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RESEARCH PAPER

Partial replacement of NPK with coal-based fertilizer improves yield and profitability of chili pepper on tropical Ultisol soil

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Abstract

Productivity of horticultural crops on tropical acidic soils is frequently constrained by low nutrient availability, poor soil fertility, and limited fertilizer-use efficiency. This study evaluated Futura coal-based fertilizer, a commercial coal-derived carbon fertilizer, as a partial substitute for NPK fertilizer in chili pepper cultivation on Ultisol soil. The field experiment was conducted in Tapin Regency, South Kalimantan, Indonesia, using a randomized complete block design with five practical fertilization regimes involving NPK, coal-based fertilizer, and Celltilizer in selected treatments. The measured variables included plant growth, yield components, fruit quality, Cd, Pb, and As concentrations in fresh fruit, and farm economic performance. Fertilization significantly affected yield and productivity, whereas early growth and most fruit quality variables showed limited treatment responses. The best overall performance was obtained with 50% NPK + 50% coal-based fertilizer without Celltilizer, which produced 10.18 t ha^{-1} compared with 7.34 t ha^{-1} under the 100% NPK treatment, representing a 38.69% increase. The yield advantage was mainly associated with a greater fruit number and cumulative fruit weight rather than an increase in individual fruit size. Cd, Pb, and As concentrations remained below their respective limits of quantification in all treatments, indicating no detectable accumulation in harvested fruit during one cropping season. The economic analysis showed that the same treatment generated the highest revenue, net profit, and R/C ratio. These findings support the potential use of coal-based fertilizer as a complementary component of integrated nutrient management, but the underlying mechanisms and long-term environmental safety require further validation.

Keywords

Capsicum frutescens, Coal-based fertilizer, Farm profitability, Fruit Cd, Pb, and As, Integrated nutrient management, Ultisol

Introduction

Chili pepper (*Capsicum frutescens* L.) is one of the most important horticultural commodities in Indonesia, with high economic value and a strategic role in the national food system. The high level of household consumption and the continuing demand from the food processing industry have caused the demand for chili pepper to increase steadily (Surya and Tedjakusuma 2022; Yusniwati et al. 2023). Fluctuations in chili pepper prices frequently affect inflation and economic stability, indicating that this commodity has broad implications for the agricultural sector and farmers' welfare (Iskandar 2022). Accordingly, improving the productivity and input-use efficiency of chili pepper is not only an agronomic issue, but also a matter of economic resilience in horticultural production systems.

Beyond the Indonesian context, low productivity of horticultural crops on tropical drylands remains a major challenge in many regions where acidic soils, low

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organic matter, and poor nutrient availability constrain crop performance. In such environments, the efficiency of conventional fertilization is often limited by nutrient loss, weak nutrient retention, and poor synchronization between nutrient release and crop demand because strongly weathered tropical soils commonly exhibit high leaching potential, phosphorus fixation, and low nutrient-use efficiency under intensive fertilization systems (Juo and Uzu 1977; Achieng et al. 2010; Mesfin et al. 2021). These constraints are particularly important in intensive horticultural systems, where yield stability and input efficiency determine both production sustainability and farm profitability.

Chili pepper production in Indonesia still faces major agronomic constraints, particularly on tropical drylands dominated by Ultisol soils. Ultisols are characterized by high acidity, low base saturation, and relatively low contents of organic matter and macronutrients (Hasbullah et al. 2014; Hamidi et al. 2021). Ultisol soils also have a high phosphorus fixation capacity due to the dominance of iron and aluminum oxides, so that phosphorus availability for plants becomes very limited. These conditions result in low fertilization efficiency and restricted uptake of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) by horticultural crops, including chili (Mesfin et al. 2021; Villalba-Martínez et al. 2022). Crop productivity on Ultisol soils is therefore often below its optimum potential unless appropriate soil fertility management strategies are applied.

One of the approaches commonly used to overcome the fertility limitations of Ultisol soils is the increased application of chemical fertilizers, particularly NPK fertilizer. Intensive fertilization can increase crop production in the short term; however, excessive dependence on chemical fertilizers also generates environmental and economic problems. The excessive use of chemical fertilizers may accelerate soil acidification, increase nutrient losses through leaching, and reduce fertilization efficiency in the long term (Achieng et al. 2010; Ren et al. 2015). Continuously increasing fertilizer prices have also become a significant burden for smallholder farmers in tropical regions. These limitations indicate the need for fertilization strategies that maintain crop productivity while reducing dependence on fully mineral-based nutrient inputs.

Integrated nutrient management approaches have increasingly been developed to improve fertilization efficiency while maintaining the sustainability of agricultural production systems. This strategy integrates inorganic fertilizers with soil amendments or alternative nutrient sources that may improve the physical, chemical, and biological properties of the soil (Sayer et al. 2012; Halmi et al. 2018). Organic materials, biochar, and various soil amendments have been reported to increase nutrient retention, improve soil structure, and enhance the activity of soil microorganisms that play important roles in nutrient cycling (Mahmud and Chong 2022). In this context, integrated nutrient management is particularly relevant for marginal tropical soils, where nutrient retention and synchronization between nutrient supply and crop demand are important for stable yield formation. However, these processes need to be verified through direct soil and nutrient-dynamics measurements in each field context.

One innovation that has received increasing attention in recent years is the utilization of coal-derived materials as fertilizer sources or soil amendments. Various studies have shown that by-products of the coal industry, such as fine coal, coal gangue, and coal ash, have potential for agricultural use. Fine coal, for example, can be mixed with urea to produce fertilizer capable of improving plant growth through the supply of organic matter and mineral nutrients (Nursanto et al. 2023). The use of coal gangue as a partial substitute for chemical fertilizer has been reported to increase soil nitrogen content, reduce nitrate leaching, and improve maize yield as well as agronomic nitrogen efficiency (Wu et al. 2025).

Other studies have shown that the combination of brown coal and vermicompost can produce organomineral fertilizer containing various bioactive compounds such as enzymes, amino acids, vitamins, and phytohormones that play important roles in improving soil fertility and plant growth (Arynov et al. 2020). Coal ash derived from coal-fired power plants can also be processed into fertilizer containing important nutrients such as nitrogen, phosphorus, and potassium, as well as various micronutrients required by plants (Ritesh et al. 2021; Petropavlovskaya et al. 2022). In the present study, the coal-based fertilizer refers to Futura Coal-based Fertilizer, a commercial coal-derived carbon fertilizer produced by Saputra Global Harvest and marketed internationally as Carbontilizer. According to the related patent, the production process involves coal crushing and filtering, mixing with salts, nutrients, and/or biostimulant substances, maturation, and granulation into granules or prills (Saputra 2020). The product contains approximately 30% organic C, 20.33% humic acid, 2% total N, 0.89% P_2O_5, and 1.5% K_2O, with a calculated C:N ratio of approximately 15:1 and a reported pH range of 6–7 (Saputra Global Harvest 2024). The utilization of these coal-derived materials may contribute to agricultural productivity and resource-use efficiency, but their agronomic performance and safety need to be evaluated empirically under field conditions.

Agronomically, coal-based fertilizers possess several characteristics that make them attractive as potential complements to conventional fertilizers. Their high organic carbon content and the presence of humic compounds in certain coal types may contribute to increasing cation exchange capacity, improving soil structure, and enhancing the soil's ability to retain water and nutrients (Otremba 2012; Janeba-Bartoszewicz et al. 2019). The slow-release property of some coal-based or coal-derived fertilizer formulations may allow nutrients to be released gradually, thereby improving fertilizer use efficiency and reducing nutrient losses through leaching or volatilization (Li et al. 2017). Several studies have also reported

that the use of coal-based fertilizers can increase nitrogen retention, improve soil microbial activity, and enhance crop quality and yield on low-fertility soils (Lei et al. 2023; Wu et al. 2025). However, such mechanisms should be interpreted as literature-supported possibilities unless directly verified through measurements of post-treatment soil properties, nutrient-release kinetics, leaching dynamics, or microbial activity.

The application of coal-based fertilizers in agricultural systems also raises several issues that need to be considered. One of the main concerns is the potential contamination by heavy metals or other trace elements that may be present in coal raw materials. Several studies have indicated that elements such as cadmium (Cd) and lead (Pb) may pose environmental risks if they are not properly managed (Badagliacca et al. 2024; Yang et al. 2025). The utilization of coal-based fertilizers therefore requires a comprehensive evaluation not only of agronomic aspects, but also of fruit heavy-metal accumulation, soil contamination risk, and environmental sustainability under repeated application.

Despite increasing interest in coal-derived materials for agriculture, the available scientific evidence remains limited in several important respects. First, most previous studies have focused on staple crops, soil remediation, or post-mining land revegetation rather than intensive horticultural production systems (Ritesh et al. 2021; Nursanto et al. 2023). Second, empirical evidence regarding the optimal substitution level of mineral NPK fertilizer with coal-based fertilizer for chili pepper cultivated on tropical Ultisol soils remains scarce. Third, studies simultaneously integrating agronomic performance, fruit quality, short-term fruit heavy-metal status, and farm-level economic feasibility within a single experimental framework are still rare. More importantly, limited evidence is available on how partial substitution strategies perform under field conditions on strongly weathered tropical acidic soils, where fertilizer-use efficiency is often the major agronomic bottleneck. In addition, the role of biostimulant inputs in coal-based fertilization regime remains insufficiently separated from fertilizer-ratio effects in many practical field applications.

Based on these gaps, the present study was designed to address three specific questions: (1) can coal-based fertilizer partially substitute mineral NPK fertilizer without reducing the growth and yield of chili pepper on Ultisol soil; (2) does such substitution affect fruit quality and Cd, Pb, and As accumulation in harvested fruit; and (3) does the integrated fertilization strategy improve farm profitability under field conditions? Because Celltilizer, a biostimulant containing saccharides, amino acids, fatty acids, vitamins, and prebiotic compounds, was included only in selected treatment regimes, the study should be interpreted as an evaluation of practical fertilization combinations rather than a full factorial separation of coal-based fertilizer and Celltilizer effects (Saputra Global Harvest 2024).

Accordingly, this study aimed to evaluate the effectiveness of coal-based fertilizer as a partial substitute for NPK fertilizer on the growth, yield, fruit quality, fruit Cd, Pb, and As accumulation, and economic feasibility of chili pepper cultivation on Ultisol soil. The working hypothesis was that partial substitution of NPK fertilizer with coal-based fertilizer would maintain or enhance crop productivity and economic return by providing a more favorable balance between immediately available mineral nutrients and the carbon- and humic-acid-containing fertilizer component. Potential mechanisms related to nutrient retention and gradual nutrient release were considered plausible based on product characteristics and previous literature.

The main novelty of this study lies in the integrative evaluation of a coal-based fertilization strategy for chili pepper on tropical Ultisol soil by simultaneously assessing agronomic response, fruit quality, short-term fruit heavy-metal status, and farm economic performance. This integrated approach provides a broader basis for evaluating whether coal-based fertilizer can function as a practical component of integrated nutrient management for horticultural production on marginal tropical land, while recognizing that long-term soil fertility changes, nutrient-release dynamics, microbial responses, and repeated-application risks require further investigation.

Materials and methods

Research site and land characteristics

The field experiment was conducted on open land located in Bitahan Village, Lokpaikat District, Tapin Regency, South Kalimantan, Indonesia (Fig. 1). The study site was situated in a lowland area at an elevation of less than 50 m above sea level and was included in a tropical dryland agroecosystem dominated by Ultisol soil. This site was selected because it represents a typical marginal dryland environment in which soil acidity and low native fertility are major constraints to horticultural production.

Before the experiment was initiated, composite soil samples were collected from five points within the experimental area at two depths, namely 0–20 cm and 20–40 cm. The soil samples were analyzed to determine the physical and chemical properties of the soil, including texture, soil pH, organic carbon content, total nitrogen, available phosphorus, total potassium, cation exchange capacity (CEC), and the composition of basic cations. The analysis was carried out at the Soil Science Laboratory, Faculty of Agriculture, University of Lambung Mangkurat, Banjarbaru. The results of the initial soil analysis were used as the basis for understanding soil fertility status and as a reference for interpreting plant responses to the fertilization treatments. The initial physicochemical properties of the Ultisol soil are presented in the Results and Discussion section to provide a baseline for interpreting crop response to the fertilization regimes. No post-harvest soil analysis was conducted.

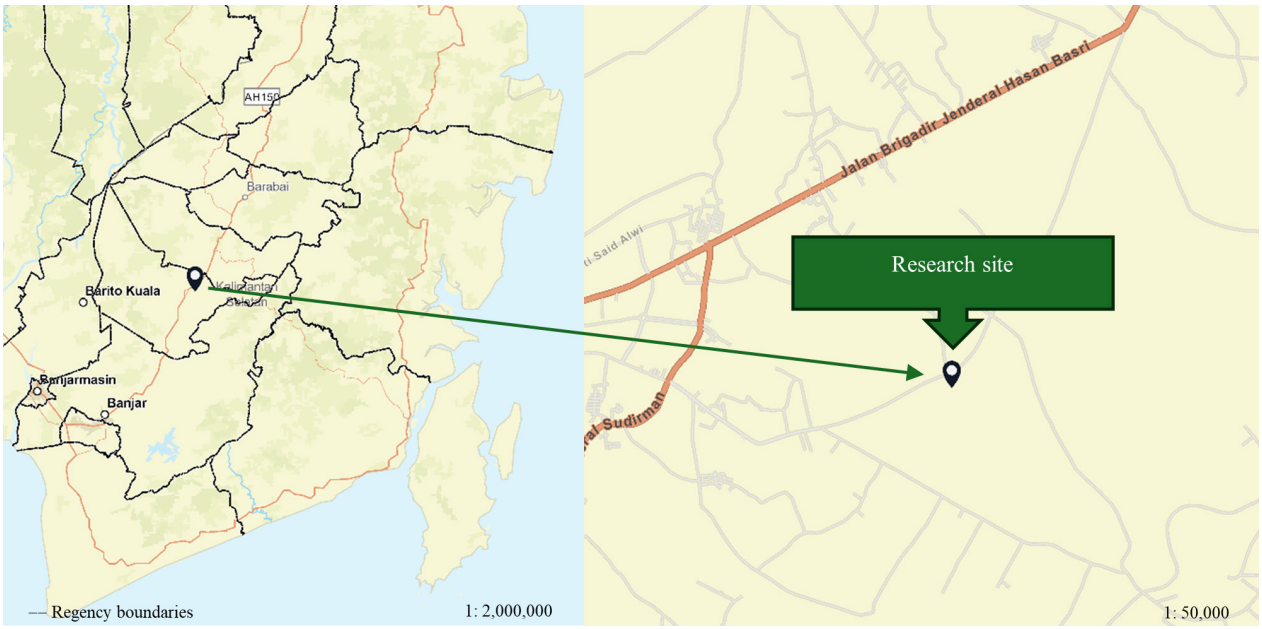

Figure 1. Research site for the evaluation of the effect of coal-based fertilizer on the productivity and profitability of chili pepper on Ultisol soil, located at coordinates 2°56′17.8"S, 115°11′28.2"E. The map was prepared using administrative boundary data from Badan Informasi Geospasial (2022), with location displays at scales of 1:2,000,000 and 1:50,000.

Research materials and equipment

The main materials used in this study included chili pepper seedlings of the CRV212/ORI212 variety as the experimental crop, chicken manure as a source of organic matter, dolomite as a liming material, compound NPK fertilizer 16–16–16 (Yaramila), Futura coal-based fertilizer, and Celltilizer as a growth-promoting input. The coal-based fertilizer and Celltilizer were commercial products manufactured by Saputra Global Harvest and were used as treatment materials to evaluate the potential partial substitution of mineral NPK fertilizer in an integrated fertilization system. The coal-based fertilizer used in this study was a commercial coal-derived carbon fertilizer marketed as Futura in Indonesia and Carbontilizer internationally. According to the related patent, coal-based fertilizer production involves crushing and filtering coal, mixing with salt, nutrients, and/or biostimulant substances, followed by maturation and granulation into granules or prills (Saputra 2020). The main characteristics of the coal-based fertilizer and Celltilizer used in this study are presented in Table 1.

In addition, silver-black plastic mulch was used to maintain soil moisture and suppress weed growth, and insect netting was used to reduce pest disturbance during the experiment. The equipment used in this study included land preparation tools such as a hand tractor, hoe, and rake; crop maintenance tools such as watering cans, hoses, and hand sprayers; and plant measurement tools such as measuring tape, digital balance, and calipers. In addition, laboratory instruments were used for soil analysis and for the determination of Cd, Pb, and As concentrations in chili fruit samples.

Experimental design

This study used a randomized complete block design (RCBD) to evaluate the effect of coal-based fertilizer as a substitute for NPK fertilizer on the growth, yield, and quality of chili pepper plants. The RCBD was selected to minimize the influence of field heterogeneity across the experimental area and to improve the precision of treatment comparisons under open-field conditions. Each treatment was replicated four times, and each experimental unit consisted of ten plants. From each experimental unit, five plants were randomly selected as observation samples.

Table 1. Main characteristics of the coal-based fertilizer and Celltilizer used in the study.

Input	Product description	Main characteristics
Coal-based fertilizer	Futura Coal-based Fertilizer, a commercial coal-derived carbon fertilizer produced by Saputra Global Harvest and marketed internationally as Carbontilizer	Organic C ±30%; humic acid ±20.33%; total N ±2%; P_2O_5 ±0.89%; K_2O ±1.5%; Na ±1.41%; Mg ±0.09%; S ±0.579%; B ±42 ppm; Mn ±252 ppm; Zn ±84 ppm; Fe ±134 ppm; Cu ±4.2 ppm; Co ±0.5 ppm; Ni ±2.82 ppm; Cd ±0.12 ppm; calculated C:N ratio approximately 15:1; reported pH 6–7
Celltilizer	Biostimulant produced by Saputra Global Harvest	Contains saccharides, amino acids, fatty acids, vitamins, and prebiotic compounds including fructo-oligosaccharides and galacto-oligosaccharides

Note: Fulvic acid content was not available in the manufacturer's technical information used in this study.
Source: Saputra Global Harvest (2024).

The experiment was designed to compare practical fertilization regimes rather than to provide a full factorial separation between coal-based fertilizer and Celltilizer effects.

The treatments consisted of five fertilization combinations, namely: D1 as the control with 100% NPK application; D2 as a combination of 50% NPK + 50% coal-based fertilizer + Celltilizer; D3 as a combination of 50% NPK + 50% coal-based fertilizer; D4 as a combination of 25% NPK + 75% coal-based fertilizer + Celltilizer; and D5 as 100% coal-based fertilizer application. The 100% NPK dose referred to the fertilization recommendation for chili pepper cultivation on dryland issued by the Ministry of Agriculture, namely 500 kg NPK ha^{-1}. The coal-based fertilizer dose was set on the same proportional basis as the NPK dose. Celltilizer was applied according to the recommended dose of 1 kg ha^{-1}. The detailed treatment structure is presented in Table 2.

Table 2. Fertilization treatments used in the field experiment.

Treatment	Fertilization regime	NPK dose (kg ha^{-1})	Coal-based fertilizer dose (kg ha^{-1})	Celltilizer dose (kg ha^{-1})
D1	100% NPK	500	0	0
D2	50% NPK + 50% coal-based fertilizer + Celltilizer	250	250	1
D3	50% NPK + 50% coal-based fertilizer	250	250	0
D4	25% NPK + 75% coal-based fertilizer + Celltilizer	125	375	1
D5	100% coal-based fertilizer	0	500	0

Note: The 100% NPK dose followed the fertilizer recommendation for chili pepper cultivation on dryland, namely 500 kg NPK ha^{-1}. The coal-based fertilizer dose was set on the same proportional basis; therefore, 100% coal-based fertilizer was equivalent to 500 kg ha^{-1}.

The treatment structure was designed to compare conventional mineral fertilization, partial substitution of mineral fertilizer with coal-based fertilizer under integrated management, and full substitution with coal-based fertilizer under practical field conditions. Because Celltilizer was included only in D2 and D4, the independent effect of Celltilizer could not be separated from the fertilizer-ratio effect in those treatments. Therefore, the results should be interpreted as responses to the tested fertilization combinations rather than as isolated effects of each input.

Land preparation and planting

Land preparation began with soil tillage using a hand tractor with a rotary system until the soil became loose and level. After tillage, dolomite was applied at a dose of 2 t ha^{-1} to reduce soil acidity and improve nutrient availability. Chicken manure was also applied at a dose of 3 t ha^{-1} as a source of organic matter to improve soil structure and support soil biological activity.

The experimental field was then divided into plots measuring 4 m × 5 m, with a spacing of 0.75 m between plots, resulting in a total of 20 experimental plots, corresponding to five treatments with four replications. Each plot was covered with silver-black plastic mulch to maintain soil moisture and reduce weed growth.

Chili pepper seedlings were raised in seedling trays using a growing medium consisting of soil, manure, and rice husk charcoal mixed at a ratio of 1:1:1. During the nursery period, regular watering was carried out to maintain medium moisture. The seedlings were transplanted to the experimental field after reaching the stage of four true leaves. Planting was carried out at a spacing of 50 cm × 70 cm.

Treatment application and crop maintenance

NPK fertilizer, coal-based fertilizer, and Celltilizer were applied one week before planting according to the assigned treatments. All fertilizers were applied on an area basis according to the treatment composition used in each fertilization regime. Celltilizer was applied only to D2 and D4 according to the treatment design. During the vegetative and generative growth phases, the plants were maintained through watering and pest management practices.

Harvesting was carried out when the chili fruits had reached approximately 80% red maturity. The first harvest was conducted at approximately 10 weeks after planting, and subsequent harvests were conducted at intervals of five days. Overall, harvesting was carried out 15 times during the study period. All 15 harvests were included in the cumulative yield and productivity calculation.

Observation parameters

Plant growth parameters were observed at six weeks after planting and included plant height, stem diameter, and number of branches. These variables were used to describe the vegetative response of the plants to the fertilization treatments.

Yield parameters included mean fruit number per plant per harvest, mean fruit weight per plant per harvest, total fruit number per plant, total fruit weight per plant, and productivity per hectare. Yield variables were calculated based on the cumulative harvest obtained from all 15 harvests in order to represent the final agronomic performance of each fertilization regime during one cropping cycle.

In addition to yield parameters, fruit quality observations were carried out, including fruit diameter, fruit length, and average fruit weight. Heavy metal analysis was

also conducted to evaluate the short-term fruit heavy-metal status of harvested chili fruits. The heavy metal parameters analyzed included cadmium (Cd), lead (Pb), and arsenic (As). Heavy metal analysis of fresh fruit was carried out at the Integrated Laboratory of University of Lambung Mangkurat using the Indonesian national standard testing method for metal contamination in food materials, SNI 01-2896-1998 (BSN 1998), with determination performed using atomic absorption spectrophotometry (AAS). The results were expressed on a fresh-weight basis. The limits of quantification (LOQ) for Cd, Pb, and As were 0.001, 0.021, and 0.024 mg kg^{-1} fresh weight, respectively, while the corresponding limits of detection (LOD) were 0.0003, 0.0063, and 0.0072 mg kg^{-1} fresh weight.

No post-harvest soil sampling was conducted in this study. Consequently, post-treatment soil pH, organic carbon, CEC, residual N, P, K, nutrient leaching, microbial activity, and nutrient-release kinetics were not directly measured. This limitation was considered when interpreting possible mechanisms underlying the agronomic response.

Data analysis

The data obtained from the observations were analyzed using analysis of variance (ANOVA) to determine the effect of treatments on growth, yield, and fruit quality parameters. ANOVA was applied in accordance with the randomized complete block design used in this study to test whether the fertilization treatments produced statistically significant differences among measured variables. When the analysis of variance indicated significant differences among treatments, mean separation was performed using Tukey's Honest Significant Difference (HSD) test at the 5% significance level. This statistical approach was used to identify the fertilization treatment that produced the best agronomic response under field conditions. Mean separation was performed only for variables showing significant treatment effects in ANOVA.

In addition to agronomic analysis, this study also included an economic feasibility analysis of chili pepper farming based on a cost–benefit approach. The economic analysis was performed by calculating total production cost, revenue, net profit, and the revenue-to-cost ratio (R/C ratio). Total production cost was calculated from fixed and variable cost components recorded during the field experiment, including land preparation, seedling production, manure, dolomite, NPK fertilizer, coal-based fertilizer, Celltilizer, mulch, plant protection materials, irrigation or watering, and labor costs for land preparation, planting, fertilization, maintenance, and harvesting. Revenue was calculated by multiplying total marketable yield by the farm-gate chili price used in the economic analysis. Net profit was calculated as total revenue minus total production cost, while the R/C ratio was calculated as total revenue divided by total production cost. The B/C ratio was calculated as net profit divided by total production cost. This analysis was intended to complement the agronomic evaluation by assessing the practical feasibility of partial NPK substitution with coal-based fertilizer under farm-level conditions.

Results and discussion

Initial soil characteristics of the study site

The results of the initial soil analysis showed that the experimental site in Tapin Regency, South Kalimantan, was classified as Ultisol, which is generally recognized as a highly weathered tropical soil with high acidity, low base saturation, and relatively low organic matter content. These characteristics were consistent with the general description of Ultisols in tropical regions, which are characterized by the dominance of Fe and Al oxides, limited cation exchange capacity, and a strong tendency toward phosphorus fixation and nutrient leaching (Juo and Uzu 1977; Ruhigwa et al. 1993; Septyani et al. 2019; Sebayang et al. 2023; Dayah et al. 2024). This condition constituted one of the major factors limiting the productivity of horticultural crops, including chili pepper, on marginal land.

The results of the physical and chemical analyses of the soil at the study site are presented in Table 3. The soil had a clay texture with a very acidic pH of approximately 4.5. Total nitrogen content and total potassium were classified as very low, while organic carbon content and base saturation were also low. Available P_2O_5 was also very low,

Table 3. Initial physical and chemical properties of the soil at the experimental site.

Properties	0–20 cm	20–40 cm	Criteria*
Texture			
Sand (%)	8.32	5.21	
Silt (%)	22.59	34.12	clay
Clay (%)	69.08	60.67	
pH			
H_2O	4.53	4.54	acidic
KCl	3.69	3.68	very acidic
C-total (%)	1.58	0.88	very low
N-total (%)	0.13	0.13	very low
$N–NH_4^+$ (ppm)	20.42	18.64	high
$N–NO_3^-$ (ppm)	1.27	1.33	low
C/N	12.15	6.76	very low
Total P_2O_5 (HCl 25%) (mg/100 g)	5.53	2.96	very low
Total K_2O (mg/100 g)	16.57	8.19	very low
Available P_2O_5 (Bray I) (ppm)	1.39	1.84	very low
CEC (me 100 g $soil^{-1}$)	30.70	27.92	high
Exchangeable cations (me 100 g $soil^{-1}$)			
K	0.05	0.06	very low
Na	0.13	0.08	very low
Ca	2.86	2.01	low
Mg	0.22	0.27	very low
Base saturation (%)	10.64	8.66	very low
Exchangeable Al (me 100 g $soil^{-1}$)	0.75	1.25	–

Note: *Criteria based on Agus et al. (2005) and Blakemore et al. (1987).

indicating severe phosphorus limitation despite the relatively high CEC value. These conditions indicate that the availability of essential nutrients in Ultisol soil at the study site was limited and potentially susceptible to nutrient loss through leaching, especially under high-rainfall tropical conditions (Juo and Uzu 1977; Fauziah et al. 2018; Dayah et al. 2024).

These characteristics are in agreement with previous reports indicating that Ultisols have inherently low fertility due to intensive weathering and the dominance of low-activity clay minerals, thereby requiring integrated nutrient management strategies to improve crop productivity (Juo and Uzu 1977; Sebayang et al. 2023; Dayah et al. 2024; Saragih 2025). However, the present soil data represent only the initial condition before treatment application and should not be interpreted as evidence of treatment-induced soil fertility changes.

The results of this study showed that the initial soil condition at the research site exhibited typical Ultisol characteristics, with high acidity, low base saturation, very low nitrogen and potassium contents, and limited organic carbon content, as shown in Table 3. These characteristics represent major limiting factors for horticultural production on tropical drylands. Ultisol soils are known to undergo intensive weathering, resulting in the dominance of iron and aluminum oxide minerals, which increase the potential for phosphorus fixation and reduce the availability of essential nutrients for plants (Septyani et al. 2019; Sebayang et al. 2023; Dayah et al. 2024). This condition helps explain why conventional fertilization systems based solely on mineral fertilizers are often less efficient on marginal soils, where part of the applied nutrients may be lost through leaching or become less available within the soil complex. Because post-harvest soil properties were not measured, the soil data should be used only as baseline information for interpreting crop response.

These initial soil characteristics indicate that chili pepper response should be interpreted against the low-fertility background of the Ultisol soil. Under such conditions, fertilization effectiveness is not determined only by the amount of nutrients applied, but also by the capacity of the fertilization regime to maintain nutrient availability during crop growth. The carbon- and humic-acid-containing component of the coal-based fertilizer may provide agronomic advantages when combined with immediately available mineral nutrients from NPK. However, this interpretation remains inferential because post-harvest soil properties and nutrient dynamics were not directly measured.

Effect of coal-based fertilizer–NPK combinations on plant growth

The growth analysis showed that early vegetative response varied among measured traits. Plant height and stem diameter were not significantly affected by fertilization treatment, whereas branch number showed a significant response (Table 4). Therefore, early growth response should be interpreted primarily from branch development rather than from overall plant size or stem thickening.

D3 produced the highest numerical plant height, but this difference was not statistically significant. For branch number, D1 produced the highest value, while D3 and D5 were statistically intermediate based on Tukey's HSD. These results indicate that early vegetative traits responded less consistently than yield-related variables.

Table 4. Effect of coal-based fertilizer–NPK combinations on the growth of chili pepper plants at 6 WAP. Values are means ± SE (n = 4). CV denotes the coefficient of variation from ANOVA. ns = not significant; * = significant (p < 0.05); ** = highly significant (p < 0.01). Different letters within a column indicate significant differences by Tukey's HSD test (p < 0.05).

Treatments	Height (cm)	Stem diameter (mm)	Branch number
D1	48.88 ± 1.67	12.53 ± 0.55	97.22 ± 4.95 [a]
D2	46.69 ± 2.22	11.22 ± 0.31	70.84 ± 2.78 [b]
D3	54.47 ± 3.11	12.03 ± 0.67	85.19 ± 3.52 [ab]
D4	46.25 ± 3.47	11.69 ± 0.73	69.13 ± 6.91 [b]
D5	41.06 ± 2.77	11.52 ± 0.49	81.21 ± 3.25 [ab]
CV	11.76 [ns]	10.50 [ns]	11.62 [**]
Tukey's HSD 5%	-	-	21.14

The growth response observed in this study was relatively limited compared with the yield response. Although D3 produced the highest numerical plant height, plant height and stem diameter were not significantly affected by fertilization treatment. The clearest vegetative response was observed in branch number, where D1 had the highest value, while D3 and D5 were statistically intermediate. This pattern indicates that early vegetative traits did not fully explain the later productivity advantage observed under D3.

The limited response of early growth variables suggests that the main benefit of the 50% NPK + 50% coal-based fertilizer regime was expressed more strongly during yield formation than during early vegetative development. Therefore, interpretation of plant growth data should remain cautious and should not be generalized as broad vegetative enhancement. Because Celltilizer was included only in D2 and D4, the growth response should also be interpreted as the response of practical fertilization combinations rather than as the isolated effect of individual inputs.

Effect of coal-based fertilizer–NPK combinations on productivity and fruit quality

The results of the production analysis showed that the combination of coal-based fertilizer and NPK significantly affected the productivity of chili pepper (Table 5). The highest productivity was obtained in treatment D3, which produced 10.18 ± 0.40 t ha^{-1}, whereas the control treatment D1 produced 7.34 ± 0.30 t ha^{-1}. Based on Tukey's HSD, productivity

Table 5. Effect of coal-based fertilizer–NPK combinations on the yield of chili pepper plants. Values are means ± SE (n = 4). CV denotes the coefficient of variation from ANOVA. ns = not significant; * = significant (p < 0.05); ** = highly significant (p < 0.01). Different letters within a column indicate significant differences by Tukey's HSD test (p < 0.05). *** Calculated from all 15 harvests.

Treatments	Mean fruit number per plant per harvest***	Mean fruit weight per plant per harvest (g)***	Total fruit number per plant	Total fruit weight per plant (g)	Productivity (t ha^{-1})***
D1	15.13 ± 0.71 ^{bc}	40.79 ± 1.69 ^{bc}	226.95 ± 10.60 ^{bc}	611.82 ± 25.32 ^{bc}	7.34 ± 0.30 ^{bc}
D2	17.79 ± 0.74 ^{ab}	47.75 ± 1.78 ^{ab}	266.80 ± 11.12 ^{ab}	716.22 ± 26.64 ^{ab}	8.59 ± 0.32 ^{ab}
D3	19.71 ± 0.73 ^{a}	56.54 ± 2.19 ^{a}	295.63 ± 10.91 ^{a}	848.08 ± 32.92 ^{a}	10.18 ± 0.40 ^{a}
D4	15.30 ± 0.76 ^{bc}	40.93 ± 2.43 ^{bc}	229.53 ± 11.40 ^{bc}	613.94 ± 36.46 ^{bc}	7.37 ± 0.44 ^{bc}
D5	13.76 ± 0.61 ^{c}	36.89 ± 1.57 ^{c}	206.33 ± 9.20 ^{c}	553.41 ± 23.49 ^{c}	6.64 ± 0.28 ^{c}
CV	9.39 **	9.33 **	9.39 **	9.33 **	9.33 **
Tukey's HSD 5%	3.46	9.36	51.86	140.66	1.69

under D3 was significantly higher than under D1, D4, and D5, but was not significantly different from D2 because both treatments shared an overlapping statistical grouping.

Compared with the control, treatment D3 increased productivity by 2.84 t ha^{-1}, equivalent to approximately 38.7%. Treatment D2 also improved productivity to 8.59 ± 0.32 t ha^{-1}, whereas D4 remained close to the control level at 7.37 ± 0.44 t ha^{-1} and D5 produced the lowest productivity at 6.64 ± 0.28 t ha^{-1}. A similar pattern was observed for total fruit number per plant and total fruit weight per plant, with D3 recording the highest values among all fertilization regimes. This indicates that the yield advantage of D3 was mainly associated with higher fruit number and greater cumulative fruit weight per plant, rather than with a clear increase in individual fruit size.

These results indicate that partial substitution of NPK with coal-based fertilizer was more favorable than both the control treatment and full substitution with coal-based fertilizer alone. The superiority of D3 was reflected not only in productivity per hectare, but also in mean fruit number per harvest, mean fruit weight per harvest, total fruit number, and total fruit weight. However, because D2 and D4 included Celltilizer whereas D3 did not, the response should be interpreted as the effect of tested fertilization regimes rather than as the isolated effect of coal-based fertilizer alone.

Taken together, the yield data indicate that partial replacement of NPK with coal-based fertilizer produced a more favorable agronomic outcome than either sole NPK application at the control rate or sole coal-based fertilizer application. Under the conditions of this experiment, the 50% NPK + 50% coal-based fertilizer treatment represented the most favorable substitution level.

The fruit quality parameters observed in this study included fruit diameter, fruit length, and fruit weight per fruit. The results showed that fertilization treatment significantly affected fruit length, whereas fruit diameter and fruit weight did not differ significantly among treatments (Table 6).

Treatment D3 showed the highest fruit length at 49.11 ± 0.56 mm, followed by D4 at 47.29 ± 0.38 mm, while D2 showed the lowest value at 42.13 ± 0.77 mm. Based on Tukey's HSD, D3 produced significantly longer fruits than D1, D2, and D5, but it was not significantly different from D4. In contrast, fruit diameter remained within a relatively narrow range across treatments, and average fruit weight also did not show a statistically significant treatment response.

These results indicate that the effect of fertilization on fruit morphology was relatively limited and was most clearly expressed in fruit length rather than in fruit diameter or average fruit weight. Therefore, the primary treatment effect appears to have been associated with production quantity rather than broad changes in fruit physical characteristics. This interpretation helps explain why D3 achieved higher productivity despite the absence of significant differences in fruit diameter and individual fruit weight.

Overall, these data indicate that fertilizer treatments had a limited effect on most fruit quality variables, with the clearest response observed in fruit length.

The results of this study showed that the integration of coal-based fertilizer with NPK significantly increased chili pepper productivity, with D3 producing the highest yield. This finding indicates that partial substitution of mineral fertilizer with coal-based fertilizer was more effective than both sole NPK application at the control rate and full substitution with coal-based fertilizer alone. Nevertheless, because D2 and D4 included Celltilizer while D3 did not, the results should be interpreted as comparisons among practical fertilization combinations rather than as a complete separation of coal-based fertilizer, NPK ratio, and biostimulant effects.

Table 6. Effect of coal-based fertilizer–NPK combinations on the fruit quality of chili pepper plants. Values are means ± SE (n = 4). CV denotes the coefficient of variation from ANOVA. ns = not significant; * = significant (p < 0.05); ** = highly significant (p < 0.01). Different letters within a column indicate significant differences by Tukey's HSD test (p < 0.05).

Treatments	Fruit diameter (mm)	Fruit length (mm)	Fruit weight (g)
D1	15.11 ± 0.23	45.09 ± 0.33 ^{b}	2.99 ± 0.13
D2	15.18 ± 0.39	42.13 ± 0.77 ^{c}	2.70 ± 0.23
D3	14.86 ± 0.16	49.11 ± 0.56 ^{a}	3.43 ± 0.24
D4	15.65 ± 0.16	47.29 ± 0.38 ^{ab}	3.33 ± 0.06
D5	14.86 ± 0.49	45.76 ± 1.02 ^{b}	2.87 ± 0.25
CV	4.18 ^{ns}	2.76 **	12.03 ^{ns}
Tukey's HSD 5%	-	1.95	-

The superiority of D3 is particularly important because it suggests the presence of an optimum integration effect rather than a linear response to increasing coal-based fertilizer proportion. In other words, the agronomic response did not improve continuously with higher coal-based substitution. Instead, the results indicate that a balanced substitution level was more advantageous than either dependence on full mineral fertilization or an excessive proportion of coal-based fertilizer. This point represents one of the central conceptual contributions of the study. Under the conditions of this experiment, partial replacement appeared to provide a more favorable balance between immediately available nutrients from NPK and the carbon- and humic-acid-containing component supplied by the coal-based fertilizer. The lower productivity of D4 and D5 may reflect insufficient immediately available mineral nutrients during critical growth and fruiting stages, or a mismatch between nutrient release from the coal-based fertilizer and crop nutrient demand. However, possible phytotoxic effects or soil chemical constraints at higher coal-based fertilizer proportions cannot be confirmed because phytotoxicity indicators, post-harvest soil properties, nutrient-release kinetics, and nutrient leaching were not measured.

Previous studies have shown that integrated nutrient management can improve crop productivity through better nitrogen and phosphorus use efficiency, improved nutrient availability, and enhanced retention of water and nutrients in the soil (Guertal 2009; Macedo et al. 2021; Ma et al. 2022). The present findings are consistent with this broader framework, particularly in the context of tropical acidic soils where nutrient-use efficiency is often constrained by soil chemical limitations. However, because post-treatment soil properties, nutrient-release kinetics, nutrient leaching, and microbial activity were not measured, the present study cannot confirm whether these mechanisms occurred in the field. The observed yield response should therefore be interpreted as treatment-level agronomic evidence, while the underlying mechanisms require further investigation.

In contrast to the clear yield response, most fruit quality parameters did not differ significantly among treatments. This indicates that the integrated fertilization strategy had a stronger effect on production quantity than on fruit morphological quality. Such a pattern is not unusual in horticultural systems, where fruit morphology is often influenced not only by nutrient management, but also by varietal characteristics and environmental factors such as temperature, radiation, and water availability (Lee et al. 2022). From an agronomic perspective, this distinction is relevant because it shows that the yield advantage associated with D3 was achieved without major alteration of the basic physical attributes of the fruit. More specifically, the higher productivity of D3 was driven mainly by a greater number of fruits and higher cumulative fruit weight per plant, while individual fruit diameter and fruit weight remained statistically unchanged.

Environmental and short-term fruit heavy-metal implications of coal-based fertilizer use

The analysis of Cd, Pb, and As concentrations in chili pepper fruit showed that all three elements were below their respective LOQ values across all treatments (Table 7). Consequently, no treatment-related differences in fruit Cd, Pb, and As concentrations could be distinguished within the analytical sensitivity of the method used.

These results indicate that the tested coal-based fertilizer regimes were not associated with detectable Cd, Pb, and As accumulation in harvested fruit within one cropping season. However, this finding should be interpreted only as short-term evidence for the measured fruit heavy metals and should not be extended to comprehensive food safety or long-term environmental safety, because soil accumulation, repeated-application effects, and other potential contaminants were not assessed.

Table 7. Effect of coal-based fertilizer–NPK combinations on Cd, Pb, and As concentrations in fresh chili pepper fruit cultivated on Ultisol soil.

Treatments	Cd (mg kg^{-1} fresh weight)	Pb (mg kg^{-1} fresh weight)	As (mg kg^{-1} fresh weight)
D1	<0.001*	<0.021*	<0.024*
D2	<0.001*	<0.021*	<0.024*
D3	<0.001*	<0.021*	<0.024*
D4	<0.001*	<0.021*	<0.024*
D5	<0.001*	<0.021*	<0.024*

Note: *Values below the LOQ. Analysis was conducted using SNI 01-2896-1998. The LOQ values for Cd, Pb, and As were 0.001, 0.021, and 0.024 mg kg^{-1} fresh weight, respectively, with corresponding LOD values of 0.0003, 0.0063, and 0.0072 mg kg^{-1} fresh weight.

The absence of detectable Cd, Pb, and As accumulation in harvested fruit suggests that the tested coal-based fertilizer regimes did not increase the measured fruit heavy metals within one cropping season. This result is consistent with previous studies indicating that coal-derived materials may be used under controlled conditions when appropriately processed and applied at suitable rates (Jackson and Miller 2000; Hesterberg et al. 2015; Amoakwah et al. 2024). Nevertheless, the present data cannot be used to infer long-term environmental safety because soil heavy metal accumulation, repeated-application effects, and other contaminant classes, including polycyclic aromatic hydrocarbons, were outside the scope of this experiment (Staf et al. 2020; Putri et al. 2023).

Economic feasibility analysis of chili pepper production

The economic analysis showed that the combination of coal-based fertilizer and NPK provided higher economic returns than the use of NPK alone. Treatment D3 produced the highest revenue value (Rp. 203,538,750) and net profit (Rp. 107,804,750), with an R/C ratio of 2.13. This

result was calculated from total production cost and marketable yield obtained during one cropping cycle.

Compared with the control treatment D1, D3 increased revenue by approximately Rp. 57,826,364 and increased net profit by approximately Rp. 60,826,364, while also providing the highest R/C ratio among all treatments. Treatment D2 also showed a clear economic advantage over the control, whereas D4 and D5 remained lower than D3 despite reduced mineral fertilizer use or complete coal-based substitution. This pattern indicates that reducing mineral NPK input did not automatically improve profitability; economic benefit was achieved only when input reduction was accompanied by sufficient yield improvement.

These results indicate that the agronomic advantage observed under D3 was accompanied by the most favorable economic return. Thus, partial substitution with coal-based fertilizer was more profitable than both conventional fertilization and full coal-based fertilizer application under the conditions of this study. Because D2 and D4 included Celltilizer while D3 did not, the economic results should be interpreted as comparisons among practical fertilization regimes rather than as isolated effects of coal-based fertilizer or Celltilizer.

Overall, the economic analysis confirmed that the most favorable agronomic treatment also produced the strongest economic outcome, thereby strengthening the practical relevance of the integrated fertilization strategy evaluated in this study. The economic conclusion is therefore treatment-specific and should be validated further under different input-price, labor-cost, and chili-market-price conditions.

The detailed economic performance of each fertilization regime is presented in Table 8, while Fig. 2 provides

Table 8. Economic performance of chili pepper production under coal-based fertilizer–NPK combinations.

Treatment	Cost (Rp)	Revenue (Rp)	Net profit (Rp)	R/C ratio	B/C ratio	Cost reduction relative to D1 (%)	Revenue increase relative to D1 (%)	Profit increase relative to D1 (%)
D1	98,734,000	145,712,386	46,978,386	1.48	0.48	0.00	0.00	0.00
D2	95,984,000	171,892,500	75,908,500	1.79	0.79	2.79	17.97	61.58
D3	95,734,000	203,538,750	107,804,750	2.13	1.13	3.04	39.69	129.48
D4	94,484,000	147,345,000	52,861,000	1.56	0.56	4.30	1.12	12.52
D5	92,734,000	132,819,375	40,085,375	1.43	0.43	6.08	-8.85	-14.67

Note: Cost = total production cost; revenue = marketable yield × farm-gate chili price; net profit = revenue − total production cost; R/C ratio = revenue / total production cost; B/C ratio = net profit / total production cost.

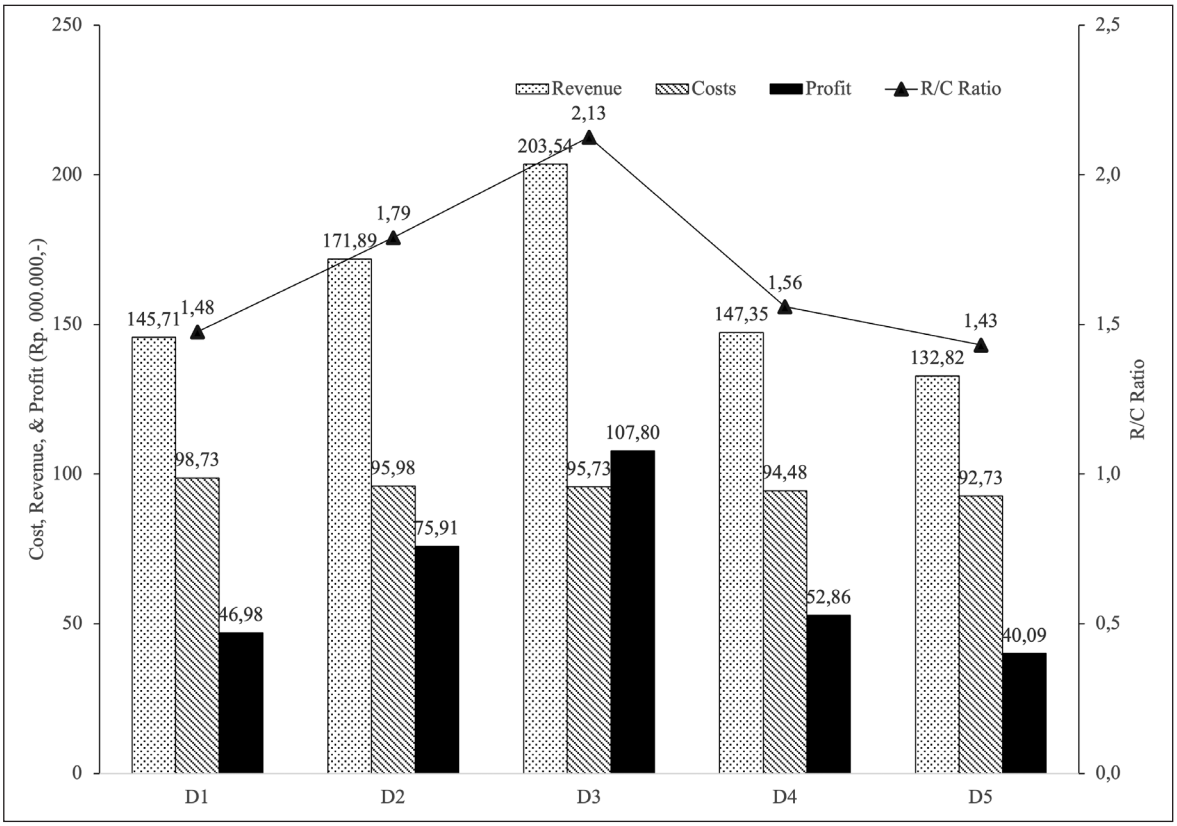

Figure 2. Cost, revenue, net profit, and R/C ratio of chili pepper production under coal-based fertilizer–NPK combinations on Ultisol soil. Revenue was calculated from marketable yield and farm-gate chili price, whereas net profit and R/C ratio were derived from total production cost and revenue.

a visual comparison of cost, revenue, net profit, and R/C ratio across treatments.

This finding reinforces the interpretation that the value of coal-based fertilizer in the present study lay primarily in its role as a complementary input within an integrated fertilization system, rather than as a full replacement for mineral fertilizer. The reduction in dependence on mineral fertilizer contributed to improved cost efficiency, while yield was maintained or increased under the optimum substitution regime. This dual advantage is particularly relevant for horticultural production systems on marginal soils, where input cost and nutrient-use efficiency are often decisive factors for farm profitability. Nevertheless, the economic advantage should not be generalized without considering seasonal yield variability, fertilizer availability, transportation cost, and chili price fluctuation.

From a broader perspective, this result is consistent with the concept of a circular economy in agriculture, in which industrial by-products are utilized as productive resources within food production systems. The use of carbon-based materials as fertilizer components or soil amendments may contribute to better resource-use efficiency while reducing dependence on conventional mineral inputs (Tang et al. 2017; Shar et al. 2021; Meshram et al. 2025). In addition, more efficient fertilization strategies may help reduce environmental pressures commonly associated with excessive chemical fertilizer use, including nitrate leaching and greenhouse gas emissions related to nitrogen transformation processes. In the present study, however, nitrate leaching, greenhouse gas emissions, and soil nutrient retention were not measured; therefore, these broader environmental implications should be regarded as potential benefits rather than directly demonstrated outcomes.

Nevertheless, the broader sustainability interpretation should be presented with caution. The present experiment supports the agronomic and economic feasibility of the tested strategy under one set of field conditions, but its longer-term contribution to sustainable nutrient management across different agroecosystems will require further validation under multi-location and multi-season conditions. Future studies should integrate post-harvest soil fertility assessment, nutrient balance analysis, long-term heavy metal monitoring, and sensitivity analysis of input and output prices.

Study limitations

Several limitations of the present study should be acknowledged. First, the experiment was conducted at a single location and within one cropping cycle, so the broader applicability of the results to other Ultisol environments or climatic conditions should be interpreted carefully. Second, the study focused on agronomic response, fruit quality, short-term fruit Cd, Pb, and As status, and farm economic performance, but did not directly measure post-harvest soil pH, CEC, organic carbon, residual N, P, and K, nutrient-release kinetics, nutrient leaching, microbial activity, or soil heavy metal accumulation. Therefore, mechanistic explanations related to nutrient retention, slow-release behavior, and soil-property improvement remain inferential. Third, because Celltilizer was included only in D2 and D4, its independent effect could not be separated from fertilizer-ratio effects. Finally, because the coal-based fertilizer and Celltilizer were commercial products, the interpretation of the results should be understood within the context of the specific formulations and field conditions evaluated in this study.

Despite these limitations, the study provides field-based evidence that partial substitution of NPK with coal-based fertilizer can improve the productivity and profitability of chili pepper on tropical Ultisol soil while showing no detectable Cd, Pb, and As accumulation in harvested fruit within the measured scope of the experiment. The findings should therefore be interpreted as treatment-specific, single-season evidence supporting the potential of 50% NPK + 50% coal-based fertilizer as a practical fertilization regime, rather than as definitive evidence of long-term soil improvement, environmental safety, or universal agronomic performance.

Conclusion

This study shows that, under the conditions of a single-season field experiment, partial replacement of NPK fertilizer with coal-based fertilizer can improve the agronomic and economic performance of chili pepper cultivated on tropical Ultisol soil. Among the tested treatments, the combination of 50% NPK + 50% coal-based fertilizer produced the most favorable overall response, as indicated by the highest fruit production, greater land productivity, and the highest economic return compared with conventional fertilization and full coal-based substitution. The growth response should be interpreted more cautiously because plant height and stem diameter were not significantly affected, whereas the treatment effect was more evident in yield-related variables.

The results further showed that fruit quality remained relatively stable across treatments, while Cd, Pb, and As concentrations in the harvested fruit were below the quantification limit of the analytical method. These findings indicate no detectable accumulation of Cd, Pb, and As in harvested fruit within one cropping season, but they should not be interpreted as comprehensive evidence of food safety or long-term environmental safety because soil accumulation, repeated-application effects, and other potential contaminants were not assessed.

Overall, the study supports the potential use of coal-based fertilizer as a complementary component of integrated nutrient management for horticultural production on Ultisol soil, particularly where fertilizer-use efficiency and farm profitability are major concerns. However, the findings should be interpreted as treatment-specific evidence for the tested fertilization regimes, because Cellti-

lizer was included only in selected treatments and its independent effect could not be separated from fertilizer-ratio effects. The broader applicability of these findings should be interpreted cautiously because the study was conducted at a single location and within one cropping cycle. Further research is required to assess long-term agronomic and environmental effects under different agroecosystem conditions, particularly through post-harvest soil assessment, nutrient-balance analysis, microbial evaluation, heavy metal monitoring, and multi-season economic sensitivity analysis.

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Additional information

Conflict of interest
The authors have declared that no competing interests exist.

Ethical statement
No ethical statement was reported.

Artificial Intelligence (AI) use
The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.
Regarding the use of AI in the preparation of this manuscript, the authors declare the following: GPT.
Used for: Language, style and writing.
During the preparation of this manuscript, the authors used generative artificial intelligence tools to assist with language refinement, grammar correction, and improvement of readability. The use of these tools was limited strictly to editorial support. No generative AI tools were used for data generation, data analysis, interpretation of results, or development of scientific conclusions. All experimental design, data analysis, interpretation, and scientific content were conducted and verified by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

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Data availability
All of the data that support the findings of this study are available in the main text.