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ORIGINAL PAPER

Improvement of Tea Yield and Quality by Chicken Manure and Wine Lees (CMWL) Substitution for Chemical Fertilizers in the Hilly Region of Western Sichuan, China

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Abstract

Currently, many organic materials, due to their high content of organic matter, can partially replace chemical fertilizers to enhance soil quality and crop yield. However, the effects of replacing different ratios of chemical fertilizers with organic materials made from chicken manure and wine lees (CMWL) on soil and tea quality are not well known. Therefore, via a 2-year field study, this study used CMWL to replace 25% (T1), 50% (T2), and 75% (T3) (based on phosphorus fertilizer) of chemical fertilizer to understand how soil nutrients, tea yield, and quality would be affected. Compared to chemical fertilizer (CF), CMWL inclusion increased the soil pH by 0.08–0.17 in the 0–20 cm soil layer and 0.02–0.07 in the 20–40 cm soil layer for 2 years. Second, the growth rate (increase per year) of soil organic matter (OM) in the 0–20 and 20–40 cm soil layers reached 7.01 and 4.55%, respectively. The T2 and T3 treatments enhanced soil total nitrogen (TN), phosphorus (TP), and potassium (TK) in both 0–20 and 20–40 cm layers. However, the T2 treatment significantly increased the soil available nutrients, tea yield, water extracts, tea polyphenols, amino acids, and caffeine. Finally, the partial least squares (PLS) analysis showed that OM and available phosphorus (AP) were the main factors affecting tea yield and quality. Therefore, the T2 treatment was the best fertilization scheme for tea production. This study provides information on partially replacing chemical fertilizers with CMWL to elevate soil fertility, thereby promoting tea quality.

Highlights

- Chicken manure and wine lees (CMWL) replacement improved soil and tea quality.
- 50% CMWL replacement had the best effect on improving soil nurients and tea quality.
- Applying CMWL to enhanced soil nutrients is an effective way to improve tea quality.
- Organic matter and avliable phosphorus were the main factors affecting tea quality.

Keywords Organic material · Tea plantation · Soil nutrients · Tea yield · Tea quality

1 Introduction

Tea (*Camellia sinensis*) is a perennial evergreen plant that is a major cash crop in many developing countries, such as China, India, and Kenya (Yan et al. 2018; Deka and Goswami 2021; Pokharel et al. 2021). In 2017, the tea plantation area in China was approximately 3.05 million ha, and tea cultivation is constantly expanding due to the high medicinal and economic values of this crop (Yan et al. 2020a). In addition, tea plantations are an important means of realizing sustainable agricultural development in the hilly region of western Sichuan (Wang et al. 2018b).

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The quality characteristics of tea include taste, which is mainly related to amino acids, tea polyphenols, and caffeine (Hemmati et al. 2021). The content of quality-related metabolites in tea is affected by plant growth and development, which depend on various nutrient elements in the soil (Zhou et al. 2022). At present, high rates of fertilizers are widely used to improve soil nutrients and thus elevate tea yield and quality. However, increasing the usage of fertilizers has not always proportionally increased the tea yield. Fertilizers also cause soil acidification, compaction, and other environmental problems (Xie et al. 2020; Milošević et al. 2022). Therefore, sustainable management measures offer significant ways to solve these problems (Lori et al. 2022). Among them, organic fertilizer substitution can both reduce nutrient losses and improve nutrient utilization rates and crop quality (Zhuang et al. 2019; Angela et al. 2020; Christian et al. 2020; Marcińczyk and Oleszczuk 2022). Organic materials such as straw, mushroom substrate, and livestock manure contain large amounts of organic matter (OM), which can increase soil nutrient levels and crop yield (Ives et al. 2011; Sala et al. 2014; Agegnehu et al. 2016; Dai et al. 2019) under intensive farming conditions. If organic materials cannot be reasonably used, then they become wasted resources that create environmental pollution (Odlare et al. 2011; Oliveira et al. 2017). For these reasons, it is beneficial to combine agricultural waste with chemical fertilizer to improve tea yield and quality by enhancing soil organic matter and nutrients.

Substitution effects vary with the types of organic fertilizers (Wu et al. 2020). Gu et al. (2019) proposed that cow manure and pig manure can improve tea yield. Sichuan, a large agricultural province, produces a large amount of organic materials annually, including straw, mushroom substrate, livestock and poultry feces, and wine lees. As an important organic material, chicken manure was reported to increase soil OM (thereby improving porosity, aeration, structural stability, and nutrient availability), thus enhancing crop yield (Gu et al. 2019; Urra et al. 2019). In addition, wine lees are rich in nutrients needed by plants and have also been studied as fertilizers (Pérez-Bibbins et al. 2015). However, few studies have investigated the effects of combining chicken manure and wine lees (CMWL) on soil nutrients and tea quality. Many studies have shown that different proportions of organic material substitution for chemical fertilizer have different effects, and that the influence of only applying organic material is not necessarily the best. Ji et al. (2018) mentioned that a 25% organic fertilizer substitute for chemical fertilizer was the most effective to enhance crop yield. However, few studies have reported how much CMWL replaced with chemical fertilizer is most effective in enhancing soil quality and tea yield. In addition to yield and other factors, tea polyphenols, amino acids, caffeine, and water extract affect tea quality (Rajapaksha and Shimizu 2022). Therefore, it is important to explore whether CMWL will increase or decrease tea quality, such as tea polyphenols and amino acids. In addition, it is necessary to determine which soil nutrients are the main factors affecting tea yield and quality.

Based on the abovementioned results, it is important to explore the potential of CMWL in partially replacing chemical fertilizers. Thus, this study applied CMWL to replace 25, 50, and 75% chemical fertilizer and then compared the differences in soil nutrients, tea yield, and tea quality between CMWL-replaced soils and chemical-fertilized soils. The variations among the three CMWL-replaced soils were also compared. Moreover, the partial least squares (PLS) analysis was used to understand the main factors affecting tea yield and quality. It was hypothesized that 25, 50, and 75% CMWL replacements could improve soil nutrients and increase tea yield and quality, and 50% substitution would have the greatest effect.

2 Materials and Methods

2.1 Site Description

A 2-year experiment was designed to be conducted in Heizhu town, southwest of the Chengdu Plain, from 2017 to 2019 (elevation 635 m above sea level; 29°58′–30°16′ N, 103°02′–103°23′ E). The average annual temperature and rainfall were 16.5 °C and 1658 mm, respectively, while summer precipitation accounted for approximately 58.5% of the average annual precipitation and was suitable for tea planting. According to the Chinese soil classification, the soil

Table 1 Soil physical and chemical properties before treatments

Parameter	Soil layers	
	0–20 cm	20–40 cm
Physical properties		
Soil bulk density (g cm^{-3})	1.43	
Soil water content (%)	19.2	
Clay (%)	61.2	
Chemical properties		
pH (-)	4.03 ± 0.13	4.33 ± 0.16
Organic matter (g kg^{-1})	15.70 ± 1.13	14.30 ± 0.93
Total nitrogen (g kg^{-1})	1.85 ± 0.13	1.19 ± 0.06
Total phosphorus (g kg^{-1})	0.67 ± 0.04	0.47 ± 0.03
Total potassium (g kg^{-1})	9.38 ± 1.93	9.00 ± 2.13
Available nitrogen (mg kg^{-1})	111.47 ± 8.83	67.40 ± 5.83
Available phosphorus (mg kg^{-1})	12.22 ± 1.43	7.97 ± 1.08
Available potassium (mg kg^{-1})	123.52 ± 7.80	101.23 ± 6.89

data correspond to means of three replicates ± standard deviation type in the study area is yellow. The basic characteristics of the 0–20 and 20–40 cm soil layers are shown in Table 1.

2.2 Experimental Design

The tea in the experimental site was planted for 20 years or more, and field management was carried out according to the conventional production mode. According to the local fertilizing standard, the conventional fertilizer application amounts of nitrogen (N), phosphorus (P), and potassium (K) (75.66, 80.15, and 42.35 kg hm $^{-2}$, respectively) were used. The phosphorus fertilizer can promote the development of tea roots, enhance the absorption of nutrients, and improve the physiological function of chlorophyll (Yan et al. 2018). Therefore, based on the amount of P applied, 5 treatments (the amount of P was equal) were set up in the experiment: (1) unfertilized control (CK), (2) chemical fertilizer (CF), (3) chemical fertilizer [75% P-based] + CMWL [25% P-based] (T1), (4) chemical fertilizer [50% P-based] + CMWL [50% P-based] (T2), and (5) chemical fertilizer [25% P-based] + CMWL [75% P-based] (T3). A randomized block design was used for three replicates, and each plot area was 30 m^2 (5 m × 6 m). A specific fertilization scheme is shown in Table 2. Moreover, the contents of nutrients in the original CMWL are shown in Table 3.

2.3 Soil and Tea Sampling

Before the experiment and after 2 years of tea plantation, the 0–20 and 20–40 cm soil layers were collected using the 5-point sampling method and brought back to the laboratory. Then, the soil was dried by natural air and ground through a 100-mesh nylon sieve to determine the soil properties. Tea leaves (one bud together with three young leaves) are usually harvested in early May (spring tea) and early July (summer tea) every year (Li et al. 2016). Six rows of tea trees were randomly selected, and one sampling point was set in each row with a size of 33 cm × 33 cm (Li et al. 2016). All sprouts (three leaves and a bud) at each sampling point were collected and counted.

Table 3 Physicochemical characteristics of CMWL

Material	Water content (%)	Organic matter (%)	TN (%)	TP (%)	TK (%)
CMWL	8.86	69.73	7.43	6.11	4.80

CMWL, chicken manure and wine lees; *TN*, total nitrogen; *TP*, total phosphorus; *TK*, total potassium

2.4 Soil and Tea Determination

Soil pH was measured using a 1:5 ratio of soil to deionized water (Shen et al. 2013). The soil OM, total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were determined by oxidization with $K_2Cr_2O_7$, the micro-Kjeldahl method, the NaOH fusion-molybdenum-antimony colorimetric method, and the dissolved NaOH-flame photometric method, respectively (Ouyang et al. 2013; Wang et al. 2016). The available nitrogen (AN), phosphorus (AP), and potassium (AK) were determined by the alkaline hydrolysis diffusion method, the Olsen-P method, and flame photometry, respectively (Yang et al. 2021).

The yield of tea leaves, 100-sprout weight, and sprout density were determined according to the method reported by Li et al. (2016). All buds (with a standard of three leaves and a bud) at each sampling point were sampled and counted to determine the sprout density. One hundred fresh sprouts were randomly selected from each plot, dried, and weighed to measure the 100-sprout weight. The tea yield was determined by multiplying the sprout number per square meter and 100-sprout weight and divided by 100 kg hm^{-1} (Yang et al. 2021). Tea polyphenols, amino acids, caffeine, and water extract were measured by the folin-ciocalteu colorimetric method, ninhydrin colorimetry, O-phenylenediamine spectrophotometry, and the differential method for weighing

Table 2 Fertilization schemes for each treatment in the experiment

Treatment	Chemical fertilizer			Organic fertilizer		
	N (kg hm^{-2})	P (kg hm^{-2})	K (kg hm^{-2})	N (kg hm^{-2})	P (kg hm^{-2})	K (kg hm^{-2})
CK	-	-	-	-	-	-
CF	75.66	80.15	42.35	-	-	-
T1	65.02	60.11	34.04	10.64	20.04	8.31
T2	54.39	40.08	25.71	21.27	40.07	16.64
T3	43.76	20.04	17.39	31.90	60.11	24.96

N, nitrogen content in the fertilizer; *P*, phosphorus content in the fertilizer; *K*, potassium content in the fertilizer; *CMWL*, chicken manure and wine lees; *CK*, unfertilized control; *CF*, chemical fertilizer; *T1*, chemical fertilizer [75% P-based] + CMWL [25% P-based]; *T2*, chemical fertilizer [50% P-based] + CMWL [50% P-based]; *T3*, chemical fertilizer [25% P-based] + CMWL [75% P-based] tea residues (Jayasekera et al. 2014; David et al. 2015; Protiva et al. 2019).

2.5 Statistical Analysis

All experimental data were sorted by Office 2019, and the SPSS 25.0 statistical software was used to conduct a one-way analysis of variance (ANOVA) for soil nutrients, tea yield, and quality. PLS was used to determine the importance of soil nutrients to tea quality.

3 Results

3.1 Changes in Soil pH

Before the experiment, the soil pH values in the 0–20 and 20–40 cm soil layers were 4.03 and 4.33, respectively (Table 1). Figure 1 demonstrates the soil pH after 2 years of experiments. In the 0–20 cm soil, the pH values with the CK, CF, T1, T2, and T3 treatments were 3.99, 3.95, 4.03, 4.09, and 4.12, respectively. Among them, the pH in the CF soil was significantly ($P < 0.05$) lower than that in the other soils, while the pH in T3 soil was significantly ($P < 0.05$) higher and was closer to the optimum range (pH = 4.5–5.5). The pH in the 20–40 cm soil layer was higher than that in the 0–20 cm soil layer, and the pH in the 0–20 cm soil layer was below 4.2, while that in the 20–40 cm soil layer was above 4.3. In addition, in the 20–40 cm soil, the pH values in CK, CF, T1, T2, and T3 were 4.32, 4.31, 4.33, 4.36, and 4.38, respectively. Compared with CK and CF soils, the pH in T2 and T3 soils was significantly higher ($P < 0.05$). Moreover, the soil pH improved with the increase in the proportion of CMWL. Therefore, in this study, the effect of increasing pH with the T2 and T3 treatments in the 0–20 and 20–40 cm soil layers was better.

3.2 Soil Organic Matter

The OM contents of the tea plantation after 2 years are shown in Fig. 2. In the 0–20 cm soil, the contents of OM were 14.8, 15.1, 16.7, 17.9, and 16.9 g kg^{-1} in CK, CF, T1, T2, and T3, respectively. On the other hand, the OM of all soils at 0–20 cm was higher than that at 20–40 cm. In the 20–40 cm soil, the OM in the CK, CF, T1, T2, and T3 soils was 14.0, 14.0, 14.8, 15.6, and 15.1 g kg^{-1}, respectively. At both 0–20 and 20–40 cm, the OM in the T2 soil was the highest and the lowest in the CK and CF soils. Moreover, the growth rate (increase per year) of OM in T2 soil at 0–20

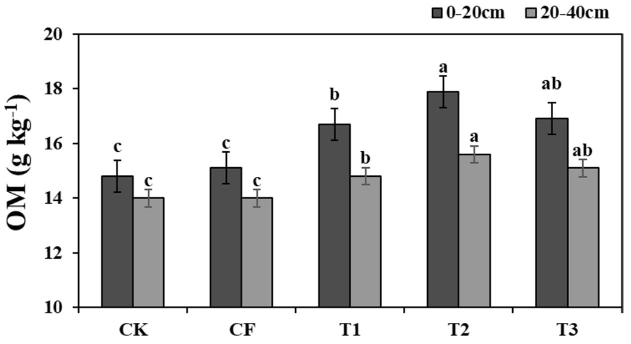

Fig. 2 Differences of soil organic matter (OM) at 0–20 and 20–40 cm in different soils. CMWL, chicken manure and wine lees; CK, unfertilized control; CF, chemical fertilizer; T1, chemical fertilizer [75% P-based] + CMWL [25% P-based]; T2, chemical fertilizer [50% P-based] + CMWL [50% P-based]; T3, chemical fertilizer [25% P-based] + CMWL [75% P-based]. Different letters indicate statistically significant differences among different treatments at $P < 0.05$

Fig. 1 Differences of soil pH in different soils after 2 years of experiment. CMWL, chicken manure and wine lees; CK, unfertilized control; CF, chemical fertilizer; T1, chemical fertilizer [75% P-based] + CMWL [25% P-based]; T2, chemical fertilizer [50% P-based] + CMWL [50% P-based]; T3, chemical fertilizer [25% P-based] + CMWL [75% P-based]. Different letters indicate statistically significant differences among different treatments at $P < 0.05$

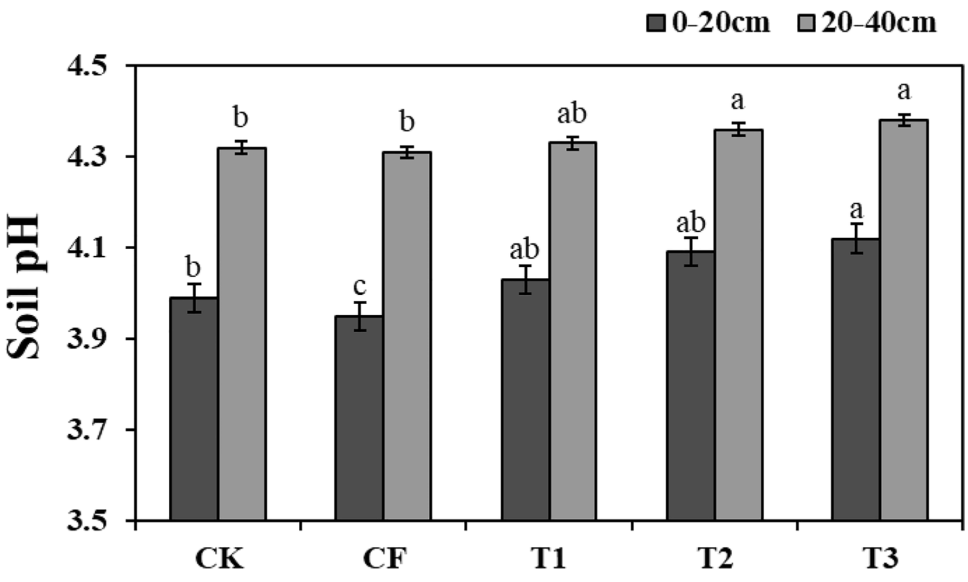

Table 4 Growth rates (%) (increase per year) of soil chemical properties at 0–20 and 20–40 cm with the five treatments

Parameter		OM	TN	TP	TK	AN	AP	AK
0–20 cm	CK	−2.87	−3.25	−2.24	−1.71	−5.14	−2.17	−8.92
	CF	−1.91	−0.81	1.50	−1.07	5.22	−0.82	2.70
	T1	3.19	1.08	2.99	−0.75	6.48	1.84	6.28
	T2	7.01	2.43	4.48	0.16	12.03	4.67	9.14
	T3	3.82	2.71	4.48	0.27	7.43	3.11	6.67
20–40 cm	CK	−1.05	−1.68	−4.65	−1.34	−3.79	−7.66	−5.55
	CF	−1.05	−1.26	−3.49	−0.78	0.46	0.38	0.39
	T1	1.75	0.84	0.00	−0.95	7.13	0.88	4.49
	T2	4.55	1.68	2.33	−0.39	8.01	2.89	8.78
	T3	2.80	2.10	3.49	−0.22	2.82	2.01	3.74

OM, organic matter; *TN*, total nitrogen; *TP*, total phosphorus; *TK*, total potassium; *AN*, available nitrogen; *AP*, available phosphorus; *AK*, available potassium; *CMWL*, chicken manure and wine lees; *CK*, unfertilized control; *CF*, chemical fertilizer; *T1*, chemical fertilizer [75% P-based] + CMWL [25% P-based]; *T2*, chemical fertilizer [50% P-based] + CMWL [50% P-based]; *T3*, chemical fertilizer [25% P-based] + CMWL [75% P-based]

and 20–40 cm reached 7.01 and 4.55%, respectively, higher than others (Table 4). In addition to CK, the OM in CF soil decreased the most, and the OM of 0–20 and 20–40 cm decreased by 1.91 and 1.05%, respectively. Therefore, the T2 treatment is the most effective method to improve soil organic matter in this study.

3.3 Soil Nitrogen, Phosphorus, and Potassium and Their Available States

The nitrogen, phosphorus, and potassium and their available contents in the 0–20 and 20–40 cm soils are shown in Fig. 3. Moreover, the growth rates of the soil properties in the different soils are shown in Table 4. As shown in Fig. 3a, b, and c, the soil total nutrients in the 0–20 cm soil were higher than those in the 20–40 cm soil. Compared with the CF treatment, TN, TP, and TK at 0–20 and 20–40 cm were significantly higher in the T2 and T3 soils ($P < 0.05$). In addition, TN, TP, and TK at 0–20 and 20–40 cm in CK soil showed a decreasing trend, while fertilization treatments (CF, T1, T2, and T3) effectively reduced nutrient loss. Moreover, the growth rates of TN, TP, and TK in the T2 and T3 soils were the highest. However, the growth rates of total nutrients in CF, T1, T2, and T3 at 20–40 cm were lower than those at 0–20 cm.

As illustrated in Fig. 3d, e, and f, AP and AK in the T2 soil at 0–20 and 20–40 cm were significantly higher ($P < 0.05$) than those in the CF soil. At 0–20 cm, the AN in the T2 soil was significantly higher than that in the CK, CF, and T1 soils ($P < 0.05$). Moreover, AN at 20–40 cm in the T1 and T2 soils was significantly higher than that in CK and CF ($P < 0.05$). In addition, the growth rates of AN, AP, and AK at 0–20 cm in the T2 treatment were 12.03, 4.67, and 9.14%, respectively. At 20–40 cm, the growth rates of AN, AP, and AK in the T2 soil were 8.01, 2.89, and 8.78%, respectively. Similarly, the growth rate in T2 soil was greater than that in the other treatments. In conclusion, the T2 and T3 treatments had a better effect on improving TN, TP, and TK, while the T2 treatment was significantly higher in AN, AP, and AK. Therefore, T2 was the best treatment for soil nutrient (total N, P, and K and their available states) enhancement.

3.4 Effect of Organic Fertilizer Application on Tea Quality and Yield

In the spring season, tea yield showed a trend of T3 (312.60) > T2 (312.20) > T1 (289.60) > CF (288.67) > CK (283.85), while in the summer season, the trend was T2 (850.00) > T3 (848.20) > T1 (809.80) > CF (784.90) > CK (741.20) (Table 5). In the spring tea, compared with CF, the tea yield, 100-sprout weight, and sprout density in T2 and T3 soils significantly increased ($P < 0.05$). Similarly, the tea yield of the summer tea in T2 and T3 soils was significantly higher than that in CF, while the sprout density in T1, T2, and T3 soils was significantly higher than that in CF ($P < 0.05$). Therefore, T2 and T3 can effectively improve tea yield in both the spring and summer teas.

The contents of tea polyphenols, amino acids, caffeine, and water extract in this study are shown in Fig. 4. Compared with before the experiment, after the experiment, the tea quality indexes in the T1, T2, and T3 soils showed an upward trend. In the spring tea, compared with CK and CF, the contents of water extract, polyphenols, and amino acids in T2 soil were significantly higher ($P < 0.05$). Among them, compared with CK and CF, the polyphenol content in T1, T2, and T3 soils was significantly higher, while the polyphenol amounts were different in different soils, and the polyphenol content in T2 soil was the highest ($P < 0.05$). Second, the caffeine in the T2 and T3 soils was

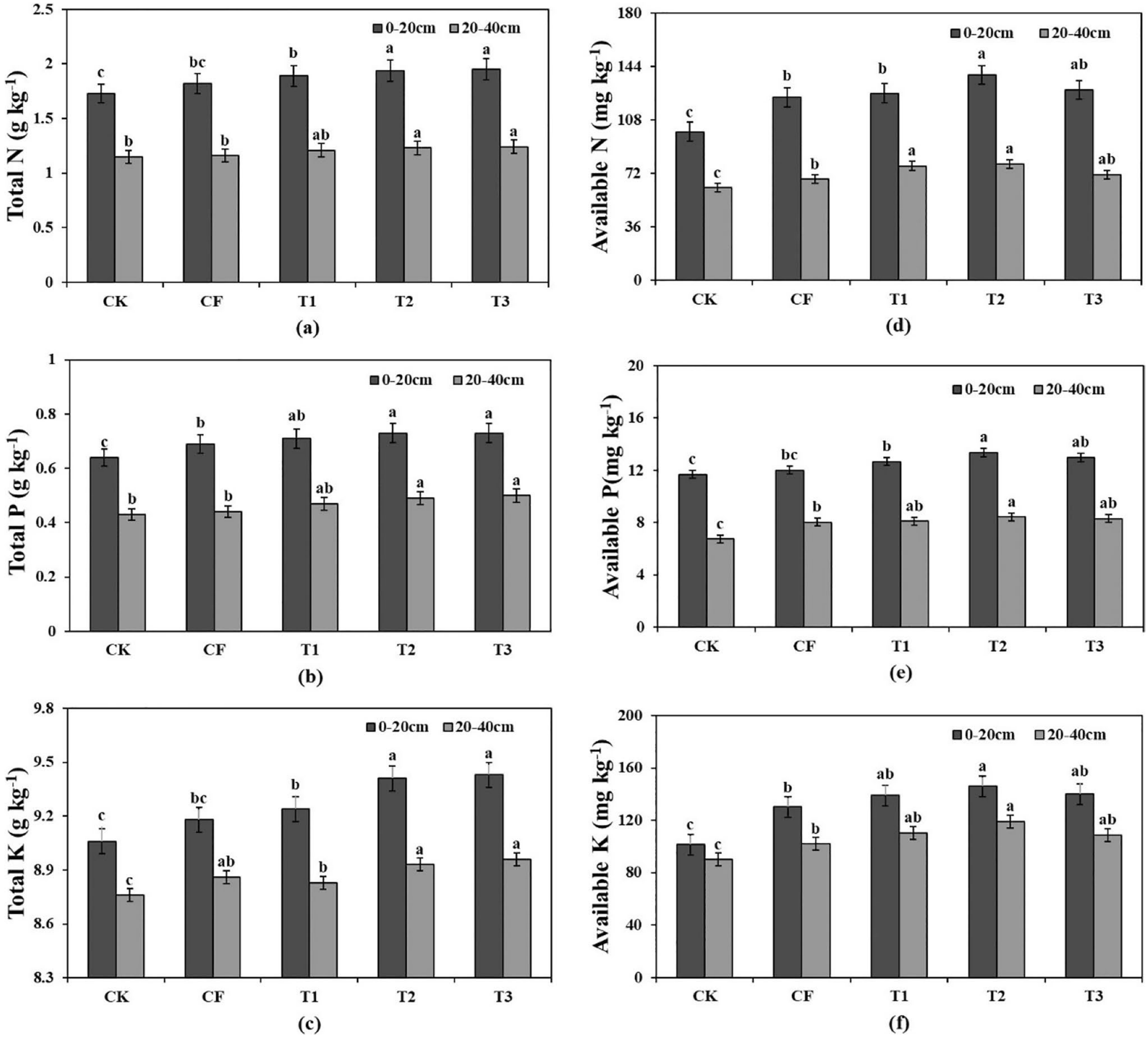

Fig. 3 The soil nutrients in the tea plantation soil at 0–20 and 20–40 cm after the 2-year experiment. Total N, Total nitrogen; Total P, Total phosphorus; Total K, Total potassium; Available N, Available nitrogen; Available P, Available phosphorus; Available K, Available potassium; CMWL, chicken manure and wine lees; CK, unfertilized control; CF, chemical fertilizer; T1, chemical fertilizer [75% P-based] + CMWL [25% P-based]; T2, chemical fertilizer [50% P-based] + CMWL [50% P-based]; T3, chemical fertilizer [25% P-based] + CMWL [75% P-based]. Different letters indicate statistically significant differences among different treatments at $P < 0.05$

significantly higher than that in CK ($P < 0.05$). Moreover, in the summer tea, the contents of water extract, polyphenols, amino acids, and caffeine in T2 and T3 soils were significantly higher than those in CK and CF ($P < 0.05$). Among them, polyphenols and amino acids in T1, T2, and T3 soils were significantly higher than those in CF, while T2 and T3 treatments improved the content more effectively. Therefore, in spring tea and summer tea, the tea quality (water extract, polyphenols, amino acids, and caffeine) in T2 soil showed a better improvement.

3.5 Correlation Between Soil Nutrients and Tea Quality

Variable importance in projection (VIP) and cross-validation analysis were performed through PLS analysis, as shown in Fig. 5 and Tables 6 and 7. The VIP was used to indicate the importance and number of principal components reflecting the influence of OM, TN, TP, TK, AN, AP, and AK on the four tea quality factors and tea yield. The higher the VIP value is, the greater the importance of the

Table 5 Fresh leaf yield, sprout density, and 100-sprout weight of spring tea and summer tea under different treatments

Parameter		CK	CF	T1	T2	T3
Spring tea	Yield of tea leaves (kg hm^{-2})	283.85 ± 4.99 b	288.67 ± 5.89 b	289.60 ± 5.28 b	312.20 ± 4.79 a	312.60 ± 5.19 a
	100-sprout weight (g)	26.40 ± 1.23 b	27.10 ± 1.33 b	27.70 ± 1.82 ab	28.20 ± 1.56 a	28.30 ± 1.13 a
	Sprout density (number m^{-2})	107.33 ± 3.23 ab	105.10 ± 3.93 b	105.30 ± 2.69 b	112.20 ± 3.29 a	110.20 ± 4.02 a
Summer tea	Yield of tea leaves (kg hm^{-2})	741.20 ± 11.93 c	784.90 ± 10.79 b	809.80 ± 13.10 ab	850.00 ± 12.38 a	848.20 ± 13.01 a
	100-sprout weight (g)	36.20 ± 1.93 b	39.92 ± 2.37 ab	41.66 ± 3.01 a	42.53 ± 2.78 a	41.70 ± 3.28 a
	Sprout density (number m^{-2})	202.60 ± 7.01 ab	200.10 ± 6.29 b	207.30 ± 7.33 a	205.80 ± 6.49 a	206.90 ± 6.98 a

CMWL, chicken manure and wine lees; *CK*, unfertilized control; *CF*, chemical fertilizer; *T1*, chemical fertilizer [75% P-based] + CMWL [25% P-based]; *T2*, chemical fertilizer [50% P-based] + CMWL [50% P-based]; *T3*, chemical fertilizer [25% P-based] + CMWL [75% P-based]. Data correspond to means of three replicates ± standard deviation. Small letters in the same column indicate significant difference among treatments at 5% probability level after Duncan test

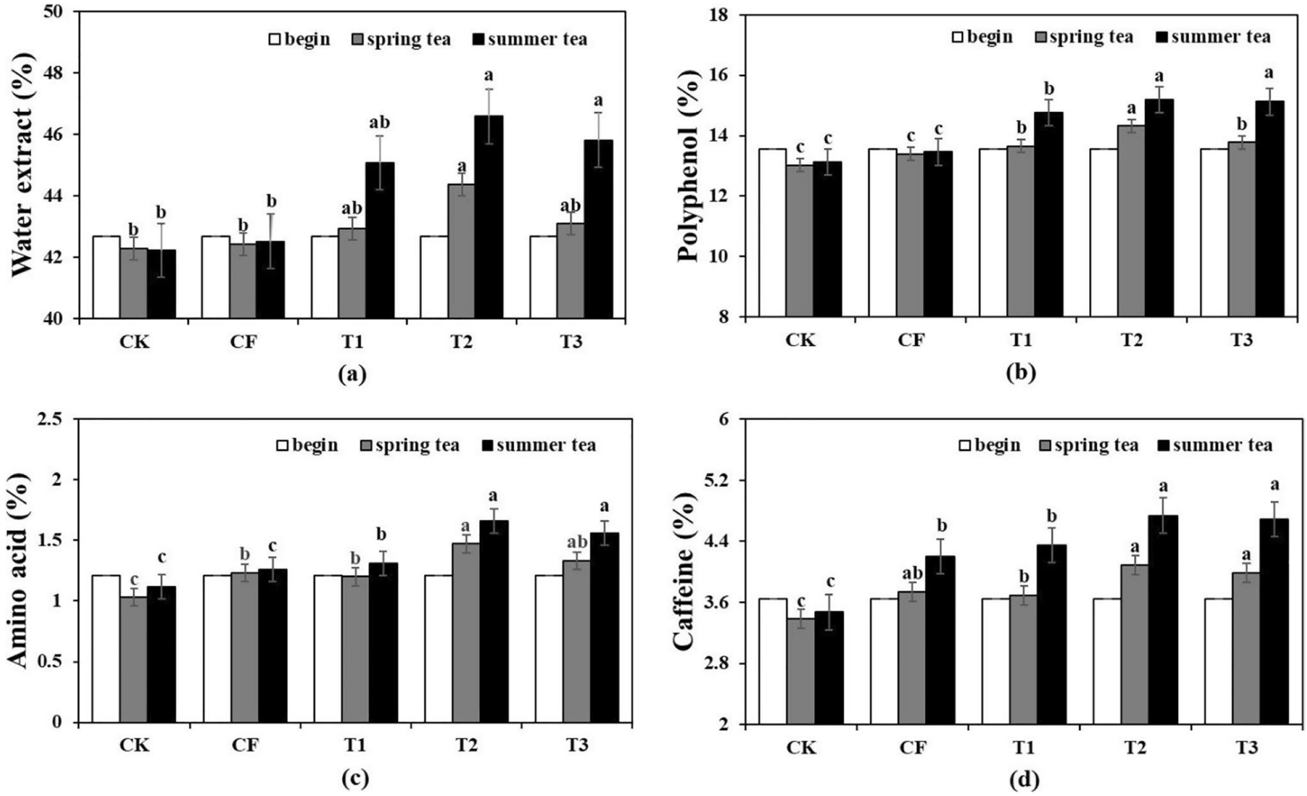

Fig. 4 Effects of different fertilization on the quality indices (water extracts, polyphenol, amino acids, and caffeine) of tea. CMWL, chicken manure and wine lees; CK, unfertilized control; CF, chemical fertilizer; T1, chemical fertilizer [75% P-based] + CMWL [25% P-based]; T2, chemical fertilizer [50% P-based] + CMWL [50% P-based]; T3, chemical fertilizer [25% P-based] + CMWL [75% P-based]. Different letters indicate statistically significant differences among different treatments at $P < 0.05$

component. Figure 5a shows that AP was the most important factor influencing tea yield and quality at 0–20 cm. Figure 5b shows that OM was the most important factor at 20–40 cm. Moreover, increasing the number of components generally did not increase the VIP value, indicating that the most appropriate number of components was 1. Therefore, the most important factors affecting tea were AP at 0–20 cm and OM at 20–40 cm. Cross-availability analysis can also be used to verify the optimal number of components. When the Qh^2 value is less than or equal to 0.0975, then it is meaningless to continue to increase the number of principal components and the current number of components is optimal. As shown in Tables 6 and 7, when there were two soil components at 0–20 and 20–40 cm, the Qh^2 values were − 1.553 and − 1.985, respectively, which were both less than 0.0975; these results indicate that the components that most affected the tea quality were AP at 0–20 cm and OM at 20–40 cm.

Fig. 5 The importance and strength of soil nutrients obtained by the partial least squares (PLS) analysis on the influence of four quality factors and tea yield, and the principal component and auxiliary component were determined. **a** 0–20 cm variable importance in projection (VIP). **b** 20–40 cm variable importance in projection (VIP). OM, organic matter; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AN, available nitrogen; AP, available phosphorus; AK, available potassium

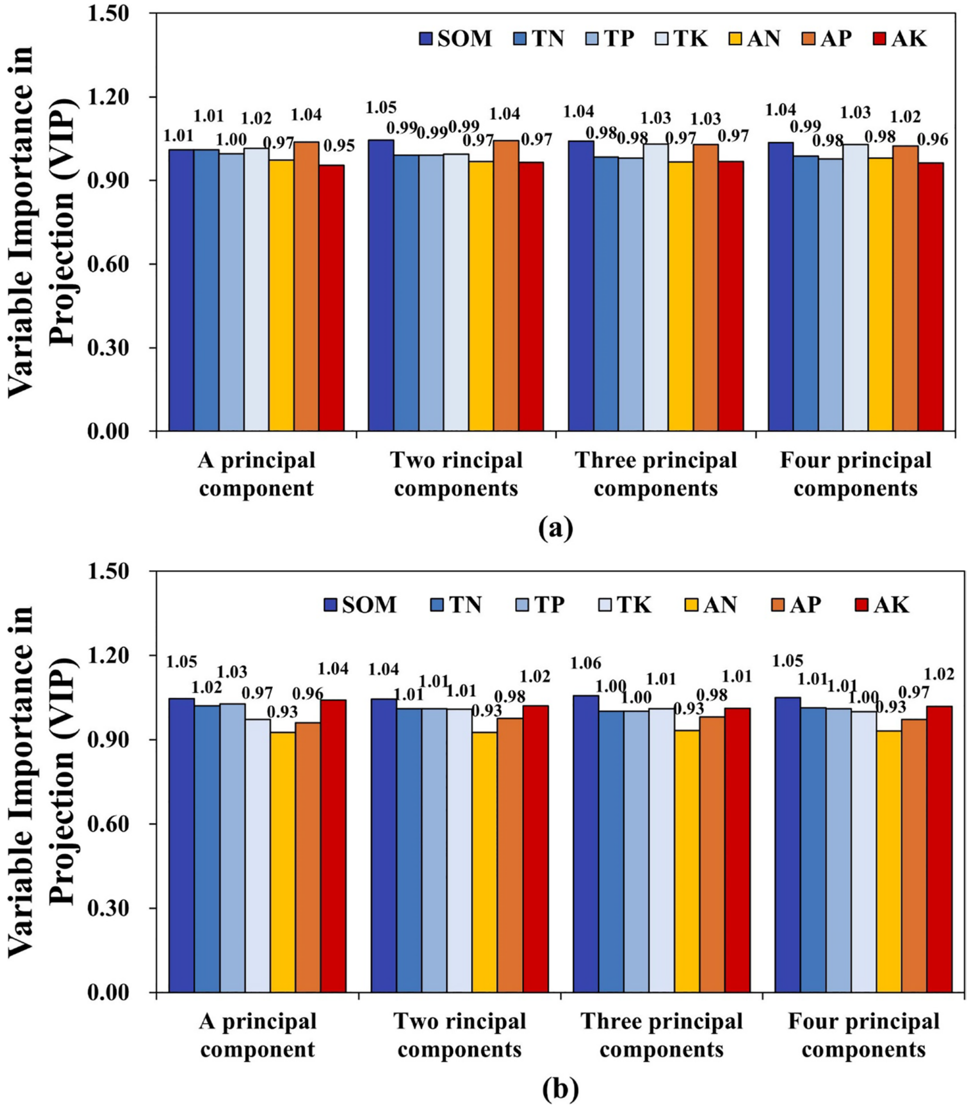

Table 6 Cross-availability analysis of soil nitrogen, phosphorus, potassium, and tea quality factors at 0–20 cm

Element (h)	SS	Press	Qh^2
1	675,141.266	1,093,306.06	1
2	675,085.127	1,723,653.796	− 1.553
3	674,828.547	2,354,106.379	− 2.487
4	674,798.618	2,699,194.473	− 3

SS is the sum of squares of error, Press is the sum of squares of prediction error, and $Qh^2 = 1 - \text{Press} \times h/\text{SS}\ (h-1)$. If the Qh^2 value is less than or equal to 0.0975, it means that it is meaningless to continue to increase the number of principal components; that is, the number of components corresponding to this point (or the previous point) is the optimal number of the principal components

Table 7 Cross-availability analysis of soil nitrogen, phosphorus, potassium, and tea quality factors at 20–40 cm

Element (*h*)	SS	Press	Qh^2
1	675,122.389	1,088,187.668	1
2	675,006.243	2,015,336.408	− 1.985
3	674,802.042	2,236,133.77	− 2.313
4	674,798.618	2,699,194.473	− 3

SS is the sum of squares of error, Press is the sum of squares of prediction error, and $Qh^2 = 1 - \text{Press} \times h/\text{SS}\ (h-1)$. If the Qh^2 value is less than or equal to 0.0975, it means that it is meaningless to continue to increase the number of principal components; that is, the number of components corresponding to this point (or the previous point) is the optimal number of the principal components

4 Discussion

Tea is an acidophilic plant. Soil acidity has a certain effect on tea yield and quality. The tea yield and quality were significantly improved when the soil pH was 4.5–5.5 (Yang et al. 2018). If the soil continued to acidify, the pH below 4.5 was not conducive to tea growth (Yan et al. 2021). This study found that CMWL replacement could elevate soil pH, perhaps because soil acid leaching could be alleviated by using an organic fertilizer instead of a chemical fertilizer (Xie et al. 2020). Moreover, the organic functional groups in organic materials enhance the adsorption of H^+ and Al^{3+} in soil, thus increasing soil pH (Yang et al. 2018; Yan et al. 2020a). The chicken manure and wine lees used in this study contained a large amount of organic matter (Soh et al. 2019; Li et al. 2021a), and the alkaline substances released during organic matter mineralization also increased the soil pH. In addition, the difference in soil structure and organic matter and the difference in pore space were established, resulting in different soil properties (such as pH) at different depths (Kang et al. 2021).

As an important factor of soil quality, soil nutrients maintain soil quality and promote plant productivity (Ribeiro et al. 2021). In this study, the CMWL replacement improved soil nutrients. Similarly, Wu et al. (2020) found that chemical fertilizer application alone could weaken the fixation of nitrogen, phosphorus, and potassium by microorganisms, leading to partial soil nutrient loss with precipitation. While an organic fertilizer can increase soil carbon content and improve soil fertility (Leon et al. 2015), organic matter can reduce soil nitrogen, phosphorus, and potassium loss and maintain soil nitrogen, phosphorus, and potassium levels (Yang et al. 2015; Wang et al. 2016). Because chicken manure contains active and moderately active organic phosphorus, its application has a better soil phosphorus retention effect than chemical fertilizers (Maëlle et al. 2021). Moreover, the input of carbon in chicken manure and wine lees improves soil porosity, pH, and aeration, which can improve the availability of nutrients (Xu et al. 2017; Gu et al. 2019). In addition, a high level of organic matter can promote the activities of microorganisms and beneficial bacteria; thus, chicken manure and wine lees can convert insoluble nutrients in soil into easily absorbed nutrients (Zhao et al. 2014). Therefore, CMWL replacement reduced soil nutrient loss and improved available nutrients (Tao et al. 2015; Wu et al. 2020). In addition, 50% CMWL replacement increased soil available nutrients more effectively than 75% CMWL replacement, which might be because of the slow-release characteristics of organic fertilizers, and the application of organic fertilizer alone or with a high proportion could not increase soil available nutrients accordingly (Ji et al. 2018; Zhai et al. 2022). Typically, an appropriate replacement ratio of organic fertilizers has a better improvement effect on soil organic matter (Li et al. 2021b) and can reduce the loss of soil nutrients (Huang et al. 2020; Wu et al. 2020). Fertilizer application is more likely to increase topsoil nutrients, possibly because soil management affects the topsoil more than natural conditions (Zhuo et al. 2022). However, 50% CMWL replacement could still effectively increase the soil nutrients in the 20–40 cm soil layer. Therefore, 50% replacement had the best effect in improving soil nutrients.

Crop growth accurately reflects the nutrient supply of plants, which mainly comes from soil nutrients (Tang et al. 2021). Organic materials contain large amounts of organic matter and beneficial bacteria, thus improving soil properties such as pH, nutrients, and tea yield (Wang et al. 2018a; Oladele et al. 2019). In addition, the application of organic materials can improve the efficiency of chemical fertilizers (Zhuang et al. 2019). In this study, 50 and 75% CMWL replacements improved the tea yield. This result is consistent with previous studies (Yang et al. 2021), which showed that chemical fertilizers could not satisfy the nutrient requirements during tea growth because their improvement effect on soil available nutrients was less than that of organic fertilizers (Oladele et al. 2019). Tea quality is also important in agricultural production. Tea polyphenols, the general term for the polyphenols in tea, are called “radiation antagonists” by the medical community (Rajapaksha and Shimizu 2022). Amino acids are one of the most important substances for tea flavor, and prepared teas with high amino acid contents taste better. Caffeine is an alkaloid that is present at high levels in some teas, and the prepared tea that is high in caffeine has an energizing effect on the human body. The water extract content of tea reflects its quality to a certain extent (Anastasiia et al. 2020). Organic materials can improve tea quality by improving soil physical and chemical properties, nutrient effects, and soil nutrients (Siddiqui et al. 2011; Yu et al. 2014; Ma et al. 2017; Nabajyoti and Kishor 2021). Moreover, organic fertilizer can improve the tea quality more than chemical fertilizer because it transports microorganisms and organic matter into the soil that can interact with the roots and affect the production of secondary metabolites in the roots, ultimately affecting leaf quality (Wu et al. 2020; Yang et al. 2021). In addition, organic materials affect the composition of the soil microbial community and promote the growth of beneficial bacteria, and the microbial community is positively correlated with the yield and quality of tea (such as tea polyphenols, amino acids, caffeine, and water extract) (Yan et al. 2020b). In general, CMWL has a good microporous structure and abundant functional groups, which are conducive to the absorption of nutrients and the improvement in tea quality. Based on the abovementioned results, applying chicken manure and wine lees to partially replace chemical fertilizers can enhance soil nutrients, thereby improving tea yield and quality. In addition, 50% CMWL replacement had a better influence on soil and tea quality than the other ratios; thus, this hypothesis was supported in this study.

There is a strong positive correlation between soil nutrients, tea yield, and quality (Ma et al. 2017). Though there are presently few studies regarding these relationships, this study did show that soil properties were closely related to tea yield and quality, and it determined which nutrient factors primarily influence tea quality. This study showed that

AP and OM were the main factors affecting tea yield and quality. Different soil layers have different influencing factors due to their different soil properties (Kang et al. 2021). Organic materials can affect tea yield and quality by influencing the soil composition (Yan et al. 2020b). Yan et al. (2021) showed that OM is positively correlated with soil bacterial abundance, thus promoting tea yield and quality. In addition, studies have also indicated that OM and AP are the main factors affecting bacterial and fungal community structures (Ji et al. 2021); thus, OM and AP were positively correlated with tea yield and quality. Because OM and AP were significantly improved in 50% CMWL replacement soil, tea yield and quality were also effectively improved.

5 Conclusions

This study revealed that applying chicken manure and wine lees to replace 25, 50, and 75% chemical fertilizer in tea plantations could not only elevate nutrient storage and cycling but also enhance tea yield and quality. Moreover, soil organic matter and available phosphorus were the main influencing factors, indicating that increasing their content could effectively enhance tea yield and quality. Among the three substitution ratios, the increment of soil organic matter and available phosphorous was highest in 50% chicken manure and wine lees replacement, resulting in best tea quality and yield. This study provides valuable information for supporting the potential of applying chicken manure and wine lees replacement in improving soil quality and tea productivity.

Author contribution Ludan Chen: performed the experiments, analyzed the data, writing—original draft, writing—review and editing. Wei Zhou: performed the experiments, writing—review and editing. Shirong Zhang: writing—review and editing. Liangji Deng: writing—review and editing. Ouping Deng: writing—review and editing. Ling Luo: writing—review and editing. Xiaoxun Xu: writing—review and editing. Chaowu Yang: writing—review and editing. Chunlin Yu: writing—review and editing.

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Declarations

Competing interests The authors declare no competing interests.

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