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Restoring subsoil degradation with mixed fertilizer-conditioner: A case study on red chili pepper (*Capsicum annuum*) cultivation

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ABSTRACT

The loss of topsoil in high-rainfall regions significantly reduces agricultural productivity, especially in degraded soils. This study investigated the effects of Mixed Fertilizer-Conditioner (MFC) on improving the chemical properties of subsoil cultivated with red chili peppers. A Randomized Block Design (RBD) with 11 treatments on subsoil and one control on normal soil was implemented, with three replications. The treatments included: A= subsoil without fertilizer, B= 0% MFC + full NPK, C= 25% MFC + full NPK, D= 50% MFC + full NPK, E= 75% MFC + full NPK, F= 100% MFC + full NPK, G= 50% MFC + 75% NPK, H= 50% MFC + 50% NPK, I= 50% MFC + 25% NPK, J= 50% MFC without NPK, and K= Full NPK on normal soil. The application of 100% MFC combined with full NPK significantly enhanced subsoil chemical properties. Soil organic carbon increased to 1.32%, pH rose to 6.3, CEC reached 22.1 cmol kg^{-1}, and base saturation improved to 49.4%. Nutrient availability also increased, including total N (1.21%), P (0.132%), K (0.677 cmol kg^{-1}), along with Ca (1362.72 ppm), Mg (311.04 ppm), and S (36.01 ppm). Micronutrients B, Co, and Zn also rose to 4.41 ppm, 18.95 ppm, and 11.97 ppm, respectively. Chili yields in subsoil treated with 50–100% MFC and full NPK exceeded 10 tons ha^{-1}. These results highlight the agronomic potential of MFC for rehabilitating degraded soils and recommend its use as a sustainable strategy to enhance soil fertility in low-fertility or erosion-prone areas, with implications for both farmers and agricultural policymakers.

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1. INTRODUCTION

Agriculture is a critical sector in the global economy, particularly in the production of horticultural commodities. However, land degradation poses a significant challenge to sustaining agricultural productivity, especially in tropical regions with high rainfall, such as Indonesia (Setyawan et al., 2019), India (Bhattacharyya et al., 2015), Brazil (Anache et al., 2018), Vietnam (Huynh et al., 2020), Thailand (Neyret et al., 2020), and Malaysia (Vijith et al., 2018). Topsoil loss due to erosion has become a pressing concern, and in countries like Indonesia, the over-exploitation of topsoil by industries such as brickmaking has further accelerated soil fertility decline. Subsoil, which often replaces the eroded topsoil layer, generally exhibits poorer chemical properties than topsoil. Consequently, the loss of topsoil leads to a marked reduction in soil fertility, characterized by lower nutrient availability, reduced cation exchange capacity (CEC) (Fang et al., 2017), decreased base saturation (Fonseca et al., 2017), and diminished organic carbon content (Angst et al., 2018). Collectively, these changes result in significantly reduced crop yields (Gomes et al., 2019; Lal, 2018; Mandal et al., 2021).

In recent years, subsoil has increasingly been considered as an alternative planting medium in regions experiencing severe topsoil depletion. Particularly in tropical developing countries, excavated subsoil—commonly left unused after activities such as mining, construction, or brick-making activities—represents a vast yet underutilized resource (Makau, 2021; Ning et al., 2022). Although its inherent fertility is low, appropriate amendments and conditioning strategies

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have the potential to restore its productivity (Armstrong et al., 2021; Tavakkoli et al., 2019). Therefore, research on subsoil rehabilitation is critical for expanding arable land availability without the need to convert additional forested areas.

Currently, the treatment of subsoil from excavation residues is largely carried out by increasing organic matter inputs, particularly through the application of compost. The use of compost has been shown to positively influence soil physical, chemical, and biological properties. Research by Cooper et al. (2020) demonstrated that the application of compost to soil significantly increases organic carbon, which in turn improves the cation exchange capacity (CEC) and base saturation (Bouajila et al., 2023). Additionally, Bremaghani (2024) reported that compost derived from agricultural waste effectively enhances the availability of nutrients in the soil. Similarly, Rahman et al. (2020) found that other organic materials, such as biochar and humus, also contribute to soil quality improvement by increasing organic carbon and enhancing the retention of macro- and micronutrients. While these findings underscore the crucial role of organic amendments in soil rehabilitation, current strategies often emphasize soil improvement alone, tend to overlook their direct effects on plant nutrient uptake. The application of a dual treatment approach, combining liquid organic matter applied both to soil and as a foliar spray, remains rarely explored. In fact, this combination could yield more optimal results, since foliar application can enhance nutrient absorption when the soil's buffering capacity is limited.

To address this gap, the present study introduces the use of Mixed Fertilizer-Conditioner (MFC), a liquid organic fertilizer enriched with humic acid and organic compounds. MFC functions both as a soil conditioner and as a source of readily available mineral nutrients for plants. According to Ren et al. (2022) and Pukalchik et al. (2019), humic acid enhances the physical, chemical, and biological properties of the soil by increasing organic carbon content, CEC, and base saturation, thereby improving the soil's ability to retain and supply essential nutrients. Additionally, MFC facilitates nutrient uptake through both root uptake and absorption. Foliar application has been found to be particularly effective for micronutrients such as zinc and boron (Tyagi et al., 2025). Herawati et al. (2021) reported that combining humic acid with ameliorants significantly increased soil organic carbon (SOC), CEC, and phosphorus availability in poor sandy soils, thereby confirming the role of organic-mineral amendments in improving subsoil fertility. Moreover, Syamsiyah et al. (2023) reported positive correlations between rising organic carbon content and increases in both CEC and base saturation, confirming that enhanced organic matter leads to improved nutrient retention and soil fertility.

To assess the agronomic response of MFC, red chili pepper (*Capsicum annuum*) was selected as the test crop. This species is widely cultivated across Southeast Asia and holds significant importance due to its economic value (Karyani et al., 2020) dietary relevance as a source of vitamins, antioxidants, and capsaicinoids (Olatunji & Afolayan, 2018), and sensitivity to nutrient availability and soil fertility (Khaitov et al., 2019). In Indonesia, red chili is not only a staple horticultural commodity but also plays a critical role in supporting smallholder farmers' household income (Karyani et al., 2020; Olutumise, 2022) and contributes to national food price stability. Moreover, chili plants display high physiological responsiveness to both macro- and micronutrient supply (Massimi & Radocz, 2021), as well as to soil amendments and environmental stressors, making them a suitable indicator species for evaluating soil conditioning treatments on degraded or marginal soils. Therefore, the study aimed to evaluate the effectiveness of MFC in improving subsoil chemical properties and enhancing the growth and yield of red chili pepper (*Capsicum annuum*) under degraded soil conditions.

2. MATERIALS AND METHODS

2.1. Formulation of Mixed Fertilizer-Conditioner (MFC)

The formulation of MFC in this study involved a combination of cow manure with particle sizes of 1–2 microns, liquid fertilizer derived from the fermentation of vegetable and fruit waste rich in essential nutrients, liquid humic acid, and the addition of several mineral components including $(NH_4)_2SO_4$, mono potassium phosphate (MKP), KCl, $CaSO_4$, $MgSO_4$, $CuSO_4$, and boric acid. These components were selected to improve the quality of subsoil, which was evaluated based on several chemical properties as indicators of soil fertility. The concentration of each component was adjusted based on the nutrient content of the raw organic materials and the target nutrient levels to be achieved in the final formulation. For instance, if the initial nitrogen content of the organic waste was 0.5% and the target concentration was 1.5%, additional nitrogen was supplied using a calculated amount of urea (46% N) or $(NH_4)_2SO_4$ (21% N) to meet the deficit. This flexible formulation approach allows the MFC to be tailored according to the nutrient profile of site-specific organic waste sources, ensuring consistency in performance despite variability in raw material composition.

The MFC production process began with the preparation of raw materials, including vegetable and fruit waste for the fermentation process. This stage followed the standard method for producing liquid organic fertilizer, utilizing *Lactobacillus sp.* bacteria as the primary inoculant due to its known ability to accelerate organic matter decomposition and produce beneficial organic acids (Amrullah et al., 2021). The fermentation substrate consisted of 60% fruit and vegetable waste and 40% water by volume, supplemented with 4% molasses (Ramadhani et al., 2022) as a carbon source to stimulate microbial activity. The mixture was placed in an anaerobic fermenter and incubated at ambient temperature, 25–35°C (López-Rubio et al., 2025) for 14-28 days to ensure optimal microbial proliferation and nutrient solubilization (Lerma-Moliz et al., 2025; Sofyan et al., 2025). Subsequently, cow manure was oven-dried to reduce moisture content to below 20%, then ground using a colloid mill to achieve particle sizes of 1–2 micrometers, which enhances surface area and nutrient release efficiency. The fine manure was then mixed with the fermented liquid fertilizer and liquid humic acid in a 4:2:1 ratio, creating a stable matrix for the subsequent addition of mineral nutrients.

Table 1. Parameters for MFC formula analysis and their methods.

No.	Parameter	Methodology
1	C-organic	Walkley & Black
2	Impurities	Sorting and screening
3	Heavy Metals	
	As (Arsenic)	Wet oxidation HNO_3+ $HClO_4$, AAS-Hydride
	Hg (Mercury)	Wet oxidation HNO_3+ $HClO_4$, AAS-Hydride Cold Vapor
	Pb (Lead) and Cd (Cadmium)	Wet oxidation HNO_3+ $HClO_4$, AAS
4	pH	Electrometry, pH meter (1:5)
5	Total Nutrients	
	N (Nitrogen)	Kjeldahl, titrimetric
	P_2O_5 (Phosphorus)	Wet oxidation HNO_3 + $HClO_4$, molybdenum-blue, spectrometry
	K_2O (Potassium)	Wet oxidation HNO_3 + $HClO_4$, AAS- flame photometry
6	Contaminant Microbes	
	E. Coli and *Salmonella* sp.	Most Probable Number (MPN)
7	Microelements	
	Fe (Iron), Mn (Manganese), Cu (Copper), Zn (Zinc), Co (Cobalt), Mo (Molybdenum)	Wet oxidation HNO_3 + $HClO_4$, AAS
	B (Boron)	Wet oxidation HNO_3 + $HClO_4$, Azomethine-H, spectrometry

Source: Wogi et al. (2021).

The mixture was allowed to ferment for an additional 7 days. Following this, the mineral components were added, and the mixture was homogenized using a mechanical stirrer for half a day. After achieving homogeneity, the MFC concentration was adjusted according to the research requirements, and nutrient content analysis was conducted to validate the accuracy of the product formulation before application. The analysis methods for the nutrient content of the MFC formulation are presented in Table 1.

2.2. Field application

2.2.1. Preparation

The subsoil used in this study was collected from Garut Regency, Indonesia (approximately 7°10′57″ S, 107°59′43″ E; elevation 707 m above sea level/asl), an area previously exploited for the red brick production. The subsoil was characterized by a neutral pH, low organic carbon content (0.79%), low C/N ratio (5.64), low total nitrogen (0.14%), very low available phosphorus (2.76 ppm), low potassium (0.29 $cmol.kg^{-1}$), low CEC (16.14 $cmol.kg^{-1}$) and low base saturation (20.33%). In contrast, the normal soil was collected from an actively cultivated and productive chili farmer's field. Both the subsoil and normal soil were placed in polybags with a 10 kg soil capacity. During the preparation and incubation of the organic fertilizer as a basic treatment, red chili seeds were sown in a screen house for 16 days before being transplanted into the polybags.

The materials used in this study included UNPAD CB 2 seeds, chicken manure, rice husks, and subsoil obtained from excavation residues of red brick production. Pest control was managed with yellow adhesive paper, carbofuran-based nematicides, profenofos-based insecticides, propineb-based fungicides, and metaldehyde-based molluscicides. The tools employed consisted of seedling trays, planting and maintenance equipment, and instruments for soil and plant tissue analysis. Data processing and statistical analysis were performed using computer software to ensure the accuracy and reliability of the results.

2.2.2. Experimental design

The study was conducted in the experimental field of the Faculty of Agriculture, Universitas Padjadjaran, from September 2023 to February 2024, located at an altitude of 740 m asl, with an average annual rainfall of 1800 mm, temperatures ranging from 28°C to 31°C, and humidity levels of 46% to 52%. A simple randomized block design (RBD) was used, consisting of 11 treatments involving different concentrations of MFC Plus and varying doses of N-P-K fertilizer. Each treatment was replicated three times. Each experimental unit consisted of two sampling groups: one group of plants was uprooted at the vegetative stage for nutrient uptake analysis, while the remaining plants were maintained until harvest for yield measurement.

The treatments included control and various MFC Plus concentrations ranging from 0% to 1%, combined with full, ¾, ½, ¼, and 0 doses of N-P-K fertilizer. The purpose of this design was to evaluate the effects of these combinations on the chemical properties of subsoil and crop yield. This approach allowed for a comprehensive assessment of both nutrient uptake during the growth phase and final yield performance, aiming to determine the optimal combination of MFC Plus and N-P-K to enhance soil fertility and increase productivity in subsoil conditions. The details of the treatment combinations are presented in Table 2.

The application of MFC Plus was carried out via two methods: soil drenching and foliar spraying. MFC was applied to the soil at the base of the plant during early growth stages to improve subsoil properties and nutrient retention, while foliar application was performed at the vegetative and early flowering stages to enhance nutrient absorption efficiency, particularly for micronutrients.

The determination of soil conditioner dosage was based on the target increase in soil organic carbon (SOC) (Eq. 1) because it serves as an indicator closely related to other soil fertility indicators such as pH and CEC.

Table 2. Combination of MFC-and N-P-K treatments.

No	Treatment	MFC (ml/polybag)	N-P-K (g/polybag)		
			Urea	SP-36	KCl
1	A=Control	0.0	0	0	0
2	B=0% MFC +1 N-P-K	0.0	13.24	9.93	13.24
3	C=25% MFC + 1 N-P-K	250	13.24	9.93	13.24
4	D=50% MFC + 1 N-P-K	500	13.24	9.93	13.24
5	E=75% MFC + 1 N-P-K	750	13.24	9.93	13.24
6	F=100% MFC + 1 N-P-K	1000	13.24	9.93	13.24
7	G=100% MFC + 3/4 N-P-K	1000	9.93	7.44	9.93
8	H=100% MFC + 1/2 N-P-K	1000	6.62	4.96	6.62
9	I=100% MFC + 1/4 N-P-K	1000	3.31	2.48	3.31
10	J=100% MFC + 0 N-P-K	1000	0.00	0.00	0.00
11	K=1 N-P-K normal soil	0.0	13.24	9.93	13.24

Notes: Description: One dose of N-P-K refers to the standard (recommendation) dosage commonly applied by local farmers (200-150-200 kg ha^{-1} with plant population 15,111). The dose of MFC was calculated based on the required concentration for each treatment.

Table 3. Soil and plant tissue analysis method.

No	Sample Type	Parameter	Unit	Methodology
1	Soil	pH	-	Electrometry, pH meter (1:5)
2	Soil	Organic Carbon (OC)	%	Walkley & Black
3	Soil	Organic Matter Content	%	OM = Organic-C × 1.724 (Van Bemmelen factor)
4	Soil	Cation Exchange Capacity (CEC)	cmol/kg	Wet oxidation with HNO_3 + $HClO_4$ Titration
5	Soil	Base Saturation (BS)	%	Wet oxidation with HNO_3 + $HClO_4$ Titration
6	Soil and Plant Tissue	Nitrogen (N)	%	Kjeldahl Method
7	Soil and Plant Tissue	Phosphorus (P_2O_5)	%	Molybdenum Blue, Spectrophotometry
8	Soil and Plant Tissue	Potassium (K_2O)		Flame Photometry

Source: Motsara and Roy (2008); Soil and Plant Analysis Council Inc. (2018).

Initial SOC content (C_i) = 0.79%
Organic carbon (OC) content in MFC (C_m)= 16.65 % = 166.5 g
Density of organic amendment (ρ) = 1 g/ml (assumed)

$$\Delta C = \frac{\text{OC in MFC}}{\text{Total weight (medium)}} \times 100 \quad [1]$$

$$\Delta C = \frac{166.5\ \text{g}}{10000\ \text{kg}}$$

ΔC = 1.665 % rounding decimals to 1.67 %
Each 1 liter of MFC was assumed to increase soil organic carbon content by up to 1.67 %.

2.2.3. Sampling method

Random sampling was conducted to select red chili plants from each treatment for vegetative observations, including stem diameter and the number of productive branches. The selected plants for vegetative analysis were chosen randomly to ensure unbiased sampling across treatments. Stem diameter was measured using a vernier caliper, while the number of productive branches was counted manually. A total of three plant samples were selected from each treatment. In addition to vegetative observations. Destructive sampling for plant tissue analysis, was conducted at 42 days after transplanting (DAT), by uprooting the entire plant, including roots, stems, and leaves. All parts of the sampled plant were used for nutrient analysis, without separating specific plant organs. The remaining plants, not used for destructive sampling, were maintained for the observation of yield parameters. These included fruit length, weight, and diameter, which were recorded at each harvest from the second to the fifth harvest. Total yield was determined by accumulating the weight of all harvested fruits throughout the study.

2.2.4. Analysis

The collected data were analyzed using analysis of variance (ANOVA) at the 5% significance level. When significant differences among treatments were detected, Duncan's Multiple Range Test (DMRT) at the 5% level was applied to separate the means. Whole plants were harvested for nutrient content analysis, using the parameters and wet destruction methods described in Table 3.

3. RESULT

The observations in Table 4 show that the formulation of the MFC meets the standards set by the Indonesian Ministry of Agriculture, both in terms of nutrient content and safety. The OC content, which reaches 16.65%, far exceeds the minimum threshold of 10%, indicating that this MFC formulation has the potential to enrich the soil with much-needed organic matter, particularly for improving subsoil conditions, which are typically poor in organic content. In addition, the content of nutrients such as N, P_2O_5, and K_2O—3.47%, 5.73%, and 5.50%, respectively—also complies with the Ministry of Agriculture standards (N-P-K in the range of 2-6%).

Table 4. The results of the MFC formulation analysis are compared to the minimum technical requirements set by the Indonesian Ministry of Agriculture regulations.

No	Parameter	Unit	Result	Technical Requirement*
1	Organic Carbon (OC)	%	16.65	min 10
2	Impurities	%	-	
3	Heavy Metals			
	Arsenic (As)	ppm	<0.01	As max 5.0
	Mercury (Hg)	ppm	<0.01	Hg max 0.2
	Lead (Pb)	ppm	<0.01	Pb max 5.0
	Cadmium (Cd)	ppm	<0.01	Cd max 1.0
4	pH	-	5.54	4-9
5	Total Nutrients			
	Nitrogen (N)	%	3.47	N+P+K 2-6
	Phosphorus (P_2O_5)	%	5.73	
	Potassium (K_2O)	%	5.50	
6	Contaminant Microbes			
	Escherichia coli	MPN	Negative	Negative
	Salmonella sp.	MPN	Negative	Negative
7	Microelements			
	Iron (Fe)	ppm	413.53	90-900
	Manganese (Mn)	ppm	366.71	25-500
	Copper (Cu)	ppm	448.12	25-500
	Zinc (Zn)	ppm	521.15	25-500
	Cobalt (Co)	ppm	17.51	25-500
	Molybdenum (Mo)	ppm	2.71	2-10
	Boron (B)	ppm	84.65	12-250

Source: Ministry of Agriculture of the Republic of Indonesia (2019).

This demonstrates that MFC not only acts as a soil conditioner but also provides essential nutrients to support the growth of the red chili pepper plant.

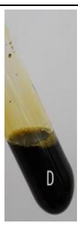
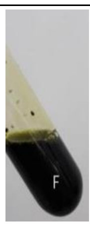
In terms of safety, the heavy metal contents (Table 4), such as As, Hg, Pb, and Cd, are all below the maximum limits allowed by the Ministry of Agriculture, confirming the safety of MFC for agricultural use without the risk of hazardous contamination. Additionally, micronutrient levels, including Fe, Mn, Cu, Zn, and B (84.65 ppm), fall within the acceptable range of 12–250 ppm, meeting the technical standards for nutrient content.

3.1. Soil chemical properties

3.1.1. Organic carbon and organic matter content

The results (Table 5) indicate that the combination of MFC with N-P-K treatment significantly improves the quality of subsoil from brick excavation, as evidenced by increased organic carbon percentage and organic matter content.

Table 5. Effects of MFC and NPK treatments on changes in organic carbon and organic matter content

Treatment	A	B	C	D	E	F	G	H	I	J	K
Color formed											
	Fig. 1a	Fig. 1b	Fig. 1c	Fig. 1d	Fig. 1e	Fig. 1f	Fig. 1g	Fig. 1h	Fig. 1i	Fig. 1j	Fig. 1k
% Organic carbon	0.71	0.72	0.81	0.89	1.13	1.32	1.05	0.90	0.87	0.85	1.71
Organic Matter (%)	1.22	1.24	1.40	1.53	1.95	2.27	1.81	1.55	1.50	1.46	2.95
Notation	a	a	ab	b	cd	d	cd	b	b	ab	e
Criteria	Poor	Poor	Poor	Poor	Low	Low	Low	Poor	Poor	Poor	Low

Description: The mean values followed by the same letter do not significantly differ based on the Duncan multiple range test at the 5% level. Figures 1a to 1k illustrate the differences in soil sample color based on variations in organic carbon content after treatment during oxidation using $K_2Cr_2O_7$ and H_2SO_4. The organic matter content was calculated by multiplying the measured organic carbon value by a factor of 1.724, following the Van Bemmelen conversion method.

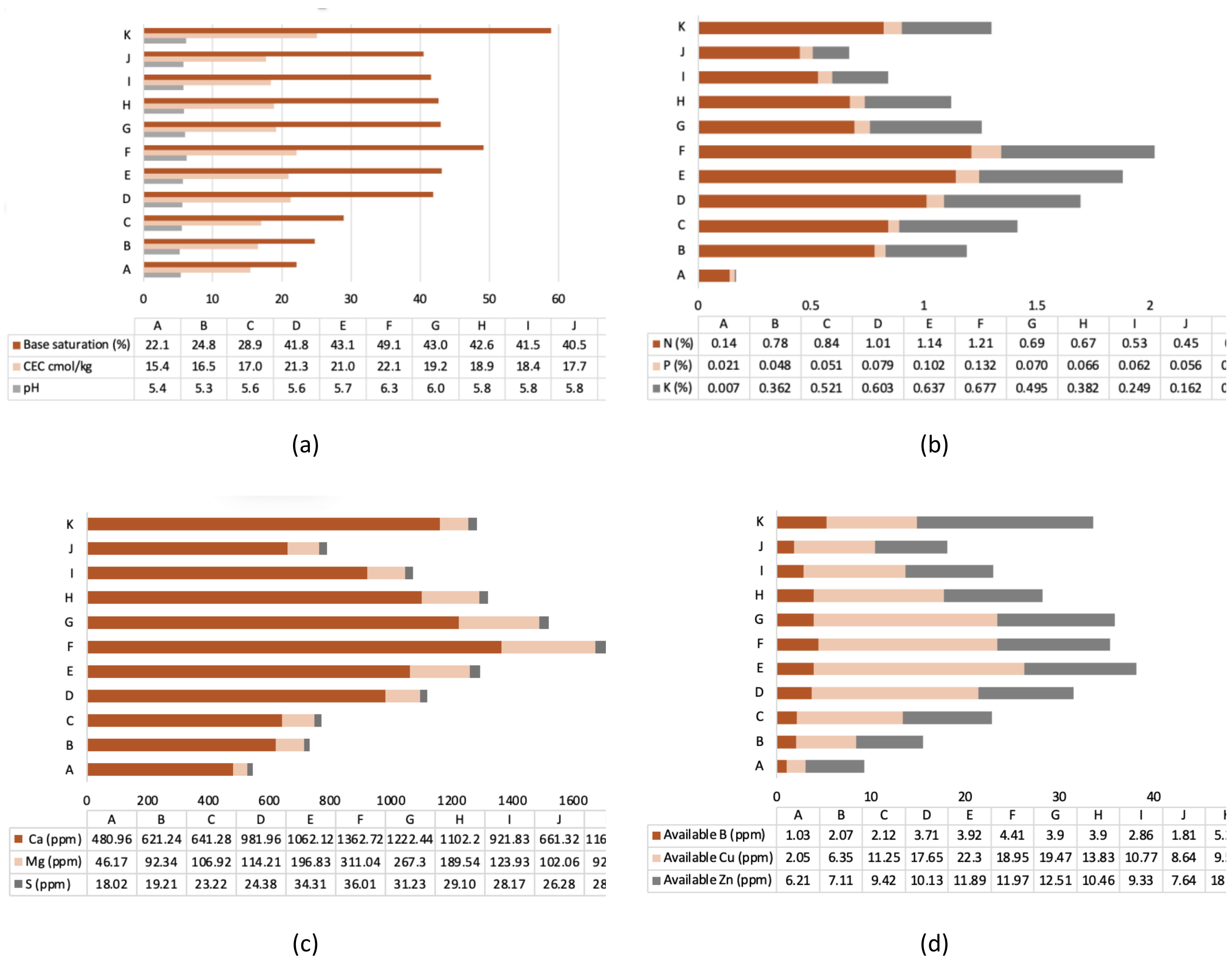


Figure 2. (a) General soil fertility variables, including pH, organic carbon, CEC, and base saturation, **(b)** Primary macronutrient content (N, P, and K) under various treatments, **(c)** Secondary nutrient content (Ca, Mg, and S), **(d)** Micronutrient content, including B, Cu, and Zn in soil.

The best results were obtained with 50%, 75%, and 100% MFC combined with a full dose of NPK (treatments E, F, and G), which increased organic matter content to 1.95%, 2.27%, and 1.88%, respectively. These values were close to the positive control of normal soil with NPK (treatment K, 2.95%). Visually, the test tube solution of treatment F exhibited a bright green color, indicating a high organic matter content compared to treatments with lower MFC doses or no MFC. The soil color variations observed in Figures 1a–1k served as qualitative confirmation of organic carbon differences, in line with standard Walkley-Black rating categories (values were categorized as very low when < 0.20%, low at 0.21–0.40%, and very high when > 1.00%). Colors were not used quantitatively, but correlated well with the measured % organic carbon values (Meersmans et al., 2009). Combinations of higher MFC doses with reduced NPK levels (G, H, I, J) still showed better results than the negative control (A). These confirm that MFC, particularly in high doses, is effective for rehabilitating subsoil and improving its quality, even with partial NPK reduction.

3.1.2. Soil base saturation, CEC, pH, and soil nutrients

The application of MLC combined with NPK resulted in significant improvements in base saturation, cation exchange capacity (CEC), and pH of subsoil (Figure 2a). Treatments with increasing MFC doses from 25% to 100% combined with the full NPK dose (C to F) consistently increased base saturation up to 49.1% (treatment F) and CEC up to 12.5 cmol/kg. However, the base saturation levels were still higher in normal soil, while CEC and pH values in the treated subsoil were comparable to those in normal soil.

Macronutrients (Figures 2b and 2c), treatment F yielded the highest levels of N (1.14%), P (0.102%), and K (0.637%) compared to other treatments, approaching the values observed in normal soil (K). Additionally, increases in Ca and Mg were recorded in treatment F, reaching 1,362.72 ppm and 311.04 ppm, respectively, indicating improved soil capacity to support plant growth.

In Figure 2d, micronutrients such as B, Cu, and Zn also showed notable increases. Treatment K (positive control) resulted in the highest Zn content of 18.72 ppm, followed by the treatments G, F, and E at 12.51 ppm, 11.97 ppm, and 1189 ppm, demonstrating that the application of MFC effectively enhances the availability of essential micronutrients in the soil. The availability of B and Cu in treatment F was also higher than in the negative control (A), further indicating improved quality of subsoil from brick excavation. In contrast, the application of MFC independently or in combination with excessively low doses of N-P-K was insufficient to significantly improve the subsoil. In contrast, the application of MFC independently or in combination with excessively low doses of N-P-K was insufficient to significantly improve the subsoil

3.2. Plant nutrient content (plant tissue analysis)

The effect of using MFC on the nutrient content and dry weight of red chili pepper plant tissues showed significant differences across all parameters among treatments (Table 6). The content of N was the highest in treatment F (3.12%), not different from E, G, and K treatments, significantly outperforming other treatments. This indicates improved nitrogen mineralization and availability due to MFC application, contributing to vegetative growth and chlorophyll synthesis. Similarly, P content peaked in treatments F and E, respectively (1.13% and 1.02%), showing higher values than the negative control, although still lower than the positive control (normal soil). The lowest P content was observed in treatment J (0.59%), reflecting the role of MFC in enhancing P availability for root development and energy transfer.

The levels of K were highest in treatment F (1.66%), indicating effective enhancement of CEC and potassium retention in the subsoil. Ca and Mg content also improved, with the highest Ca recorded in treatment E (0.76%) and Mg in treatment F (0.45%). Micronutrient levels, including Cu and B, followed a similar trend, with the highest Cu concentration in treatment F (5.85 ppm) and Boron in treatment K (382.94 ppm). Dry weight, an integrative indicator of biomass accumulation, was the highest in treatment F (69.12 g), significantly exceeding other treatments. This suggests that the balanced nutrient profile provided by the MFC directly contributed to improved productivity in red chili pepper cultivation.

The macro- and micronutrient uptake (Figure 3) in red chili pepper demonstrated a strong correlation with tissue nutrient content and plant dry weight, as shown in Figure 3. Treatment F (1.0% MFC + 1 dose N-P-K) consistently resulted in the highest uptake of N, P, and K, each supporting vegetative growth, root development, and osmotic balance, respectively. Additionally, micronutrient uptake, such as Cu and B, was also the highest in treatments F and K, corresponding to Cu (5.85 ppm) and B (382.94 ppm) content in plant tissues.

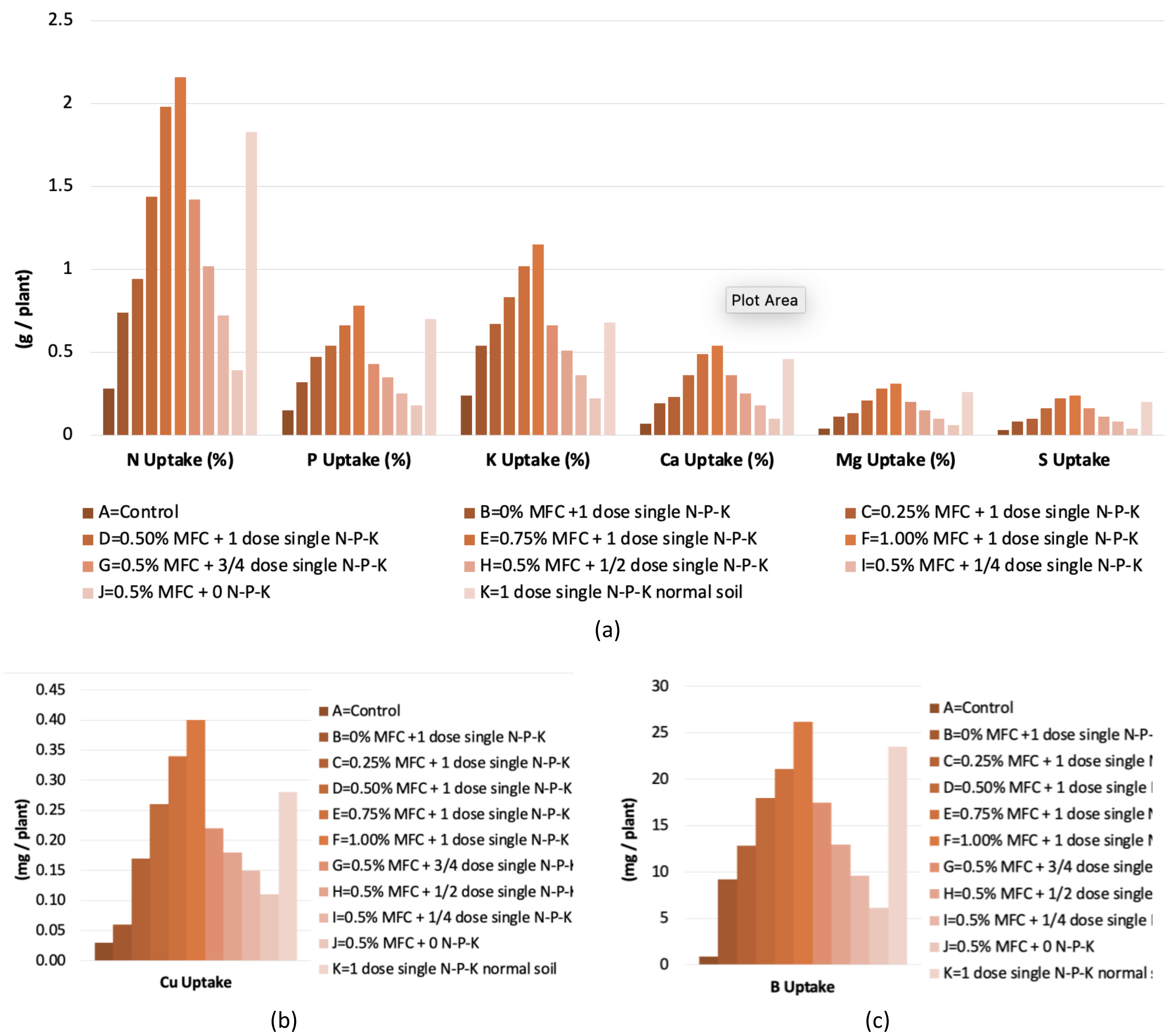


Figure 3. (a) Macronutrient uptake in various treatments, **(b)** Cu uptake, and **(c)** B uptake (mg/plant) in various treatments.

Table 6. Nutrient content in plant tissue and dry weight under different treatments.

Treatment	Content in plant tissue								Dry weight
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Cu (ppm)	B (ppm)	(g/plant)
A	1.01 a	0.54 a	0.84 a	0.25 a	0.14 a	0.11 a	0.95 a	130.28 a	28.13 a
B	1.67 ab	0.72 ab	1.22 ab	0.42 b	0.24 b	0.19 ab	1.25 ab	206.48 b	44.52 b
C	1.78 ab	0.90 ab	1.28 ab	0.44 b	0.25 b	0.20 ab	3.15 b	243.45 bc	52.67 c
D	2.49 b	0.93 ab	1.43 b	0.62 c	0.36 bc	0.28 b	4.55 bc	310.59 c	57.83 cd
E	3.04 c	1.02 b	1.57 bc	0.76 d	0.43 c	0.34 c	5.20 cd	324.06 cd	65.11 de
F	3.12 c	1.13 b	1.66 c	0.78 d	0.45 c	0.35 c	5.85 d	378.51 d	69.12 e
G	2.77 bc	0.84 ab	1.28 ab	0.69 cd	0.40 c	0.31 bc	4.37 bc	339.26 cd	51.44 c
H	2.08 b	0.71 ab	1.04 ab	0.52 bc	0.30 bc	0.23 ab	3.73 b	264.55 bc	48.84 bc
I	1.81 ab	0.63 ab	0.92 a	0.45 b	0.26 b	0.20 ab	3.67 b	242.62 bc	39.62 ab
J	1.26 ab	0.59 a	0.72 a	0.31 ab	0.18 a	0.14 a	0.95 a	199.71 b	30.59 ab
K	2.98 bc	1.85 c	1.11 ab	0.74 d	0.43 c	0.33 bc	1.25 ab	382.94 d	61.25 d

Description: The mean values followed by the same letter do not significantly differ based on the Duncan multiple range test at the 5% level.

Table 7. Yield response of red chili pepper in various treatments of the concentration of MFC with NPK doses.

	Treatment	Fruit weight per plant (g)		Fruit weight (g)		Fruit length (cm)		Fruit circumference (cm)	
A	Control (without fertilizer)	143.4	a	6.21	a	5.2	a	0.9	a
B	0 % MFC + 1 N-P-K	309.9	bc	10.33	c	9.6	c	1.4	c
C	0.25 % MFC + 1 N-P-K	369.6	c	10.56	c	8.3	bc	1.4	c
D	0.50 % MFC + 1 N-P-K	499.4	cd	9.08	bc	9.4	c	1.6	d
E	0.75 % MFC + 1 N-P-K	504.71	d	12.31	e	7.3	ab	1.8	e
F	1.00 % MFC + 1 N-P-K	494.52	cd	12.28	e	11.5	d	1.5	cd
G	0.5 % MFC + 3/4 N-P-K	426.36	cd	11.22	d	9.3	c	1.4	c
H	0.5 % MFC + 1/2 N-P-K	345.84	c	10.48	c	8.9	bc	1.2	b
I	0.5 % MFC + 1/4 N-P-K	294.72	bc	9.21	bc	8.2	bc	1.2	b
J	0.5 % MFC + 0 N-P-K	196.88	b	8.56	b	7.7	ab	1.1	ab
K	1 N-P-K on normal soil	497.60	cd	12.44	e	10.0	cd	1.4	c

Description: Numbers followed by the same letter are not significantly different based on the Duncan multiple range test at the 5% level.

These results confirm that the application of MFC at the optimal dose not only enhances tissue nutrient content but also improves nutrient uptake efficiency, contributing to increased biomass and overall plant productivity in subsoil from excavation sites.

3.3. Yield

The application of MFC combined with N-P-K significantly improved several yield components (Table 7), including fruit weight, length, and circumference. Treatments with higher MFC concentrations, such as 0.75% MFC + 1 N-P-K (treatment E) and 1.00% MFC + 1 N-P-K (treatment F), resulted in fruit weights of 12.31 g and 12.28 g, which were comparable to the normal soil treatment (12.44 g).

Fruit length and circumference were also enhanced, with treatment F producing the longest fruit (11.5 cm) and treatment E showing the largest circumference (1.8 cm). These results indicate that the combination of MFC and N-P-K enhances nutrient availability, improving fruit development by promoting cell expansion and elongation. The observation of fruit length and diameter showed significant differences among treatments. The improvement in soil chemical properties, including increased organic carbon, CEC, base saturation, and nutrient availability in soil, positively influenced chili pepper yield. Treatments with 0.5%, 0.75%, and 1.0% MFC combined with a full dose of NPK (D, E, and F) resulted in optimal yields, comparable to those grown on normal soil. This suggests that the restoration of key soil properties through MFC and N-P-K application enhances nutrient availability and uptake, leading to improved red chili growth on subsoil from former clay brick industrial land.

The application of MFC combined with N-P-K significantly improved the yield and visual quality of chili peppers, aligning with the enhancements observed in individual fruit components, such as fruit weight, length, and circumference (Table 7). Treatments with higher MFC concentrations, like 0.75% MFC + 1 N-P-K (E) and 1.00% MFC + 1 N-P-K (F), produced the highest yields of 10.21 t ha^{-1} and 10.01 t ha^{-1}, respectively, comparable to the normal soil in the K treatment (10.07 t ha^{-1}) (Table 8). These treatments also resulted in visually superior fruits (visual appearance, Table 8)—uniform in size, straight, and vibrant red—meeting market standards. In contrast, the control without fertilizer (A) yielded the lowest results (0.88 t ha^{-1}) with inferior fruit quality.

The regression analysis results (Figure 4(a-h)) indicate a strong relationship between the uptake of macro- and micronutrients and the yield of red chili peppers. Nitrogen (N) uptake exhibited the highest correlation with yield, as evidenced by an R^2 value of 0.8662, followed by calcium (Ca) with R^2 = 0.8626, sulfur (S) with R^2 = 0.8722, and magnesium

(Mg) with R^2 = 0.8647. Potassium (K) uptake also showed a positive effect on yield with an R^2 value of 0.654, while phosphorus (P) uptake, although significant, demonstrated a lower correlation with yield (R^2 = 0.4815). Among micronutrients, boron (B) uptake showed a strong correlation with yield (R^2 = 0.8201), whereas copper (Cu) uptake had a weaker correlation (R^2 = 0.4542). These data confirm that nutrient uptake efficiency, particularly of N, Ca, S, Mg, and B, plays a critical role in enhancing crop yield.

Table 8. Effect of MFC application on the yield and visual appearance of red chili pepper.

Treatment		Yield (t ha^{-1})		Visual appearance
A	Control (without fertilizer)	0.88	a	
B	0 % MFC + 1 N-P-K dose	6.27	abc	
C	0.25 % MFC + 1 N-P-K dose	7.48	bc	
D	0.50 % MFC + 1 N-P-K dose	10.11	d	
E	0.75 % MFC + 1 N-P-K dose	10.21	d	
F	1.00 % MFC + 1 N-P-K dose	10.01	d	
G	0.5 % MFC + 3/4 N-P-K dose	8.63	c	
H	0.5 % MFC + 1/2 N-P-K dose	7.00	bc	
I	0.5 % MFC + 1/4 N-P-K dose	5.96	b	
J	0.5 % MFC + 0 N-P-K dose	3.98	ab	
K	1 N-P-K on normal soil	10.07	d	

Description: Numbers followed by the same letter are not significantly different based on the Duncan multiple range test at the 5% level.

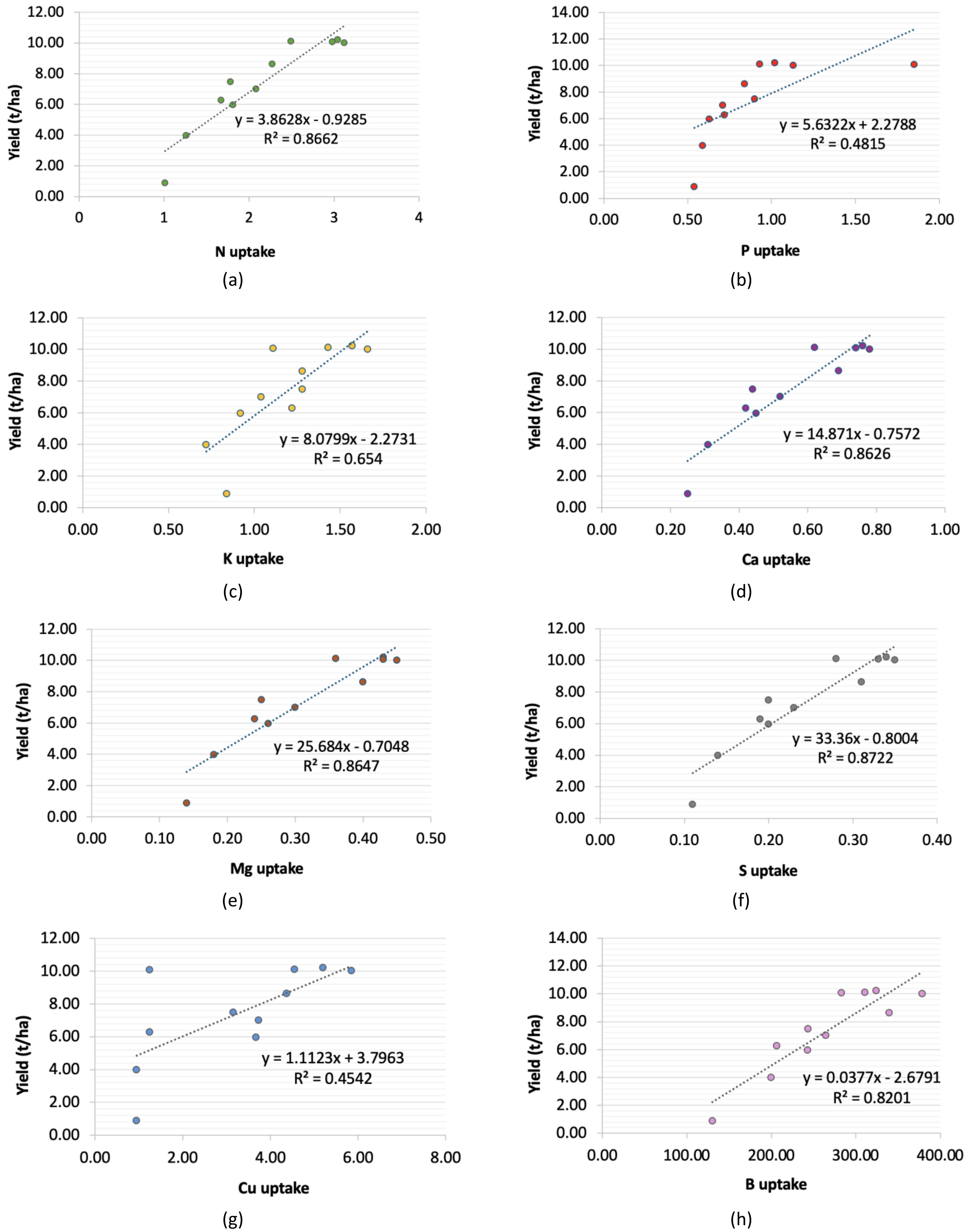


Figure 4. Correlation between nutrient uptake (N, P, K, Ca, Mg, S, Cu, B) and yield of red chili pepper (t ha^{-1}) under different fertilizer treatments.

4. DISCUSSION

Research has demonstrated that the application of a combination of MFC and N-P-K significantly improves subsoil quality, nutrient uptake, and the yield of red chili peppers. Subsoil generally has low organic matter content (Antony et al., 2022), and an inadequate supply of available nutrients (Osman, 2018). Such soil conditions require organic conditioners that provide carbon sources and nutrient supply, helping to improve soil quality and address these deficiencies. The increase in carbon and organic matter content in Table 5 and Figure 1 is attributed to the decomposition process, wherein microbial activity breaks down organic compounds into simpler substances, such as organic acids. This process is followed by humification, which produces stable organic compounds like humic and fulvic acids that enrich soil organic carbon. By the end of the observation period, organic matter mineralization had progressed further, resulting in the accumulation of carbon in more stable forms, which significantly contributed to the increased organic matter content in subsoil treated with MFC. Additionally, the improved soil condition facilitated greater nutrient availability and uptake by plants, as evidenced by increased concentrations of nitrogen, phosphorus, potassium, and micronutrients such as zinc and boron in plant tissue**.** These findings are consistent with earlier studies by Gill et al. (2008) and Fang et al. (2021), which showed that deep incorporation of organic amendments into sodic subsoils significantly improves soil chemical and physical properties, enhances nutrient uptake, and ultimately increases crop yield—with wheat yields in degraded subsoil systems reported to rise by 20–60%.

Other soil properties, such as base saturation, CEC, pH, and the availability of macro- and micronutrients, also improved (Figure 2a). This mechanism occurs because MLC provides base cations derived from the decomposition of organic waste and added mineral materials. Furthermore, active organic compounds such as humic and fulvic acids enhance CEC through negative charges that bind base cations and improve soil buffering capacity by balancing soil reactions and pH. The negative charges in MFC organic compounds, like other organic conditioners, are attributed to their chemical formula $(C_6H_{10}O_5)n$, primarily derived from –COOH functional groups, which act as the main carbon source. Carboxylate and phenolic groups can increase soil cation exchange capacity (CEC) and produce organic colloids with a high surface area (Ikbel et al., 2015). Additionally, several elements from added mineral materials supply essential nutrients, including base cations such as K^+, Na^+, Ca^{2+}, and Mg^{2+}, which are available in the soil solution to improve soil base saturation. Recent studies emphasize that the addition of mineral amendments significantly increases the concentration of exchangeable base cations (Suswati, 2023), leading to higher base saturation and enhanced soil fertility, particularly in acidic or weathered soils. Similarly, El-Desoky et al. (2018) and Yuniarti et al. (2018) reported a significant rise in exchangeable K^+, Na^+, Ca^{2+} , and $Mg^{2+}$and base saturation following the application of weathered volcanic ash as a soil ameliorant in tropical soils. Treatments with MFC and reduced N-P-K doses (G to J) still showed improvements compared to the control, but were less effective than the full-dose MFC and N-P-K combination (treatment F). Furthermore, MFC alone was insufficient for optimal subsoil improvement without the support of inorganic fertilizers. Overall, the combination of MFC and N-P-K has been proven to enhance subsoil quality, but the appropriate proportion is necessary to achieve optimal results.

Beyond soil properties, evaluating nutrient uptake efficiency by plants is crucial in assessing the impact of MFC application on subsoil (Table 6 and Figure 3), as this directly influences crop yield. The positive impact of organic materials, particularly MFC, on nutrient absorption is supported by previous studies, which highlight their role in improving degraded soil fertility and enhancing plant nutrient uptake (Lal, 2018). The indirect effects of organic materials on nutrient uptake start with improved soil structure and greater nutrient retention, leading to increased crop productivity on degraded soils. Additionally, the supplementary nutrient absorption provided by foliar applications of liquid nutrients further enhances nutrient uptake efficiency, especially in addressing deficiencies (Havlin et al., 2005; Kannan, 2010; Tejada & Gonzalez, 2004). This is due to the direct penetration of MFC nutrients into plant tissues without undergoing secondary processes in the soil, where nutrients might otherwise bind to soil sorption complexes (Rosmarkam & Yuwono, 2001).

Effective nutrient absorption significantly impacts plant growth and yield (Table 7 and Table 8). Nutrient sufficiency directly contributes to various physiological processes in plants (Pandey, 2018), including photosynthesis, protein synthesis, and tissue formation (Karthika et al., 2018). Essential macronutrients such as N are crucial for chlorophyll formation, which enhances photosynthetic efficiency (Massimi et al., 2023) and promotes vegetative growth (Vadillo et al., 2024) as well as generative development leading to harvest (Gokkus, 2025). Phosphorus (P) plays a role in energy transfer via ATP (Sriwantoko et al., 2020), Potassium (K) regulates osmotic pressure and nutrient transport in plants (Wang & Wu, 2017). Micronutrients such as zinc (Zn) (Umair Hassan et al., 2020), copper (Cu) (Mir et al., 2021), and boron (B) (Seth & Aery, 2017) support enzymatic and hormonal activities that influence fruit formation and yield quality (Manas et al., 2014; Salim et al., 2019; Turhan et al., 2021). Increased nutrient availability through MFC application has been proven to enhance the growth and yield of red chili plants.

This mechanism is reflected in the increased yield of red chili peppers, where treatments with MFC and N-P-K combinations resulted in higher yields, more uniform fruit length and diameter, and improved shape. These visual characteristics indicate optimal maturity levels and high commercial quality. Research shows that MFC use can enhance yield components such as fruit weight and size, ultimately leading to higher yields and improved fruit quality. Therefore, the combination of MFC and N-P-K not only improves soil quality but also significantly influences plant physiological processes, resulting in red chili peppers with optimal visual appearance. These findings are aligned with prior research indicating that combining humic substances with conventional fertilizers significantly improves chili performance**.** Foliar application of humic acid has been shown to enhance plant growth, fruit weight, diameter, and total yield in *Capsicum annum*. Jan et al. (2020) reported significant increases in fruit weight and size following humic foliar sprays. Similarly, Ichwan et al. (2022) demonstrated that chili plants treated with a mixture of humic acid and NPK exhibited superior soil fertility, nutrient availability, and yield compared to treatments without humic acid, with an optimal combination of 25% humic acid + 75% NPK yielding the best results

The uptake of specific macro- and micronutrients directly influences physiological processes that are essential for crop development and productivity. The strong correlation (Figure 4) between nitrogen uptake and yield highlights the critical role of nitrogen in promoting vegetative growth and chlorophyll synthesis (Muhammad et al., 2022), which ultimately enhances photosynthetic efficiency and biomass accumulation (Chen et al., 2018). Similarly, the significant correlations observed for calcium, sulfur, and magnesium uptake reflect their contribution to structural integrity, enzymatic activity, and energy metabolism within the plant. Calcium is particularly important for cell wall stability and membrane function (Thor, 2019), which supports robust fruit development (Gao et al., 2019), while sulfur and magnesium are key components in amino acid synthesis (Narayan et al., 2023) and chlorophyll structure, respectively (Pranckietiene et al., 2020). The moderate correlation of potassium uptake indicates its role in regulating osmotic balance and nutrient translocation, although with variability depending on environmental conditions (Sardans & Peñuelas, 2021). The relatively lower correlation of phosphorus suggests that while essential for energy transfer, its uptake may be more influenced by soil chemistry and availability (Sharpley & Halvorson, 2020). Boron's strong correlation with yield underscores its role in reproductive growth (Zeist et al., 2018) and fruit set (Salim et al., 2019), whereas the weaker association for copper suggests that, although necessary for enzymatic functions, its contribution to yield may be limited under the tested conditions (Adhikari et al., 2016). Overall, the data emphasize that optimizing the uptake of key nutrients through balanced fertilization strategies is vital for improving yield outcomes in red chili cultivation. However, further research is needed to evaluate these relationships under different soil types and environmental conditions, which represents a limitation of this study.

5. CONCLUSION

The use of MFC proved effective in improving several chemical properties of subsoil, as reflected by increases in organic-C content, base saturation, CEC, and soil pH. Application of MFC, either alone or in combination with NPK, enhanced soil structure and improved its ability to store and supply essential nutrients through the action of active organic compounds. The study also showed that combining MFC with optimal NPK doses (100% MFC + ¾ to 1 recommended NPK dose) led to more efficient nutrient uptake by plants, thereby supporting key physiological processes such as photosynthesis and tissue formation. This improvement directly contributed to higher yields of red chili peppers, both in terms of fruit weight and visual quality. Thus, integrating MFC with NPK not only improves the quality of degraded subsoil but also enhances chili productivity and harvest quality, making it a strategic approach for managing marginal soils in sustainable agricultural systems.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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