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Research Article

Effects of Organo-Mineral Fertilizers on Nitrogen, Phosphorus, and Potassium Uptake in Tea (*Camellia sinensis* L.) under Acidic Highland Soils in Mufindi, Tanzania

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Abstract
Tea (*Camellia sinensis* L. O. Kuntze) is a globally important beverage crop that requires high inputs of nitrogen (N), phosphorus (P), and potassium (K) to sustain optimum yield and quality. However, tea is commonly grown in strongly acidic soils where nutrient availability and uptake efficiency are constrained by nutrient fixation, leaching, and low nutrient retention. Organo-mineral fertilizers (OMFs), which combine organic and inorganic nutrient sources, may improve nutrient availability and fertilizer use efficiency under such conditions, but their effectiveness in Tanzanian tea-growing soils remains poorly understood. This study evaluated the effects of three FOMI Chai OMF formulations on N, P, and K uptake in clonal tea under strongly acidic soil conditions (pH 4.86) at Ngwazi Tea Research Station, Mufindi, Tanzania, during 2024–2025. Three formulations—FOMI Chai, FOMI Chai+, and FOMI Chai++—were applied at 100, 150, and 200 kg N ha^{-1}, generating nine treatments (T1–T9) alongside a standard inorganic NPK fertilizer (TP) and an unfertilized control (TN) in a randomized complete block design with three replicates. Fertilizer type significantly affected N and K uptake ($p < 0.001$) and P uptake (p = 0.044), while application rate had no significant effect ($p > 0.05$). FOMI Chai++ produced the highest N, P, and K uptake, exceeding the standard inorganic fertilizer by 38.7%, 69.6%, and 33.5%, respectively. The results suggests that organo-mineral fertilizers had influence on nutrient uptake than the application rate within the tested range.

Keywords: *Camellia sinensis,* organo-mineral fertilizer, FOMI Chai fertilizer, nutrient uptake, soil fertility, sustainable te*a.*

1. Introduction

Tea (*Camellia sinensis L. O. Kuntze*) is one of the most economically significant and widely consumed beverage crops worldwide, particularly in countries of Asia and Africa [1]. The leaves of the tea plant are used to produce tea, a non-alcoholic beverage that ranks second to water in global consumption [2]. It is cultivated in more than 48 countries across the globe, covering approximately 4.2 million hectares, with an annual production reaching 6.34 million tons [3]. According to the Food and Agriculture Organization of the United Nations (FAO), China, India, Japan, Sri Lanka, and Kenya are the world's top tea producers, each producing more than 160 thousand metric tons [4]. In Africa, Kenya is the leading producer, with an output exceeding 570 thousand metric tons, which accounts for nearly 70% of the continent's total tea production, followed by Malawi, Tanzania, and Uganda [5].

Globally, tea production generates over USD 17 billion annually, while the tea trade is valued at approximately USD 9.5 billion. This makes tea an important source of export revenue for low-income and developing countries, particularly in Asia [4, 6].

Tea plant flourishes in acidic soils with a pH range of 4.5 to 5.5; soils outside this range, either above 5.5 or below 4.5, are unsuitable for optimal growth. It requires an annual rainfall of at least 1200 mm, well distributed and grows best at an average temperature of around 18°–25 °C [7]. Air temperatures lower than 13 °C or higher than 30 °C have been shown to inhibit shoot growth [8]. Tea is a demanding crop due to the frequent harvesting of its young leaves, which depletes soil nutrients and requires substantial nutrient inputs to maintain productivity [9]. Along with other important nutrients like magnesium (Mg), iron (Fe), and zinc (Zn), tea demands a high amount of nitrogen (N), potassium (K), calcium (Ca), and phosphorus (P) to maintain yield and quality [10]. N is important in tea cultivation as it is a component of plant tissues and plays a role in numerous physiological functions that support the growth and productivity of tea plants. N typically makes up 3.5% to 5% of the dry weight of harvested tea leaves [11]. In acidic soil, less than 50% of the N applied in tea plantation is lost by converting into nitrate, which is prone to leaching, soil acidification, water eutrophication and greenhouse gas emissions. The preferred absorbed form of N by the tea plant is ammonium (NH_4^+) [12].

P is an essential nutrient involved in the formation of adenosine triphosphate (ATP) and plays a critical role in various biochemical processes, including photosynthesis, respiration, N fixation, and overall plant development [13]. The application of phosphate fertilizers has been shown to enhance both the yield and quality of tea [12,14]. However, the availability of P in the soil is highly influenced by soil pH. In acidic soils, only about 20% or less of the applied P is utilized by plants, while 80–90% becomes fixed and unavailable due to the formation of insoluble complexes with iron (Fe) and aluminum (Al) [15]. Conversely, in alkaline soils, phosphorus tends to precipitate with calcium (Ca), forming insoluble calcium phosphate compounds [16, 17]. Poor P availability leads to poor root development, stunted growth, reduced yield, and lower tea quality [13].

K, second only to N in terms of plant uptake, is critical for growth and stress tolerance. Adequate K levels significantly enhance tea yield and quality by boosting metabolic activity, promoting catechin synthesis, and improving resistance to both biotic and abiotic stresses through the activation and regulation of various enzymes [18]. However, in acidic soils, K uptake may be reduced due to elevated levels of other cations such as hydrogen (H), Al, and Fe. These excess cations can either compete with K for absorption by plant roots or alter soil conditions in ways that hinder the efficient use of K by plants [19]. For many years in East Africa, the primary source of major nutrient elements for tea cultivation has been synthetic fertilizers, particularly compound formulations such as NPK 25:5:5:3S or NPK 20:10:10. These are typically applied at rates of 150–250 kg of N per hectare per year to meet the high nutrient demands of tea plants [1, 14, 20].

Research has indicated that the prolonged use of N-based chemical fertilizers contributes to soil acidification, reduces nutrient availability especially of P, and causes environmental degradation [21]. According to the Intergovernmental Panel on Climate Change [22], synthetic fertilizers are responsible for a significant portion of global nitrous oxide (N_2O) emissions, with 10–15% of total applied N released as N_2O from agricultural soils [23]. Tea plantations have been identified as notable sources of N_2O emissions [24].

Organo-mineral fertilizers (OMFs), which blend inorganic nutrient sources with organic materials such as composted cow manure, offer a balanced approach that supports both environmental sustainability and agricultural productivity. These fertilizers provide immediate nutrient availability from the inorganic component while contributing to long-term soil health through the organic fraction [25, 26].

Despite the demonstrated potential of OMFs in improving soil fertility and nutrient bioavailability in other perennial crop systems, data on their effectiveness under the strongly acidic, P-fixing highland soils of Mufindi, Tanzania remain lacking. This study therefore aimed to evaluate the effects of three NPK-based organo-mineral fertilizer formulations (FOMI Chai, FOMI Chai+, and FOMI Chai++) applied at three N based rates on N, P, and K uptake in mature clonal tea under field conditions, and to compare their performance against a conventional synthetic NPK fertilizer.

2. Materials and Methods

2.1 Study Area Description.

This study was conducted at the Tea Research Institute of Tanzania (TRIT) experimental farm at the Ngwazi Tea Research Station (NTRS), Mufindi District, Iringa Region, Tanzania during 2024-2025 season. The station is situated at a latitude of 8°32′S, longitude 35°10′E, and an altitude 1840 m above sea level (Figure 1). The climate in Ngwazi- Mufindi is divided into three main seasons based on rainfall and temperature. The warm wet season occurs from late November to May, during which there is over 95% of the annual rainfall that is between 800 and 1100 mm. The mean air temperature ranges from 16°C to 19°C of which from June to August, the area experiences a cool season temperature ranging between 13°C and 16°C, during which tea yields are limited by both low temperatures and drought. The period from September to November is warm with 16°C to 19°C, but tea yields remain low due to limited soil moisture availability [27, 28]. The physicochemical properties of the soil at the experimental site are summarized in table 1, while the site's temperature and rainfall patterns during the trial are shown in figure 2.

2.2 Experimental design and Treatments

The experiment was arranged as a two-factor factorial treatment structure within a Randomized Complete Block Design (RCBD) with three replicates. The two factors were: (i) fertilizer type, with five levels — FOMI Chai, FOMI Chai+, FOMI Chai++, a standard inorganic NPK fertilizer (positive control, TP), and an unfertilized negative control (TN); and (ii) application rate, with three levels based on N dose (100, 150, and 200 kg N ha^{-1}). The three FOMI Chai formulations applied at three rates generated nine fertilizer treatments (T1–T9). Details of all treatment codes and their compositions are presented in table 2.

Each experimental plot measured 3.6 m × 2.4 m (8.64 m^2) and contained 12 tea bushes. Plots and blocks were separated by 2.4 m. Tea bushes were spaced at 1.2 m between rows and 0.6 m between individual plants within a row. Fertilizers were applied by broadcasting evenly over the soil surface within each plot (top-dress broadcasting), a method widely recommended for mature tea plantations [29].

2.3 Sampling, processing and laboratory procedures

2.3.1 Soil

Soil physical and chemical properties were determined before setting up a trial. Soil samples were collected in each plot using a soil auger at a depth of 0-30cm in a zig-zag pattern. The soil was composited within each plot, and a subsample was taken to the Soil and Plant Laboratory under the Tea Research Institute of Tanzania (TRIT) for analysis.

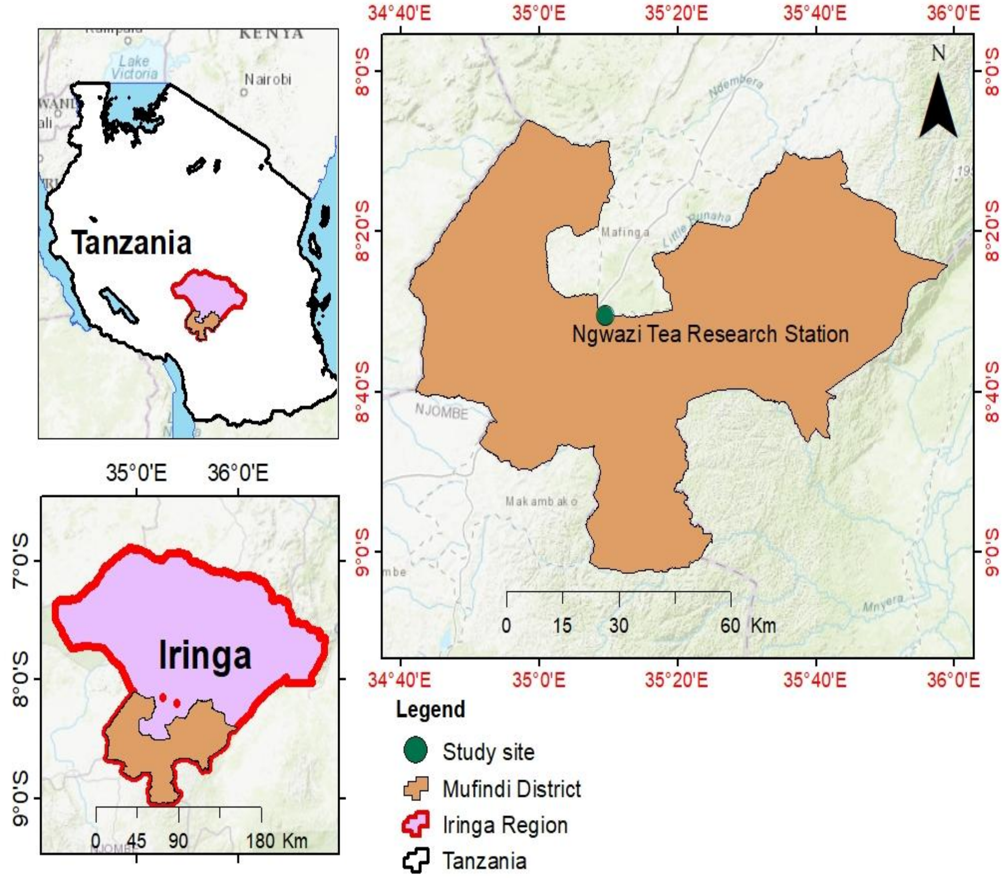

Figure 1. Location map of the study area showing the Ngwazi Tea Research Station (NTRS) of the Tea Research Institute of Tanzania (TRIT) in Mufindi District, Iringa Region, Tanzania (latitude 8°32′S, longitude 35°10′E; altitude 1,840 m above sea level), where the field experiment was conducted during the 2024–2025 growing season.

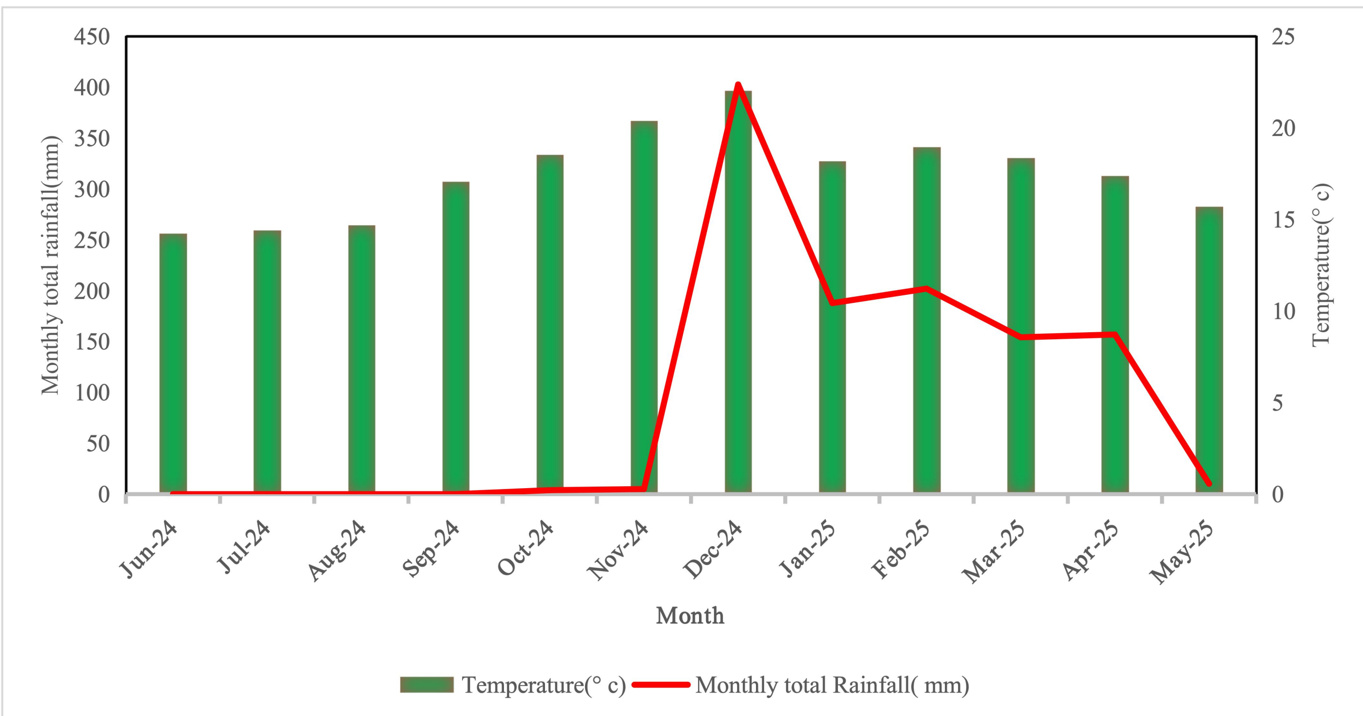

Figure 2. Rainfall and temperature during the trial.

Soil samples were air-dried, ground to pass through a 2 mm sieve, and stored for subsequent physical and chemical analysis. The particle size distribution was assessed using the Bouyoucos hydrometer technique [3]. Soil pH was determined potentiometrically in a 1:2.5 soil-to-water suspension [31]. Cation exchange capacity (CEC) was measured by saturating the soil with neutral 1 M ammonium acetate (NH_4OAc), displacing the adsorbed ammonium ions (NH_4^+) with 1 M potassium chloride (KCl), and quantifying the released NH_4^+ using the Kjeldahl distillation method [32]. Organic carbon content was evaluated using the Walkley and Black wet oxidation method [33], and total nitrogen was measured via the Kjeldahl method [34]. Available phosphorus was analyzed using the Bray-I method [35]. Exchangeable bases were extracted with ammonium acetate; calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels were determined using atomic absorption spectrophotometry [32], while exchangeable potassium (K^+) was measured via flame photometry [31].

2.3.2 Leaf Sampling, Preparation and Digestion Procedure.

The third mature leaf from the apical bud was harvested from each plot to obtain a representative sample. Fresh samples were collected in perforated paper bags to allow aeration and transported to the laboratory. Each sample was weighed immediately (fresh weight, W_1) using a digital scale in grams and then converted to kilograms per ha. The samples were then placed in pre-weighed containers (W_0) and oven-dried at 65 °C for 48 hours to a constant weight for dry matter (%). After cooling in a desiccator (10–15 minutes), the combined weight of the dry sample and container (W_2) was recorded. Dry matter content was calculated using Equation (1):

$$\text{Dry matter (\%)} = [(W_2 - W_0)/ W_1] \times 100 \quad \text{… (Equation 1).}$$

Dried samples were ground using a stainless-steel mill to passed through a 1 mm sieve for uniform particle size. Approximately 0.5 g of ground material was digested using a modified Kjeldahl method with sulphuric acid (H_2SO_4), selenium (Se) catalyst, and salicylic acid ($C_7H_6O_3$). The samples were left overnight to stabilize nitrate reduction. Digestion was initiated with the gradual addition of hydrogen peroxide (H_2O_2) to oxidize organic matter, followed by heating with concentrated H_2SO_4. This process converted nitrogen to ammonium (NH_4^+) and phosphorus to orthophosphate (PO_4^{3-}).

Nitrogen concentration (%) was quantified using the Kjeldahl method, while phosphorus and potassium were determined using the dry-ash method and finally quantified by colorimetric (UVVIS Spectrophotometer) and flame photometry methods for P and K, respectively [36]

The concentrations of N, P, and K in digested solutions were determined following standard procedures described by Okalebo et al. [31]. Nutrient uptake was calculated from dry matter yield and nutrient concentration using Equation (2):

$$\text{Nutrient uptake (kg ha}^{-1}) = [\text{Dry matter yield (kg ha}^{-1}) \times \text{Nutrient concentration (\%)}] / 100 \quad \text{… (Equation 2)}$$

2.4 Statistical analysis.

Data were analyzed using a two-way analysis of variance (ANOVA) with fertilizer type and application rate as fixed factors and replication as a random factor, following the two-factor factorial RCBD statistical model. Both main effects and the two-way interaction (fertilizer type × application rate) were included in the model. GenStat 15th edition was used for all analyses. Tukey's Honestly Significant Difference (HSD) test was used for post-hoc mean separation at a significance level of $p \leq 0.05$. The coefficient of variation (CV%) was calculated for each measured parameter to assess within-experiment variability

Table 1. Physicochemical properties of soil before setting up the experiment.

Parameter	SI-Units	Value	Rating category	Reference
pH. (H_2O)		4.86	very strongly acid (4.5-5.0)	[37,38]
available P	Mg kg^{-1}	4.1	Very low (>20)	[39, 40]
Exch.bases: -	**(cmol(+)/kg soil)**			
Potassium		0.22	Low (0.2–0.3)	[37]
Magnesium		1.1	Moderate (1–3)	[37]
Calcium		1.71	low (0-2)	[37]
Sodium		0.36	Low (0.1–0.3)	[37]
Total Nitrogen (%)		0.18	low (>0.5)	[4]
Organic Carbon(%)		2.72	medium (1.80–3.00)	[37]
CEC (cmol(+)/kg soil)		11.76	Low (6.0-12)	[37]
Micronutrients:	**mg kg^{-1}**			
Iron		41.87	High (>4.5)	[37]
Manganese		20.01	High (>1)	[37]
Zinc		1.83	High (>1)	[37]
Cupper		1.19	high (0.4-1.19)	[37]
Boron		0.54	low (>1)	[37]

3. Results

3.1. Fertility status of the experimental site

The physicochemical properties of the soil at the experimental site are presented in table 3. The soil was classified as very strongly acidic with a pH of 4.86. Available phosphorus was very low (4.1 mg kg^{-1}), while total nitrogen content was low (0.18%). Exchangeable potassium (0.22 cmol(+)/kg soil) and calcium (1.71 cmol(+)/kg soil) were also low, whereas magnesium (1.10 cmol(+)/kg soil) was within the moderate range. The soil had a low cation exchange capacity (CEC) of 11.76 cmol(+)/kg soil. Organic carbon (2.72%) and organic matter (4.7%) were rated as moderate. Micronutrient concentrations varied from adequate to high, with iron (41.87 mg kg^{-1}), manganese (20.01 mg kg^{-1}), zinc (1.83 mg kg^{-1}), and copper (1.19 mg kg^{-1}) recorded at relatively high levels, while boron (0.54 mg kg^{-1}) was low. The soil texture was classified as sandy clay loam.

3.2. Effect of fertilizers formulation and application rate on Greenleaf and dry matter yield.

Fertilizer formulation and application rate significantly influenced green leaf yield and dry matter yield of tea ($p < 0.001$) (Table 4). The unfertilized control recorded the lowest green leaf yield (4,718 kg ha^{-1}) and dry matter yield (1,321 kg DM ha^{-1}). Application of both inorganic and organo-mineral fertilizers increased yield relative to the control. Among the treatments, FOMI Chai++ applied at 200 kg N ha^{-1} produced the highest green leaf yield (8,807 kg ha^{-1}) and dry matter yield (2,466 kg DM ha^{-1}), representing substantial increases over the control and the standard inorganic fertilizer treatment Generally, yield increased progressively with increasing application rate within each fertilizer formulation. .

Table 2. Fertilizer type composition and treatment rate description.

Fertilizer Type	Treatment code	Application rate (kg ha⁻¹)	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Fertilizer Nutrient Composition
NPK FOMI Chai	T1	667	100	20	20	NPK FOMI 15-3-3 + 4CaO + 1MgO + 3S
	T2	1000	150	30	30	
	T3	1333	200	40	40	
NPK FOMI Chai +	T4	500	100	20	20	NPK FOMI 20-4-4 + 3CaO + 1MgO + 3S
	T5	750	150	30	30	
	T6	1000	200	40	40	
NPK FOMI Chai ++	T7	400	100	20	20	NPK FOMI 25-5-5 + 4CaO + 1MgO + 3S
	T8	600	150	30	30	
	T9	800	200	40	40	
NPK-Inorganic Fertilizer	TP	600	150	30	30	NPK (25-5-5 + 5S) positive control
Control	TN	0	0	0	0	Negative control (no fertilizer applied)

Table 3. Green leaf yield, dry matter (DM) yield, and Tukey HSD groupings for the fertilizer formulation × application rate interaction.

Fertilizer Formulation	N Rate (kg N ha⁻¹)	Green Leaf Yield (kg ha⁻¹)	Dry Matter Yield (kg DM ha⁻¹)
Control	0	4,718a	1,321
Inorganic fertilizer (NPK)	150	5378ab	1,328
FOMI Chai	100	5,463ab	1,530
FOMI Chai	150	6,162ab	1,725
FOMI Chai++	100	6,605abc	1,849
FOMI Chai+	100	6,628abc	1,856
FOMI Chai	200	6,785abc	1,900
FOMI Chai+	150	6,798abc	1,903
FOMI Chai++	150	7,319abc	2,049
FOMI Chai+	200	7,609bc	2,131
FOMI Chai++	200	8,807c	2,466
LSD (5%) = 1,066 SED = 514.6		CV = 11.9%	F-pr < 0.001

The FOMI Chai formulations consistently produced higher yields than the standard inorganic fertilizer at comparable application levels. FOMI Chai++ showed the greatest response to increasing application rate, indicating superior efficiency in promoting tea biomass production. The highest yielding treatment, FOMI Chai++ at 200 kg N ha^{-1}, differed significantly from the control and several lower-yielding treatments

3.3. Effect of Fertilizer on Nitrogen, Phosphorus, and Potassium Uptake

Two-way ANOVA) revealed that fertilizer type had a highly significant ($p < 0.001$) effect on N and K uptake, and a significant ($p = 0.044$) effect on P uptake (Table 4). Application rate was not statistically significant for N, P, or K uptake ($p > 0.05$), nor was the two-way interaction between fertilizer type and application rate ($p > 0.05$). This means the variations in fertilizer dosage tested did not substantially influence how much N, P, and K the plants (or system under study) absorbed. The observed differences in nutrient uptake across different application rates were likely due to random chance or normal biological variation, rather than being a direct consequence of the fertilizer dosage itself. Increasing or decreasing the application rate within the range tested did not lead to a reliable, measurable change in nutrient uptake.

Table 4. Effect of organo-mineral fertilizer types on mean nitrogen (N), phosphorus (P), and potassium (K) uptake in tea crop.

Fertilizer type	Mean N uptake (%)	Mean P uptake (%)	Mean K uptake (%)
No fertilizer	15.08a	0.751a	12.46a
Standard inorganic NPK	41.49b	1.531ab	28.02ab
FOMI Chai	45.15b	1.676ab	28.57b
FOMI Chai+	47.36b	2.016ab	30.88b
FOMI Chai++	57.53b	2.597b	37.41b
LSD	17.2	1.533	11.06
SED	8.065	0.7233	5.219
CV (%)	3.2	13.1	4.8
F-probability	*< 0.001*	0.044	*< 0.001*

Note: LSD = least significant difference; SED = standard error of the difference; CV = coefficient of variation. Means within a column followed by different letters differ significantly at $p \leq 0.05$.

For N, fertilizer type accounted for the largest portion of the variation ($F = 10.63$, $p < 0.001$). A similar trend was observed for K uptake ($F = 8.89$, $p<0.001$), whereas P exhibited a moderate but significant response ($F = 3.13$, $p = 0.044$) (Table 4).

N uptake (57.53%) was recorded under FOMI Chai++, followed by FOMI Chai+ (47.36%) and FOMI Chai (45.15%), which all differed significantly ($p<0.001$) from the control (15.08%). The standard fertilizer (Mineral fertilizer) also improved N uptake (41.49%) relative to the control, but was less effective than the enhanced FOMI Chai formulations. Therefore, all three FOMI Chai formulations significantly improve N uptake compared to a baseline, with the "FOMI Chai++" formulation being the most effective, followed by "FOMI Chai+" and then FOMI Chai.

For P uptake, although the differences were less pronounced, FOMI Chai++ again achieved the highest mean (2.6%), significantly exceeding the control (0.751%) and marginally surpassing other treatments ($p = 0.044$). K uptake followed a similar trend, with FOMI Chai++ chai+ showing the greatest increase (37.41%), followed by FOMI Chai+ (30.88%) and FOMI Chai (28.57%), all significantly higher than the control (12.46%) ($p < 0.001$).

4. Discussion

4.1. Soil Fertility Status and Implications for Tea Production

The experimental soil was characterized by very strong acidity (pH 4.86), low available P, low N, low exchangeable K, and low cation exchange capacity. These conditions are typical of highly weathered tea-growing soils in humid tropical highlands and are generally associated with reduced nutrient availability and nutrient use efficiency.

Although tea plants are adapted to acidic soils, excessively low pH conditions can restrict nutrient availability through increased Al and Fe activity, which promote P fixation and reduce the availability of exchangeable base cations such as K, Ca, and Mn. The very low P content observed in this study suggests severe P fixation, a common constraint in acidic tropical soils. Similarly, the low total N and K levels indicate insufficient native nutrient supply to sustain optimum tea growth and productivity.

The low cation exchange capacity recorded at the site further suggests limited nutrient retention capacity, which may increase nutrient losses through leaching under high rainfall conditions. Such conditions highlight the importance of improved fertilizer management strategies capable of enhancing nutrient availability and retention in acidic tea soils.

Available P (4.1 mg kg^{-1}) was extremely low in Ngwazi, indicating severe P fixation. In soils with a pH below 5.5, soluble P rapidly forms insoluble complexes with Al, Fe and Mn oxides, drastically limiting its plant availability [41, 34]. Limited P availability restricts health root growth and surface area and impairs energy transfer processes, ultimately reducing shoot yield and plucking density [12, 42]. Moreover, P deficiency suppress the production of essential metabolites such as polyphenols and catechins, which affects tea taste and antioxidant potential [12] .

Exchangeable K was also low (0.22 me/100 g), contributing to the overall low cation exchange capacity (11.76 me/100 g). The K deficiency is known to impair shoot turgor and leaf expansion, reduce photosynthetic efficiency, and consequently lower yield and deteriorate leaf quality in tea [43]

4.2. Effect of Fertilizer Formulation and Application Rate

on Green Leaf and Dry Matter Yield

The significant increase in green leaf and dry matter yield following the application of organo-mineral fertilizers demonstrates the importance of balanced nutrient supply in improving tea productivity under acidic soil conditions. The experimental site was characterized by very strongly acidic soil (pH 4.86), low total nitrogen, low available phosphorus, and low exchangeable potassium, conditions that are known to limit tea growth and biomass accumulation. Similar constraints of nutrient availability in acidic tea-growing soils have been reported by Hajiboland [8] and Ye et al. [7], who noted that strong soil acidity reduces nutrient availability and limits tea productivity.

The unfertilized control recorded the lowest green leaf and dry matter yields, confirming that the native soil nutrient supply was insufficient to sustain optimum tea growth. Tea is a nutrient-demanding perennial crop because continuous harvesting of young shoots removes large quantities of nutrients from the field. Owuor et al. [14] and Kwach et al. [20] similarly reported that inadequate nutrient replenishment in tea plantations leads to reduced shoot growth, low biomass production, and poor tea yields.

The superior performance of the FOMI Chai formulations compared with the standard inorganic fertilizer indicates that organo-mineral fertilizers enhanced nutrient use efficiency beyond what could be achieved using mineral fertilizers alone. This improvement may be attributed to the synergistic effects of combining organic and inorganic nutrient sources. The inorganic component provides readily available nutrients for immediate uptake, while the organic component improves soil structure, microbial activity, soil moisture retention, and nutrient-holding capacity. Similar findings were reported by Ventura et al. [26] and Uddin et al. [25], who observed that organo-mineral fertilizers improve crop productivity through gradual nutrient release and improved soil physicochemical properties.

Among all treatments, FOMI Chai++ at 200 kg N ha^{-1} produced the highest green leaf yield (8,807 kg ha^{-1}) and dry matter yield (2,466 kg DM ha^{-1}), indicating superior effectiveness in promoting tea biomass production. The enhanced performance of FOMI Chai++ may be associated with its higher nutrient density and improved formulation quality, which likely enhanced nutrient availability and reduced nutrient losses under high rainfall conditions. Wang et al. [43] reported similar results in tea plantations where partial substitution of inorganic fertilizer with organic amendments significantly improved tea yield and biomass accumulation through improved soil fertility and nutrient retention.

The progressive increase in yield with increasing nitrogen application rate within each fertilizer formulation confirms the critical role of nitrogen in tea productivity. N is essential for chlorophyll synthesis, amino acid formation, photosynthesis, and vegetative growth, all of which directly influence shoot development and harvestable yield. Sedaghathoor et al. [11] reported that nitrogen application significantly increased tea leaf production and biomass accumulation due to enhanced vegetative growth and photosynthetic efficiency. Similarly, Zhang et al. [12] observed that nitrogen availability strongly influences shoot growth, leaf expansion, and tea productivity because nitrogen is central to metabolic and physiological processes in tea plants.

The stronger response observed under FOMI Chai++ suggests that nitrogen supplied through organo-mineral formulations was utilized more efficiently than nitrogen supplied through conventional inorganic fertilizer. Integrated fertilization strategies have previously been shown to improve nitrogen use efficiency by synchronizing nutrient release with plant demand and reducing nutrient losses through leaching and volatilization. Miao et al. [44] found that combined organic and inorganic fertilization enhanced tea yield by improving rhizosphere microbial activity and nutrient mineralization, thereby increasing nutrient uptake efficiency. The higher dry matter yield observed in the FOMI Chai treatments further suggests improved assimilation and conversion of absorbed nutrients into plant biomass. Enhanced uptake of nitrogen, phosphorus, and potassium likely promoted metabolic activity, photosynthesis, and biomass accumulation. Li et al. [45] reported that integrated organo-mineral fertilization improved nutrient uptake and biomass production in tea gardens by enhancing soil nutrient availability and organo-mineral associations. Similarly, Supriyanto et al. [46] observed improved biomass production in tea and coffee systems following the application of bio-organo-mineral amendments under acidic soil conditions.

Although the standard inorganic fertilizer increased yield relative to the control, its performance remained lower than that of the FOMI Chai formulations at comparable nitrogen levels. This finding suggests that the benefits of organo-mineral fertilizers extend beyond nutrient supply alone and include improvements in soil quality and nutrient retention. Yang et al. [21] reported that long-term use of organic amendments in tea plantations improved soil physicochemical properties, microbial activity, and nutrient availability, leading to sustained improvements in tea productivity.

4.3. Influence of Fertilizer on N, P, and K Uptake

The application of FOMI Chai-based organo-mineral fertilizers significantly improved N, P, and K uptake compared to both the control and standard mineral fertilizer, demonstrating enhanced nutrient bioavailability under the acidic soil conditions of Ngwazi (pH 4.86). The ANOVA results confirmed a highly significant effect ($p < 0.001$) on N and K uptake and a significant effect on P uptake ($p = 0.044$), indicating that the fertilizer type strongly influenced nutrient assimilation efficiency. The superior performance of FOMI Chai++, which achieved the highest N (57.53%), P (2.597%), and K (37.41%) uptake, underscores the synergistic role of combining organic matter with mineral nutrients in enhancing nutrient use efficiency.

Compared with the standard mineral fertilizer, all FOMI Chai formulations markedly increased nutrient uptake, with N uptake rising by 8.8–38.7%, P by 9.5–69.6%, and K by 2.0–33.5% (Table 6). The steady increase across FOMI Chai, FOMI Chai+, and FOMI Chai++ reflects the progressive improvement in nutrient availability with higher organic enrichment. The organic fraction likely improved soil structure, microbial activity, and nutrient retention, while the mineral component provided readily available macronutrients for plant uptake. Similar synergistic effects of organo-mineral fertilizers have been observed in other tea-growing systems and acidic soils, where organic matter and oxides of Ca and Mg added in FOMI Formulation buffer soil acidity, enhance cation exchange capacity, and promote the solubilization of fixed phosphorus. [44, 45, 46]

The N uptake improvement in this study suggests that the organo-mineral matrix mitigated volatilization and ammonium fixation losses, common challenges in strongly acidic soils, by stabilizing nitrogen forms and supporting microbial nitrification processes. Comparable findings were reported by Dai et al. [47], who observed that the prolonged application of organic fertilizers increased total N availability, leading to higher tea yields and improved leaf quality. Similarly, Miao et al. [44]. found that integrated organic and inorganic fertilization enhanced N mineralization and uptake efficiency in tea plants by stimulating rhizosphere microbial activity and enzyme function.

P uptake showed the greatest relative increase under FOMI Chai++ (69.6% higher than mineral fertilizer). This can be attributed to the capacity of organic ligands in FOMI Chai to complex Fe and Al ions, thereby reducing P fixation, a mechanism also reported in integrated tea nutrition studies by Li et al [45]. The improved P availability consequently supports greater root proliferation and energy transfer, enhancing overall shoot biomass and plucking density.

Similarly, K uptake increased by up to 33.5% with FOMI Chai++, reflecting improved K retention and reduced leaching losses. The organic component of the fertilizer likely contributed to greater K adsorption through enhanced soil CEC and better moisture retention [48]. These findings align with those of Supriyanto et al [46] who reported that bio-organo-mineral amendments improved K uptake in perennial crops such as tea and coffee grown in leached, acidic soils.

The observed improvement in nutrient uptake across all FOMI Chai formulations can be attributed to the synergistic interactions between their organic and inorganic components, which enhanced nutrient bioavailability and soil chemical properties. The incorporation of organic matter improves soil structure, increases moisture retention, and stimulates microbial activity, thereby enhancing nutrient mineralization and root absorption [44]. At the same time, the mineral fraction of the organo-mineral fertilizers provides readily available macronutrients that ensure an immediate nutrient supply to the plants [45] The FOMI Chai++ fertilizers formulation demonstrated a greater influence on nutrient uptake compared to the other two variants. For instance, the FOMI Chai required 1,333 kg ha^{-1} to supply an equivalent 200 kg N ha^{-1}, whereas FOMI Chai++ achieved the same nitrogen level with only 800 kg ha^{-1}. This disparity indicates that nutrient uptake efficiency was not primarily determined by application rate but rather by the quality and nutrient density of the formulation, highlighting the superior nutrient-release characteristics and bioavailability associated with its formulation.

This study was conducted at a single experimental site during one growing season. Therefore, the results may not fully represent the variability of soil, climatic, and management conditions across tea-growing regions in Tanzania and East Africa. In addition, the study focused primarily on nutrient uptake and did not evaluate changes in soil microbial activity, post-harvest soil fertility, or long-term soil organic matter dynamics. Further multi-site and long-term studies are therefore recommended to validate the performance of FOMI Chai fertilizers under different agroecological conditions and to assess their long-term effects on soil health and tea productivity.

5. Conclusion

The findings of this study demonstrate that FOMI Chai–based organo-mineral fertilizers significantly enhance N, P, and K uptake in tea plants compared to conventional inorganic fertilizers under acidic soil conditions. Among the treatments evaluated, FOMI Chai++ consistently recorded the highest nutrient uptake, with increases of 38.7% for N, 69.6% for P, and 33.5% for K relative to the inorganic fertilizer. These results highlight the synergistic benefits of integrating organic and inorganic nutrient sources, which improve nutrient bioavailability, retention, and overall utilization efficiency.

The substantial increase in P uptake suggests that FOMI Chai formulations reduce P fixation through the complexation Al and Fe, while the enhanced uptake of N and K is likely linked to improved cation exchange capacity and synergistic N–K interactions that minimize nutrient losses through leaching. Notably, FOMI Chai++ achieved superior performance at relatively lower application rates for equivalent nitrogen supply, indicating that fertilizer formulation quality is a key driver of nutrient use efficiency.

Based on these findings, the incorporation of organo-mineral fertilizers particularly FOMI Chai++ into nutrient management strategies for tea cultivation on acidic soils is recommended. These formulations offer a sustainable alternative to conventional inorganic fertilizers by improving soil fertility, enhancing nutrient efficiency, and reducing the risk of environmental losses. However, further long-term, multi-site studies are required to validate these results across diverse agro-ecological conditions and to support the development of robust, nationally applicable fertilizer recommendations for the tea sector in Tanzania.

Author contributions

Conceptualisation & formal analysis, Braison E Mjanja; data curation & funding acquisition, Braison E. Mjanja, Joel Meliyo; Supervision and investigation, Mawazo J Shitindi, Boniface H. Massawe, methodology and review, Elias Niyongabo, Braison E. Mjanja and Catherine Senkoro. All authors read and approved the final manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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