assumption violations. Overall, the bootstrap analysis validates the robustness of the organic-C mean, while the tested variables do not significantly explain their variability under current conditions.

The bootstrap distribution of total nitrogen means displays a near-normal shape centered around approximately 0.15, as illustrated by the histogram and the smooth density curve derived from 1,000 bootstrap resampling iterations (Figure 5). This visualization confirms the stability and reliability of the sample means as an estimate of the population's means.

The OLS regression results reveal that ST, IT, and MOW applications do not have statistically significant effects on total nitrogen, as reflected by high p-values ( $>0.05$ ) and a low  $R^2$  (0.206). Diagnostic tests confirm no major violations of model assumptions. Overall, the bootstrap analysis supports the robustness of the mean total nitrogen estimate, while the explanatory variables tested do not significantly account for its variation under the current experimental conditions.

The bootstrap distribution of C/N means (Figure 6) shows a near-normal pattern centered around approximately 12.9, with the histogram depicting the frequency of mean values obtained from 1,000 bootstrap resampling iterations and the overlaid curve representing the estimated probability density. This indicates a stable and reliable sample mean estimate for the C/N ratio. The OLS regression results reveal no significant effects of ST, IT, and MOW on the C/N ratio, as supported by high p-values ( $>0.05$ ) and a low  $R^2$  (0.073). Diagnostic tests indicate no major violations of regression assumptions. Overall, the bootstrap analysis confirms the stability of the mean C/N ratio, while the tested explanatory variables do not significantly explain its variation under the current experimental conditions.

The bootstrap distribution of phosphorus means shows a near-normal pattern centered around 29 mg kg<sup>-1</sup>, indicating the sample mean is a reliable estimate of the population mean. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations, with the overlaid smooth curve representing the estimated probability density. This visualization confirms the stability and consistency of the phosphorus mean estimate across resampled datasets (Figure 7). The OLS regression results reveal no significant effects of ST, IT, and MOW on phosphorus levels, supported by a low  $R^2$  (0.035) and high p-values ( $>0.05$ ). Diagnostic tests confirm no major violations of model assumptions. Overall, P concentration appears stable but is not explained by the

tested variables, suggesting other factors may influence its variability.

The bootstrap distribution of potassium means shows a near-normal pattern centered around 165 mg/kg, confirming the stability and reliability of the sample mean (Figure 8). This is illustrated by the histogram of 1,000 bootstrap resamples with the overlaid density curve. OLS regression results show no significant effects of ST, IT, and MOW on potassium levels (all  $p>0.05$ ), though incubation time approaches significance ( $p=0.070$ ). The model explains 29.9% of variance ( $R^2=0.299$ ) but has limited explanatory power (adjusted  $R^2=0.137$ ). Diagnostic tests reveal a slight deviation from normality but no major model issues. Overall, the bootstrap confirms the robustness of the potassium mean estimate, while regression results suggest the tested variables do not strongly influence potassium variability under current conditions.

The bootstrap distribution for soil pH exhibited an approximately normal distribution centered on a mean of 6.83, signifying a reliable and stable estimate (Figure 10). The histogram, representing 10,000 iterations, defines a 95% confidence interval between 6.44 and 7.18, which points toward adequate data representativeness and controlled variability. Regarding the impact of experimental variables, OLS regression revealed that ST, IT, and MOW had no statistically significant effects ( $p > 0.05$ ), indicating that variations in these parameters did not substantially affect soil acidity levels. Despite the model's limited explanatory power regarding total pH variability, diagnostic assessments confirmed the absence of major assumption violations. In conclusion, the analysis confirms the robustness of the soil pH mean and suggests that pH levels remain stable across various experimental conditions in the post-mining soil context.

The bootstrap analysis for base saturation (BS) yielded a near-normal distribution centered at 59.95%, suggesting that the calculated sample mean serves as a robust proxy for the population mean. Figure 11 displays the frequency of mean values generated from 10,000 iterations, where the probability density curve highlights a consistent and stable estimation process. This reliability is further supported by a tight 95% confidence interval spanning from 58.79% to 61.11%. Although the BS values remain stable across the study site, OLS regression analysis indicated that the independent variables tested had no significant impact, as reflected by the low  $R^2$  and p-values exceeding 0.05. Since model diagnostics showed no fundamental violations of assumptions, the observed variability in BS is likely driven by external factors not included in this model, such as leaching rates or parent material composition.

The regression analysis showed that ST, IT, and MOW applications did not significantly affect soil CEC. The overall model was not statistically significant ( $p=0.304$ ), and the  $R^2$  value was low (0.236), indicating limited explanatory power. None of the individual predictors had p-values below 0.05, meaning no variable showed a significant relationship with CEC. Although organic waste had a positive coefficient, the result was not statistically reliable. Diagnostic tests confirmed that model

assumptions, such as normality of residuals and independence, were met.

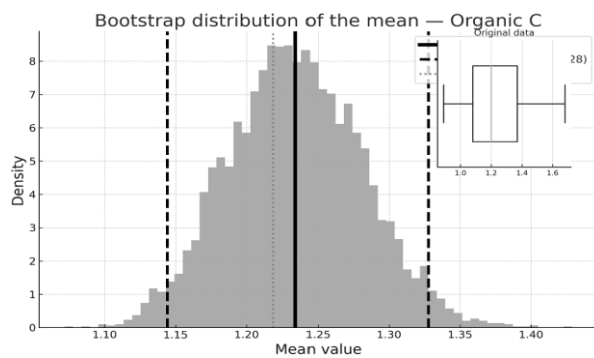
To further assess the stability and variability of the sample mean CEC, a bootstrap analysis with 1,000 resamples was conducted. The resulting distribution (Figure 9) is approximately normal and symmetric, centred around a mean of approximately 14, with most values ranging from 12 to 16. This indicates that the estimate of the mean CEC is relatively stable and reliable, despite the small sample size. The bootstrap distribution provides additional support for constructing confidence intervals, which can offer more robust inference when traditional parametric assumptions are in doubt.

The small sample size ( $n=17$ ) and unmeasured soil variables may have limited the regression model's ability to detect significant relationships, as larger training sample sizes are generally associated with improved prediction accuracy (Schmidinger et al. 2024). Therefore, future studies should consider larger datasets and potentially nonlinear or interaction models, as well as more

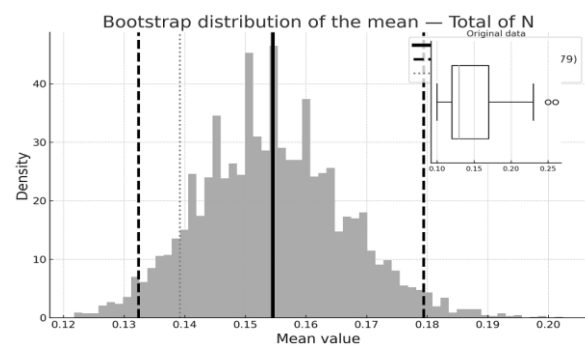
comprehensive soil property data, to better understand the factors influencing CEC.

### Optimization

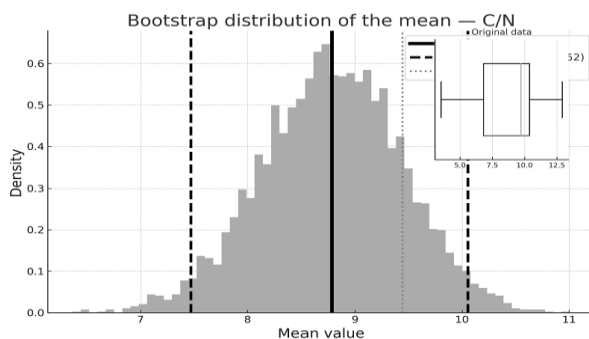
The optimization conditions for the chemical characteristics of post-mining soils following organic waste application were established based on the criteria presented in Table 7. To achieve these conditions, Response Surface Methodology (RSM) was employed. RSM has become a widely accepted optimization tool across various scientific domains due to its capacity to model and analyze complex interactions among multiple variables with fewer experimental runs (Aristizábal-Alzate et al. 2025). In contrast to the conventional one-factor-at-a-time (OFAT) approach, RSM offers a more efficient and systematic framework for optimizing multifaceted systems. Consequently, this study applied RSM to identify the optimal combination of ST, IT, and OW application for improving the selected chemical properties of post-mining soils.



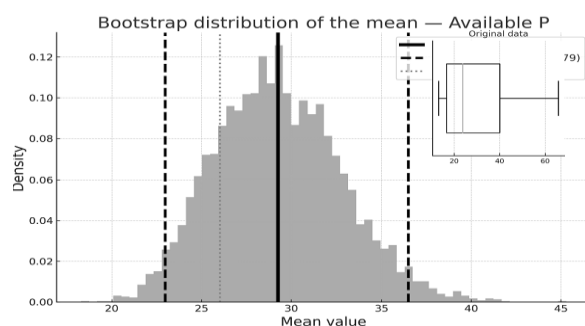
**Figure 4.** Distribution of bootstrap means for the C-organic parameter. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization demonstrates the stability and variability of the sample mean and provides the basis for constructing confidence intervals for the mean of organic-C



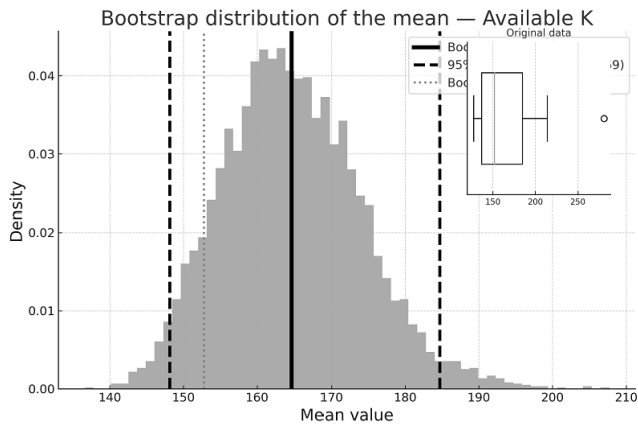
**Figure 5.** Distribution of bootstraps means for the total of N parameter. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization demonstrates the stability and variability of the sample mean, and provides the basis for constructing confidence intervals for the mean of total of N



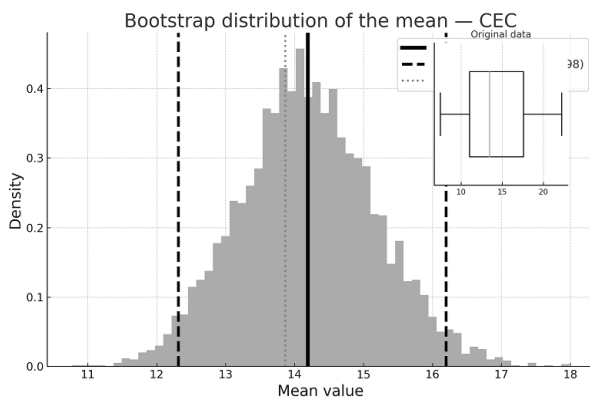
**Figure 6.** Distribution of bootstrap means for the C/N parameter. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization demonstrates the stability and variability of the sample mean and provides the basis for constructing confidence intervals for the mean of the C/N ratio



**Figure 7.** Distribution of bootstrap means for the available phosphorus (P) parameter. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization demonstrates the stability and variability of the sample mean, and provides the basis for constructing confidence intervals for the mean of available phosphorus

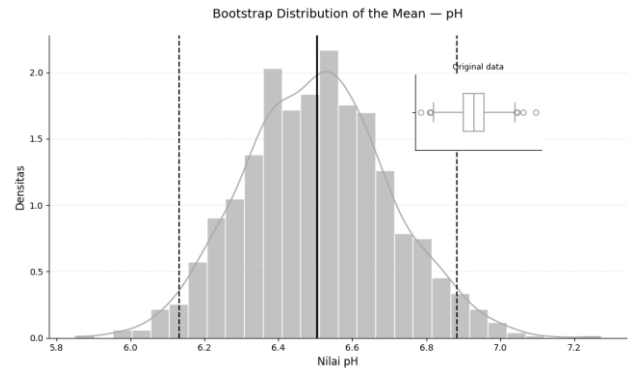


**Figure 8.** Distribution of bootstrap means for the available potassium (K) parameter. The histogram illustrates the frequency of mean values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization demonstrates the stability and variability of the sample mean, and provides the basis for constructing confidence intervals for the mean of available potassium

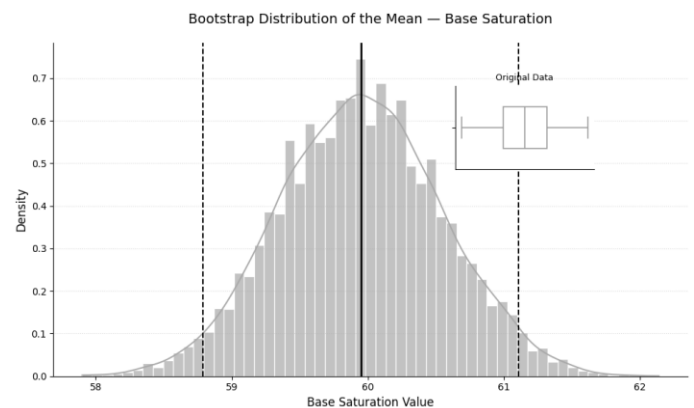


**Figure 9.** Distribution of bootstrap means for soil Cation Exchange Capacity (CEC). The histogram illustrates the frequency of mean CEC values obtained from 1,000 bootstrap resampling iterations based on the original dataset. The overlaid blue curve represents the estimated probability density, resembling a normal distribution. This visualization highlights the stability and variability of the sample mean and provides a statistical foundation for constructing confidence intervals for the mean CEC value in the studied soil samples

The optimization process yielded a treatment combination that maximized soil pH and BS—the two variables showing statistically significant responses. The optimal combination involved moderate tillage depth, an intermediate incubation period, and a specific dose of organic waste, collectively resulting in improved soil chemical conditions suitable for rehabilitation. The detailed results of these optimized conditions, comparing the predicted values against the observed experimental data, are summarized in Tables 8 and 9. Although some parameters, such as organic-C, N, and CEC did not show statistically significant changes, the use of RSM provided a



**Figure 10.** Distribution of bootstrap means for the soil pH parameter. The histogram illustrates the frequency of mean pH values obtained from 10,000 bootstrap resampling iterations based on the original dataset. The distribution exhibits a near-normal pattern centered around the sample mean, indicating stable resampling behavior. This visualization demonstrates the stability and variability of the soil pH mean and provides the basis for constructing the 95% confidence interval for the mean soil pH



**Figure 11.** Distribution of bootstrap means for the Base Saturation (BS) parameter. The histogram illustrates the frequency of mean BS values obtained from 10,000 bootstrap resampling iterations based on the original dataset. The distribution exhibits a near-normal pattern centered around the sample mean (59.95), indicating stable resampling behavior. This visualization demonstrates the stability and variability of the soil base saturation mean and provides the basis for constructing the 95% confidence interval for the mean BS, ranging from 58.79 to 61.11

structured approach to identifying effective input levels for specific outcomes. These results align with prior research demonstrating the value of RSM in optimizing soil amendments and land management practices under constrained experimental settings. The findings also emphasize the importance of variable interaction analysis, which is often overlooked in traditional experimental methods. Future work should focus on validating these optimized conditions under field settings and exploring RSM integration with other modeling tools to improve its applicability in more heterogeneous environments (Ibrahim et al. 2021; Itam et al. 2024; Hazbawi et al. 2025).

**Table 6.** Effect of soil tillage, incubation time, and municipal organic waste on coal mining soil characteristics

Run	Factors			Response															
	ST (cm)	IT (days)	MOW (g)	pH		Org C (%)		N (%)		C/N		P (ppm)		K (ppm)		CEC (me 100 <sup>-1</sup> g)		BS (%)	
				A	P	A	P	A	P	A	P	A	P	A	P	A	P	A	P
1	10	60	60	7.31	6.65	1.43	1.34	0.16	0.12	8.94	10.55	33.18	33.33	132.05	147.04	10.24	11.12	100.00	90.64
2	15	90	20	7.53	7.24	1.44	1.33	0.17	0.12	8.47	10.48	45.17	37.93	190.87	172.04	13.49	14.09	100.00	94.05
3	10	120	60	6.30	6.26	0.89	0.94	0.25	0.22	3.54	5.17	13.20	13.67	181.71	144.74	15.68	16.18	79.46	77.75
4	10	90	40	7.75	7.27	1.39	1.38	0.13	0.13	10.69	10.59	65.81	37.42	137.33	145.75	10.56	16.62	100.00	98.67
5	10	90	40	7.10	7.27	1.24	1.38	0.12	0.13	10.33	10.59	14.60	37.42	139.78	145.75	16.24	16.62	100.00	98.67
6	10	90	40	7.45	7.27	1.20	1.38	0.13	0.13	9.23	10.59	19.67	37.42	127.52	145.75	18.80	16.62	100.00	98.67
7	5	120	40	7.20	6.95	1.33	1.16	0.26	0.23	5.04	5.42	22.63	14.92	135.44	153.59	13.28	13.38	100.00	95.76
8	15	120	40	7.82	7.45	1.00	1.02	0.23	0.24	4.34	3.94	16.74	24.13	151.80	185.63	11.60	11.88	100.00	96.59
9	15	60	40	6.98	7.23	1.16	1.33	0.17	0.19	6.82	6.44	16.04	23.75	213.99	195.84	11.04	10.94	93.30	97.54
10	10	60	20	6.27	6.31	1.07	1.01	0.11	0.13	9.73	8.10	14.16	13.69	191.54	228.51	8.70	8.20	90.73	92.44
11	10	120	20	7.47	8.13	1.15	1.24	0.10	0.13	12.13	10.52	23.81	23.66	142.21	127.22	11.12	10.24	100.00	109.36
12	10	90	40	7.30	7.27	1.68	1.38	0.13	0.13	12.92	10.59	40.11	37.42	170.44	145.75	19.92	16.62	100.00	98.67
13	10	90	40	6.76	7.27	1.37	1.38	0.14	0.13	9.79	10.59	46.93	37.42	153.68	145.75	17.60	16.62	93.35	98.67
14	15	90	60	5.81	6.22	1.35	1.27	0.13	0.14	10.38	9.15	43.03	35.17	136.92	140.07	22.24	21.45	72.75	77.87
15	5	90	60	5.20	5.49	1.15	1.26	0.10	0.14	11.50	9.49	31.54	38.78	130.79	149.62	18.00	17.40	67.61	73.56
16	5	60	40	5.38	5.75	1.04	1.02	0.19	0.17	5.47	5.87	32.38	24.99	280.79	246.97	7.50	7.22	87.38	90.79
17	5	90	20	6.42	6.01	1.08	1.16	0.11	0.09	9.82	11.05	18.50	26.36	184.74	181.59	15.12	15.90	95.90	90.78

Note: ST: Soil Tillage, IT: Incubation Time, MOW: Municipal Organic Waste, pH : Potential of Hydrogen, Org C : Organic carbon, N : Nitrogen, C/N : Carbon Nitrogen Ratio, P : Phosphorus, K : Potassium, CEC: Cation Exchange Capacity, BS: Base Saturation. A: Actual; P: Predicted

### Point prediction

The point prediction analysis of chemical and biological soil parameters revealed substantial variability and a lack of statistical significance in several key indicators, despite the application of RSM using a Box–Behnken design.

### Soil chemical properties

Table 10 shows the predicted mean soil pH was 7.69, accompanied by a moderate standard deviation of 0.58 and a 95% Confidence Interval (CI) ranging from 6.64 to 8.74. However, the 95% Tolerance Interval (TI) covering 99% of the population was considerably wide (4.18 to 11.20), indicating notable variability and potential outliers within the dataset.

Organic-C exhibited a predicted mean of 1.19%, with a 95% CI of 0.84% to 1.54%, yet the tolerance interval ranged broadly from near zero (0.01%) to 2.36%, reflecting an unpredictable response across treatment levels. Total nitrogen (N) content was low (0.19%) and highly variable, with a 95% CI of 0.12% to 0.27% and an even wider TI extending into negative values (-0.04% to 0.43%), suggesting inconsistency in organic nitrogen mineralization.

The C/N ratio, an important indicator of organic matter quality and decomposition rate, showed a predicted mean of 6.79, but with high variability (standard deviation = 2.08) and an extremely broad confidence interval (3.01-10.57) and TI (-5.86 to 19.44). This instability may be attributed to the application of raw municipal organic waste, which likely exhibited variable composition and mineralization rates.

Available-P and K also demonstrated considerable uncertainty. Available-P had a predicted mean of 32.82 mg kg<sup>-1</sup>, with a TI ranging from -74.97 to 140.61 mg kg<sup>-1</sup>, while available-K had a mean of 173.25 mg kg<sup>-1</sup> and a TI from -32.07 to 378.58 mg kg<sup>-1</sup>. The extremely wide prediction intervals, including biologically implausible negative values, indicate substantial dispersion in the response data. Cation exchange capacity exhibited a moderate predicted mean of 12.46 cmol(+) kg<sup>-1</sup>; however, its 95% CI (7.24-17.67) and TI (-5.01 to 29.92) reflected considerable variability. Although Base Saturation (BS) reached a predicted value of 100%, it was associated with an unexpectedly large standard deviation (7.55) and an overly broad TI (54.07 to 145.93), exceeding theoretical maxima and thereby compromising model reliability.

### Explanation for non-significance

The lack of statistically significant responses in most soil parameters can be explained by multiple interacting factors, including the use of raw municipal organic waste rather than mature compost, which introduced high nutrient variability, slow mineralization rates, and inconsistent microbial activity. Previous studies have shown that immature organic materials or mixtures with recalcitrant components, such as biochar, tend to release nutrients more slowly and inconsistently, thereby reducing their immediate effectiveness for soil fertility improvement (Grigatti 2024). The relatively short incubation period also limited the extent of organic matter decomposition and

nutrient release, particularly in degraded post-mining soils with inherently low microbial biomass. Moreover, in tropical regions where organic carbon decomposition proceeds rapidly, seasonal applications of soil amendments, particularly compost, are necessary to sustain soil fertility (Maftukhah et al. 2023).

From a land rehabilitation standpoint, extending and managing incubation periods can also promote the recovery of beneficial soil fungi, which play essential roles in nutrient cycling, organic matter decomposition, and ecosystem stabilization. The combined use of organic amendments with native or well-adapted fungal strains has further been suggested to enhance bioremediation efficacy, improve soil structure, and mitigate toxic residues in mining-affected soils (Zainudin et al. 2025). Furthermore, the high spatial heterogeneity and poor initial fertility of tropical post-mining soils contributed to residual variability, reducing the model's power to detect significant effects. Finally, the presence of large standard errors and wide prediction intervals indicates possible violations of statistical assumptions such as normality and homoscedasticity, which could potentially be addressed through appropriate data transformations.

Unlike most previous studies that applied Response Surface Methodology (RSM) primarily to optimize fertilizer dosages or compost formulations under relatively homogeneous conditions, recent research highlights its application to highly degraded post-mining soils, characterized by high heterogeneity and low baseline fertility. The optimal conditions identified—moderate tillage depth, intermediate incubation time, and specific organic waste application rates—provide valuable insights for developing predictive land management models tailored to post-mining rehabilitation (Mohrazi et al. 2023; Emran et al. 2024).

**Table 7.** Optimization criteria

	Goal	Limit (lower-upper)	Importance (1-5)
<b>Factors</b>			
A-ST (cm)	In range	5-15	3
B-IT (days)	Maximized	60-120	3
C-MOW (t ha <sup>-1</sup> )	Maximized	20-60	3
<b>Response</b>			
pH	Maximized		5
Org C (%)	Maximized		1
N (%)	Maximized		1
C/N	In range		1
P (%)	Maximized		1
K (%)	Maximized		1
CEC (me 100 <sup>-1</sup> g)	Maximized		1
BS (%)	Maximized		5

Note: A: Soil Tillage, B: Incubation Time, C: Municipal Organic Waste dosage, pH: Potential of Hydrogen, Org C: Organic carbon, N: Nitrogen, C/N: Carbon Nitrogen Ratio, P: Phosphorus, K: Potassium, CEC: Cation Exchange Capacity, BS: Base Saturation

**Table 8.** Soil characteristics of post-mining land after the application of municipal organic waste

Characteristics	Predicted mean	95% PI low	95% PI high
pH	7.43	5.81	9.05
Org C (%)	1.26	0.72	1.81
N (%)	0.17	0.06	0.28
C/N	7.58	1.75	13.41
P (ppm)	36.34	-13.36	86.06
K (ppm)	168.73	74.03	263.43
CEC (me 100 <sup>-1</sup> g)	15.54	7.48	23.59
BS (%)	96.61	75.42	117.79

Note: pH: Potential of Hydrogen, Org C: Organic carbon, N: Nitrogen, C/N: Carbon Nitrogen Ratio, P: Phosphorus, K: Potassium, CEC: Cation Exchange Capacity, BS: Base Saturation

**Table 9.** The optimal conditions application of soil tillage, incubation time, and organic waste to coal mining soil

A-ST (cm)	B-IT (days)	C-OW (t ha <sup>-1</sup> )
15	103.48	36.48

Note: A: Soil Tillage, B: Incubation Time, C: Municipal Organic Waste dosage

**Table 10.** Point prediction

Solution 1 of 3 response	Predicted mean	Predicted median	Observed Std Dev	SE mean	95% CI low for mean	95% CI high for mean	95% TI low for 99% pop	95% TI high for 99% pop
pH	7.69	7.69	0.57	0.44	6.64	8.74	4.17	11.20
Org C	1.18	1.187	0.19	0.14	0.83	1.53	0.01	2.36
Total of N	0.19	0.194	0.03	0.03	0.12	0.26	-0.04	0.43
C/N	6.79	6.79	2.07	1.59	3.01	10.56	-5.85	19.43
Available P	32.81	32.81	17.71	13.61	0.62	65.00	-74.97	140.60
Available K	173.25	173.25	33.74	25.93	111.93	234.57	-32.07	378.57
CEC	12.45	12.45	2.86	2.20	7.24	17.67	-5.00	29.92
BS	100.00	100.00	7.54	5.80	86.28	113.71	54.07	145.92

Note: pH: Potential of Hydrogen, Org C: Organic carbon, N: Nitrogen, C/N: Carbon Nitrogen Ratio, P: Phosphorus, K: Potassium, CEC: Cation Exchange Capacity, BS: Base Saturation

Response Surface Methodology (RSM) facilitates the integration of statistical predictions with soil chemical parameters, such as pH and Base Saturation (BS), thereby enabling evidence-based decision-making for soil amendment strategies and offering an alternative to traditional trial-and-error approaches. Previous research has shown that RSM is effective in optimizing nitrogen retention and enhancing plant biomass in sandy soils amended with organic materials (Mu et al. 2025). This methodology highlights RSM's capability to address highly heterogeneous and extreme soil conditions, where conventional models often fail to account for the interactive effects of tillage, incubation duration, and organic amendments. In addition, RSM has been successfully employed in applications such as soil remediation and industrial waste carbonation, demonstrating its adaptability across diverse contexts of land rehabilitation (Gomari et al. 2025; Li et al. 2025). Consequently, these studies not only validate the effectiveness of RSM in optimizing soil management practices but also broaden its applicability to predictive modeling frameworks aimed at achieving sustainable land rehabilitation under challenging environmental conditions.

To enhance the robustness and predictive power of future models, it is recommended to employ well-matured compost to ensure nutrient consistency, extend the incubation period to capture longer-term effects of organic matter decomposition, increase replication and treatment

levels to minimize experimental error, and apply suitable data transformations prior to modeling to address non-normality and variance heterogeneity.

In conclusion, soil pH and BS were the only chemical properties of post-coal mining land that showed significant treatment responses, though BS was inconsistent. Soil pH was mainly affected by tillage depth, while BS responded to organic waste application. Response Surface Methodology identified an optimal combination of 36.48 t ha<sup>-1</sup> organic waste, 15 cm tillage depth, and 103.4 days incubation, yet improvements remained modest and limited to pH and BS. These results indicate that targeted management, particularly organic waste and tillage integration, can moderately improve certain soil properties, but broad claims of fertility recovery are premature, as most variables showed no change. Limitations include short incubation, lack of plant growth data, exclusion of microbial dynamics, and absence of field validation. Future studies should lengthen incubation, assess biological and physical parameters, and conduct large-scale field trials to test robustness and applicability across post-mining landscapes.

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