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Comprehensive Assessment of the Correlation Between Ancient Tea Garden Soil Chemical Properties and Tea Quality

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Abstract: Understanding the correlation between soil chemical properties and tea quality is essential for the comprehensive management of ancient tea gardens. However, the specific links between these factors in ancient tea gardens remain underexplored. This study analyzes the soil chemical properties of four distinct research regions in Nanhua County to explore their effects on key chemical components in ancient tea garden teas, providing a scientific basis for improving the quality of ancient tea garden teas through soil management. Employing high performance liquid chromatography (HPLC) and inductively coupled plasma mass spectrometry (ICP-MS), the chemical components of tea and the chemical properties of the soil were meticulously quantified. Following these measurements, the integrated fertility index (IFI) and the potential ecological risk index (PERI) were evaluated and correlation analysis was conducted. The results revealed that ancient tea garden tea quality is closely linked to soil chemical properties. Soil's total nitrogen (TN), total sulfur (TS), and available potassium (AK) negatively correlate with tea's catechin gallate (CG) component and AK also with polyphenols. Most other soil properties show positive correlations with tea components. The research also evaluated soil heavy metals' IFI and PERI. IFI varied significantly among regions. Hg's high pollution index indicates ecological risks; Cd in Xiaochun (XC) region poses a moderate risk. PERI suggests moderate risk for XC and Banpo (BP), with other areas classified as low risk. Implementing reasonable fertilization and soil amelioration measures to enhance soil fertility and ensure adequate supply of key nutrients will improve the quality of ancient tea gardens. At the same time, soil management measures should effectively control heavy metal pollution to ensure the quality and safety of tea products. Insights from this study are crucial for optimizing soil management in ancient tea gardens, potentially improving tea quality and sustainability.

Keywords: tea garden soil; tea quality; IFI; heavy metals; PERI

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1. Introduction

Tea plants, as a significant economic crop, produce tea leaves that are renowned worldwide as one of the three major non-alcoholic beverages. The ancient tea tree communities located in Yunnan Province, southwestern China, are considered living fossils of the origin of tea trees worldwide, especially within the Ailao Mountain National Nature Reserve, where the largest and most complete wild ancient tea tree communities currently known are found [1,2]. These ancient varieties of *Camellia talinensis* are deeply rooted in the local history and culture through long-term cultivation, domestication, and consumption. The extensive cultivation by local residents and the natural selection process has given birth to a diverse germplasm resource library of tea trees, endowing the region's tea culture with a profound heritage and a unique biological diversity [3,4]. Ancient tea trees are not only of significant economic value but also a precious treasure for culture, science, and natural landscapes [5]. Despite this, these precious ancient tea trees are facing threats from various aspects: habitat destruction, uncontrolled picking, mechanical exploitation, disorderly logging, and lack of effective management measures. A good soil environment is key to the vigorous growth of tea trees and the production of high-quality tea. Achieving sustainable protection and development of ancient tea tree resources requires the urgent protection of tea's rich diversity and utilization of it in a scientific and reasonable manner.

Tea polyphenols, amino acids, and caffeine are essential metabolic substances in tea plants and play a pivotal role in determining tea's quality [3]. The nutritional status of the soil in tea gardens directly affects the growth of tea plants and the quality of the tea they produce. The optimal soil pH for tea plant growth ranges from 4.0 to 5.5, with good drainage and a soil organic matter content exceeding 2%, which together provide the best growth conditions for tea plants [4]. Furthermore, the cation exchange capacity of the soil and the interactions between its elements significantly impact soil quality [5]. Studies have shown that the nitrogen content in tea garden soil is significantly and positively correlated with tea yield and the content of free amino acids and caffeine, thereby affecting the level of tea polyphenols. Additionally, the elements of nitrogen, potassium, and magnesium play an active role in reducing the phenol-ammonia ratio, an important indicator for assessing tea quality [6,7]. Trace elements like iron and copper are also indispensable for the physiological functions of tea plants, participating in the synthesis of chlorophyll and the composition of polyphenol oxidase [8]. Sun et al. [9] demonstrate that refining the mineral nutrition management practices within tea gardens is an effective strategy for boosting the quality and yield of the tea produced. Conversely, Liu et al. [10] reveal a concerning trend: soil acidification in tea gardens could lead to the accumulation of heavy metals to levels that may be detrimental to both the quantity and quality of the tea harvested.

In the rapid development of China's tea industry, the quality and safety of tea have become the sector's primary focus. The issue of heavy metal pollution in tea garden soils has garnered widespread concern in environmental and public health circles, as these contaminants may pose potential health risks to consumers through tea consumption [11]. The use of chemical fertilizers and pesticides, as well as industrial activities, are identified as the primary causes of heavy metal contamination in tea garden soils [12,13]. Heavy metals such as cadmium, mercury, lead, chromium, and arsenic are significant threats to human health, associated with various diseases including cardiovascular disorders, neurological conditions, and even cancer [14,15]. The ecological risks of heavy metal pollution in tea garden soils are multifaceted. They directly affect soil microbial communities, crucial for soil fertility and ecosystem functionality, while also posing a long-term threat to human health through the food chain [16,17]. The bioavailability of heavy metals in the soil and their subsequent absorption by tea plants are influenced by a combination of factors, including soil pH and organic matter content [18,19]. Research by Hu et al. [20] indicates that while some regions in China have higher levels of heavy metals in tea, the overall non-carcinogenic risk of heavy metals in tea is within a safe range. Huang et al. [21] discovered that heavy metals like Cd, Hg, and Cu are major factors affecting the composition of soil microbial communities. He et al. [22], using the Potential Ecological Risk Index (PERI) and the Nemerow Comprehensive Pollution Index, found that the ecological risk indices in Tibet, Guangdong, and Fuzhou are at a moderate level, whereas the ecological risk assessment indicators for both organic and conventional tea gardens in Anxi are classified as low.

Therefore, in this industry driven by quality, the condition of the soil has a decisive impact on the management of tea gardens. Despite a growing body of research on how soil properties affect the growth of tea plants and the quality of tea, there is a noticeable gap in understanding the relationship between specific soil properties (soil nutrient properties, heavy metal elements) of ancient tea gardens and the key chemical components of tea. Particularly in Yunnan's ancient tea gardens, which are highly valued for their unique historical and cultural significance, studies on the soil–tea quality nexus are scarce. Our research aims to fill this gap by analyzing soil samples from four distinct regions in Nanhua County, examining their influence on key chemical components in ancient tea garden teas. This work not only pinpoints the principal soil properties that influence tea quality but also provides practical and economic significance for developing sustainable cultivation practices for ancient tea gardens. It increases both the yield and the quality of the tea produced and offers a scientific foundation for the remediation and management of heavy metals in the soils of ancient tea gardens, fostering the sustainable growth of the tea industry.

2. Materials and Methods

2.1. Research Information and Experimental Design

On 10 April 2023, soil samples were collected from four regions in Tujie Town, Nanhua County, as depicted in Figure 1, specifically from Changliangzi (CLZ) as shown in Figure 1a, BP in Figure 1b, XC in Figure 1c, and Ganlongtan (GLT) in Figure 1d. The ancient tea tree resource information of the study area is presented in Table 1 below, with all tea cultivars being Pu'er tea, and tree girth measurements were taken at a height of 40 cm above the ground. Select study areas had a slope of 10°–15° and faced the sun. Due to the scattered distribution of ancient tea trees and the lack of a unified cultivation pattern, we meticulously divided each research area into 3 sampling zones, and within each sampling zone, we used a grid method to determine 9 sampling points. Each sampling point was selected in the area where tea trees were most densely grown, with an area of 50 × 50 m. Within each sampling point, these points were sampled following an "S" shaped route to ensure that the soil samples collected from each area were representative. A total of 27 samples were collected from each research area. Soil samples were taken vertically under the edge of the tea trees where tender leaves are typically harvested. After removing sur-face debris, the original soil from the 0–20 cm and 20–40 cm layers was extracted using a soil ring cutter and mixed into a single sample representing each depth for the study area, and then brought back to the laboratory. Fresh tea leaves were harvested corresponding to the soil sampling blocks, following the "one bud and two leaves" standard, and processed according to green tea production methods.

Figure 1. Representative ancient tea trees from four regions. In (**a**): represents the typical tea tree of the CLZ research region; In (**b**): represents the typical tea tree of the BP research region; In (**c**): represents the typical tea tree of the XC research region; In (**d**): represents the typical tea tree of the GLT research region.

Table 1. Information on ancient tea tree resources in the four study areas.

Sites	**Varieties**	**Tree Age**	**Latitude and Longitude Range**	**Altitude/m**	**Area/ha**	**Tree Girth/m**
CLZ	*C.sinensis* var. assamica (J. W. Mast.) Kitam.	≥100 years	24°44′10″~24°44′16″ N 100°43′31″~100°43′35″ E	2100–2200	3.43	0.8–1.8
BP	*C.sinensis* var. assamica (J. W. Mast.) Kitam.	≥100 years	24°45′01″~24°45′10″ N 100°50′49″~100°50′54″ E	2000–2300	2.56	0.6–1.6
XC	*C.sinensis* var. assamica (J. W. Mast.) Kitam.	≥100 years	24°45′30″~24°45′40″ N 100°51′20″~100°51′23″ E	2100–2300	2.84	0.8–1.6
GLT	*C.sinensis* var. assamica (J. W. Mast.) Kitam.	≥100 years	24°46′27″~24°46′35″ N 100°49′75″~100°49′80″ E	2000–2200	3.04	0.8–2.1

2.2. Integrated Fertility Index (IFI)

The IFI method was employed to assess the soil fertility in the four research regions. The equation utilized in the calculations was as follows:

$$IFI = \sum_{i=1}^{n} W_i F(x_i) \tag{1}$$

In the equation, W_i denotes the weight coefficient for the i-th quality indicator of soil fertility, $F(x_i)$ signifies the contribution score of the i-th indicator to soil fertility, and n represents the total number of indicators considered [23–25]. The scores for each soil fertility indicator were determined by integrating the monitored values with a standardized scoring function (SSF) [26], the specific form of which was defined by a particular "S" function:

$$f(x) = \begin{cases} 1.0 & x \geq x_2 \\ \frac{0.9(x-x_1)}{x_2-x_1} + 0.1 & x_1 < x < x_2 \\ 0.1 & x \leq x_1 \end{cases} \tag{2}$$

For soil pH, because there is an optimum range, the SSF is:

$$f(x) = \begin{cases} 1.0 - \frac{0.9(x-x_3)}{x_4-x_3} & x_3 < x < x_4 \\ 1.0 & x_2 \leq x \leq x_3 \\ \frac{0.9(x-x_1)}{x_2-x_1} + 0.1 & x_1 < x < x_2 \\ 0.1 & x \leq x_1,\ x \geq x_4 \end{cases} \tag{3}$$

The monitored value of the parameter is denoted by x, with the parameter's score, $f(x)$, ranging from 0.1 to 1. The values x_1 and x_2 represent the lower and upper thresholds, respectively, which determine their influence in Chinese tea garden soil on plant growth [27,28]. The specific values for x_1 and x_2 are listed in Table 2.

Table 2. The values of the turning points of the membership function curves for each fertility indicator.

	Soil Parameters									
	pH	**OM g/kg**	**TP g/kg**	**AP mg/kg**	**TK g/kg**	**AK mg/kg**	**TN g/kg**	**AN mg/kg**	**TS g/kg**	**CEC cmol/kg**
X1	4.5	20	0.3	0.2	13	20	0.5	60	0.08	11
X2	5.0	60	0.5	1.2	14	60	1.2	190	0.11	17
X3	5.5									
X4	6.5									

Note: OM—soil organic matter, TP—total phosphorous, AP—available phosphorus, TK—total potassium, AN—alkali-hydrolyzable nitrogen, CEC—cation exchange capacity.

The weights of soil parameters in soil fertility evaluation were determined by the entropy method, which is an objective weighting method based on the principle of information entropy. It determines the weights by calculating the variability of each parameter's values [29].

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{4}$$

The calculation formula for the weight coefficient (W_i) is shown in Equation (4), where the weight coefficient accurately reflects the magnitude of the role played by each soil fertility evaluation indicator in the soil fertility assessment process. V_i is the average of the correlation coefficients of the i-th indicator with other indicators.

2.3. Potential Ecological Risk Assessment

The Potential Ecological Risk Index (PERI) was employed for data assessment. As a widely recognized approach, it takes into account the interplay among heavy metals, their toxicological profiles, chemical behaviors, and the sensitivity of ecosystems [30]. The PERI was derived from the following equations:

$$E_h^j = T_h^j \cdot C_f^j = T_h^j \cdot C_s^j / C_n^j \tag{5}$$

$$PERI = \sum E_h^j = \sum T_h^j \cdot C_f^j = \sum T_h^j \cdot C_s^j / C_n^j \tag{6}$$

where E_h^j is the potential ecological hazard index of heavy metal j; and T_h^j is the toxicity coefficient of heavy metal j. The toxicity coefficients of Zn, Cr, Pb, Cu, Ni, As, Cd, and Hg are 1, 2, 5, 5, 5, 10, 30 and 40, respectively [30,31]. C_f^j is the enrichment factor of heavy metal j. C_s^j is the measured value of heavy metal j. C_n^j is the background value of heavy metal j [32]. The grading standards for both E_h^j and Rl are shown in Table 3 [33].

Table 3. Grading standards of potential ecological risk assessment, source.

E_h^j Grade	Pollution Grade	*PERI* Grade	Comprehensive Ecological Risk Grade
$E_h^j < 40$	Slight (Low)	$PERI < 135$	Slight (Low)
$40 \leq E_h^j < 80$	Mid (Medium)	$135 \leq PERI < 265$	Mid (Medium)
$80 \leq E_h^j < 160$	Strong (Heavy)	$265 \leq PERI < 525$	Strong (Heavy)
$160 \leq E_h^j < 320$	Stronger (Heavier)	$525 \leq PERI$	Stronger (Heavier)
$320 \leq E_h^j$	Strongest (Serious)		

2.4. Determination of Tea Compositions

The tea water extract (WE) was determined according to GB/T 8305-2013 [34], the content of tea polyphenol (TPL) was measured using the Folin–Ciocalteu method [35], the content of free amino acid (AA) was determined by ninhydrin chromogenic spectrophotometry [36], the content of soluble sugar (SS) was determined using the anthrone–sulfuric acid colorimetric method, the content of flavonoid glycosides (FLA) was determined using the method of Douglas [37], and the analysis of caffeine (CA) and catechin components were conducted using HPLC [38], with quantification based on peak areas.

2.5. Determination of Soil Chemical Properties

Soil samples were naturally air-dried, cleared of stones and plant roots, ground, and sifted through a 100-mesh (0.15 mm) sieve to ensure a uniform sample for subsequent chemical analysis. Following the methods described by Webster [39], soil pH was determined using a glass combination electrode. Cation exchange capacity (CEC) was extracted using the ammonium acetate exchange-distillation method; TN was determined using the concentrated sulfuric acid-hydrogen peroxide digestion-Kjeldahl nitrogen method; total phosphorous (TP) was determined using the sulfuric acid-hydrogen peroxide digestion-molybdenum antimony anti-colorimetric method; total potassium (TK) was determined using the concentrated sulfuric acid-hydrogen peroxide digestion-flame photometry method; while alkali-hydrolyzable nitrogen (AN) was determined using the 1 mol/L NaOH alkaline extraction diffusion method [40]. Soil organic matter (OM) was determined by the oxidative thermal potassium dichromate oxidation-colorimetric method [41]. Available phosphorus (AP) was extracted using a 0.5 mol·L^{-1} $NaHCO_3$ solution and then determined by the molybdenum antimony colorimetric method, and AK was determined by the molybdenum antimony-ascorbic acid colorimetric method [42]. The concentrations of As, Cu, Hg, Cd, Ni, Pb, Cr, Zn, TS, exchangeable magnesium (Mg), and fluoride (FL) in soil samples were determined by microwave digestion-inductively coupled plasma optical emission spectrometry based on the method of Wen et al. [43].

2.6. Statistical Analysis

In our study, to assess the linear relationship between tea quality indicators and soil parameters, we employed the Pearson correlation coefficient for correlation analysis. This analysis was conducted using SPSS 26.0 software to ensure accurate measurement of the linear relationships between variables. Each measurement was conducted in triplicate, and results are presented as mean ± standard deviation to ensure the reliability and stability of the data. Data processing was performed using Excel 2010, while the generation of radar charts, bar graphs, and principal component analysis (PCA) was carried out using Origin 2022 software.

3. Results

3.1. Analysis of Components of Tea

Table 4 shows that the basic biochemical components in the four research regions had water extractions exceeding 50%, with tea polyphenol content exceeding 19%, which is consistent with the characteristics of Yunnan large-leaf tea. The phenol–amino acid ratio ranged from 8.52 to 13.59, with a coefficient of variation of 18.82%. Among these, the variation in flavonoid glycosides was the greatest, with a coefficient of variation of 68.67%, indicating moderate variability. Other indicators had coefficients of variation not exceeding 20%, indicating weak variability. This suggests that the biochemical components of tea across the four research regions are relatively stable, with the most significant variations observed in flavonoid glycosides, free amino acids, soluble sugars, and tea polyphenols.

Table 4. Principal compositions of tea at four research regions.

Tea Properties	CLZ	BP	XC	GLT	CV (%)
Water extraction (%)	51.57 ± 0.32 b	53.53 ± 0.47 a	54.15 ± 0.51 a	52.82 ± 0.23 a	2.09%
Tea polyphenol (%)	26.46 ± 0.31 a	19.46 ± 0.27 c	22.68 ± 0.34 b	26.01 ± 0.34 a	13.08%
Free amino acid (%)	1.95 ± 0.02 c	1.61 ± 0.06 d	2.66 ± 0.05 a	2.08 ± 0.05 b	21.08%
Soluble sugars (%)	7.45 ± 0.08 b	6.19 ± 0.04 d	9.29 ± 0.13 a	6.98 ± 0.07 c	17.59%
Caffeine (%)	4.62 ± 0.05 d	6.00 ± 0.06 a	4.82 ± 0.04 c	5.11 ± 0.04 b	11.86%
Flavonoid glycosides (mg/g)	2.34 ± 0.07 d	2.76 ± 0.04 c	9.49 ± 0.10 a	4.52 ± 0.08 b	68.67%
Polyphenols/amino acids ratio	13.59 ± 0.03 a	12.07 ± 0.40 b	8.52 ± 0.20 c	12.51 ± 0.22 b	18.82%

Note: Significant differences were indicated by different letters at the level of 0.05.

Catechins are the main substances of tea polyphenols, accounting for 75% to 80% of tea polyphenols, and mainly impart a bitter taste, which is an important tea flavor substance. As shown in Figure 2a, a percentage bar graph, the catechin components in the four research regions were mainly highlighted by the XC region, while the BP and GLT regions had comparatively lower content levels than the other two regions, with a 10% difference in the proportion of component catechin (C) and an 18% difference in the proportion of component EC compared to the other three regions. Correspondingly, from Figure 2b, a radar chart, it can be seen that the difference between the maximum and minimum values of C was 5 mg/g, for epicatechin (EC) it was 10 mg/g, and epigallocatechin gallate (EGCG) 20 mg/g. From the analysis of Figure 2, it can be concluded that the major differences in catechin components among the four research regions were mainly C, catechin gallate (CG), gallocatechin gallate (GCG), EC, gallocatechin (GC), and epigallocatechin (EGC).

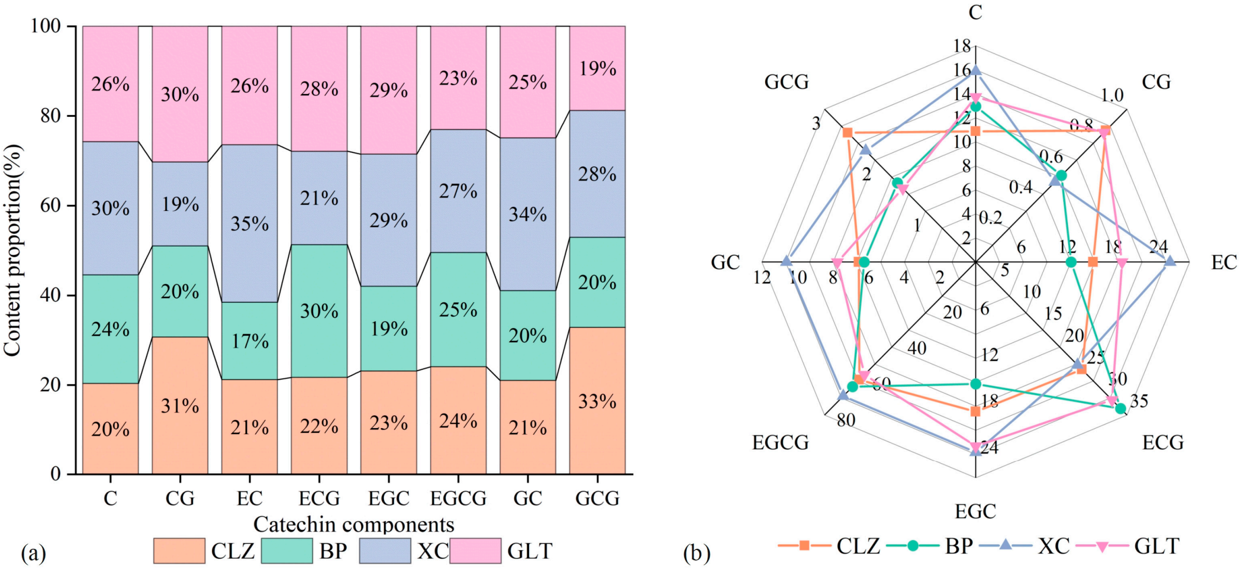

Figure 2. Analysis of the components of epicatechin distribution in four research regions. Note: ECG-epicatechin gallate. In (**a**): Percentage stacked bar chart of catechin composition; In (**b**): Radar chart of catechin composition.

3.2. Analysis of Soil Chemical Properties

The soil chemical properties of the research regions, including AP, AN, AK, CEC, FL, Mg, OM, pH, TP, TN, TK, and TS, were comprehensively analyzed across the 0–20 cm and 20–40 cm soil layers in the four study regions, with the results presented in Figure 3. The CLZ showed higher levels of AN, CEC, OM, and TK compared to the other three regions. The BP showed significantly higher levels of AP and Mg. The XC demonstrated notably higher levels of AK, CEC, FL, OM, pH, TN, and TS. The GLT had significantly higher levels of TP and TK ($p < 0.05$). Examining the 10 primary soil properties, it is evident that the XC possessed a richer content of soil chemical properties than the other three research regions. In contrast, the BP and GLT exhibited a relative deficiency in soil chemical properties compared to the other two research regions, which aligns with the trend observed in the components of the tea. This suggests a correlation between variations in tea composition and the soil properties of the tea garden.

3.3. Assessment of Soil Fertility

The weight coefficients of soil fertility indicators were mainly calculated by the coefficient of variation method, and we determined the weight coefficients of each soil fertility evaluation indicator (Table 5).

Table 5. The estimation of communality and weight values for various soil fertility parameters.

	Soil Parameters									
	pH	**OM**	**CEC**	**TN**	**TK**	**TP**	**TS**	**AK**	**AN**	**AP**
Weight	0.014	0.001	0.005	0.064	0.005	0.145	0.638	0.002	0.001	0.078

The Integrated Fertility Index (IFI) was determined by the membership degree of these component parameters and their weighted coefficients (Table 5). During the comprehensive assessment of soil indicators for the 0–20 cm and 20–40 cm soil layers across the four research regions, ten soil indices were selected to measure the IFI. As shown in Table 6, the

IFI values in the CLZ and XC regions were significantly higher than those in the BP and GLT regions, which corresponds with the trends observed in the components and the soil properties of the tea garden.

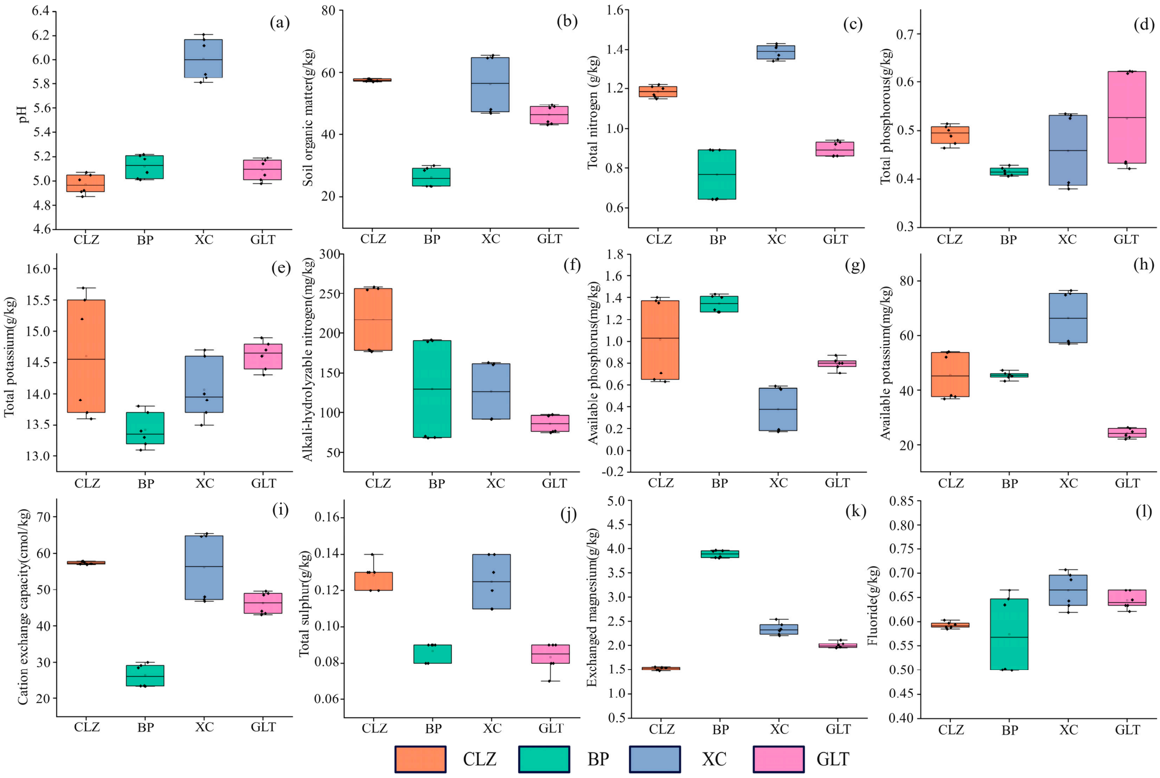

Figure 3. Box plots of ten soil properties at four research regions. In (**a**): Box plot of soil pH distribution in four research regions; In (**b**): Box plot of Soil Organic Matter distribution in four research regions; In (**c**): Box plot of soil Total Nitrogen distribution in four research regions; In (**d**): Box plot of soil Total Phosphorus distribution in four research regions; In (**e**): Box plot of soil Total Potassium distribution in four research regions; In (**f**): Box plot of soil Alkali-hydrolyzable nitrogen distribution in four research regions; In (**g**): Box plot of soil Available Phosphorus distribution in four research regions; In (**h**): Box plot of soil Available Potassium distribution in four research regions; In (**i**): Box plot of soil Cation Exchange Capacity distribution in four research regions; In (**j**): Box plot of soil Total Sulfur distribution in four research regions; In (**k**): Box plot of soil Exchanged magnesium distribution in four research regions; In (**l**): Box plot of soil Fluoride distribution in four research regions.

Table 6. The Soil Fertility Index and Integrated Fertility Index (IFI).

Fertility Index	pH	OM	CEC	TN	TK	TP	TS	AK	AN	AP	IFI
CLZ	0.910	0.940	0.393	0.974	0.880	0.944	1.000	0.671	0.957	0.759	0.919
BP	1.000	0.242	0.248	0.444	0.475	0.619	0.364	0.670	0.580	1.000	0.447
XC	0.544	0.857	0.681	1.000	0.865	0.744	1.000	0.972	0.562	0.268	0.850
GLT	1.000	0.692	0.291	0.609	1.000	0.841	0.250	0.194	0.280	0.636	0.392

To delve deeper into the specific impact of these soil chemical properties on the IFI, a linear regression analysis was conducted on these indicators. In analyzing the results, as depicted in Figure 4, filtering was based on the R^2 values and Pearson correlation coefficients (r) ($p < 0.05$), which helped identify the soil properties that had a significant influence on the IFI. The selected soil properties, with $r > 0.60$ and $R^2 > 0.40$, were arranged in descending order of their impact: TS ($r = 0.96$), TN ($r = 0.87$), OM ($r = 0.81$), CEC ($r = 0.71$), and AK ($r = 0.67$). These key factors will guide further research into the interactions between tea components and tea garden soil, providing crucial scientific evidence to uncover the intrinsic connections between soil properties and tea quality.

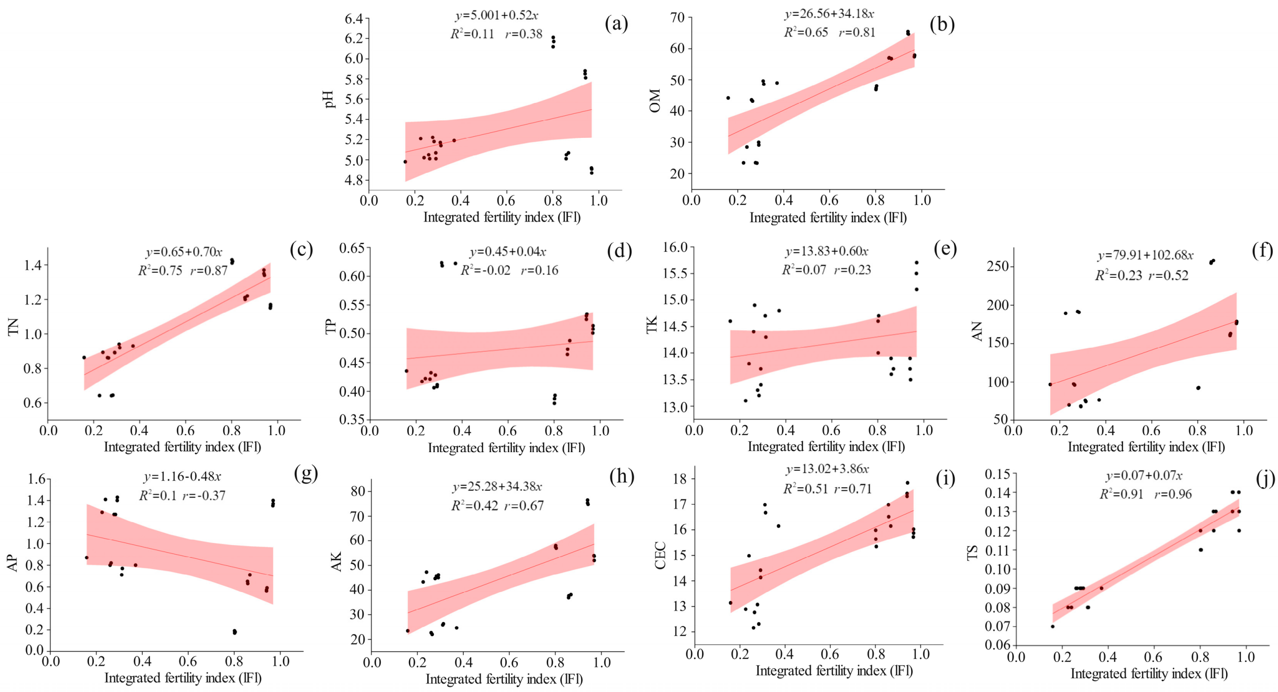

Figure 4. The linear correlation between individual soil fertility indicators and the comprehensive IFI. In (**a**): Linear correlation between soil pH and Integrated fertility index in four research regions; In (**b**): Linear correlation between Soil Organic Matter and Integrated fertility index in four research regions; In (**c**): Linear correlation between Total Nitrogen and Integrated fertility index in four research regions; In (**d**): Linear correlation between Total Phosphorus and Integrated fertility index in four research regions; In (**e**): Linear correlation between Total Potassium and Integrated fertility index in four research regions; In (**f**): Linear correlation between Alkali-hydrolyzable nitrogen and Integrated fertility index in four research regions; In (**g**): Linear correlation between Available Phosphorus and Integrated fertility index in four research regions; In (**h**): Linear correlation between Available Potassium and Integrated fertility index in four research regions; In (**i**): Linear correlation between Cation Exchange Capacity and Integrated fertility index in four research regions; In (**j**): Linear correlation between Total Sulfur and Integrated fertility index in four research regions.

3.4. Analysis of Heavy Metal Elements at Four Regions

The concentrations of heavy metal elements (As, Cu, Hg, Cd, Ni, Pb, Cr, Zn) in soil layers of 0–20 cm and 20–40 cm at four research regions are illustrated in Figure 5. In CLZ, the concentrations of As, Cu, and Cr in soil layers of 0–20 cm and 20–40 cm were significantly higher than those at the other three research regions. In BP, the concentrations of Hg and Ni in soil layers of 0–20 cm and 20–40 cm were significantly higher than those at the other three research regions. In XC, the concentrations of Pb, Zn, and Cd in soil layers of 0–20 cm and 20–40 cm were significantly higher than those in the other three research regions. However, in GLT, the concentrations of heavy metal elements in both the 0–20 cm and 20–40 cm soil layers ranged from lower to middle levels compared to the other three regions. This pattern aligns with the tea components and soil properties observed in the tea garden, suggesting a relationship between tea components, soil properties, and heavy metal concentrations in tea garden soil.

Heavy metal contamination in tea garden soils has emerged as a significant environmental concern in recent years. With the rapid expansion of the tea industry, heavy metal pollution in the soil has become a critical factor affecting the quality of tea and the safety of agricultural products. Thus, conducting an assessment of the PERI for heavy metals in tea garden soils is of paramount importance. Distinct variations in the potential ecological hazard index (E_h^j) for the 0–20 cm and 20–40 cm soil layers were observed across different research regions (as shown in Table 7). Among the four research regions, Hg exhibited the highest index, posing a medium to heavy potential ecological risk, as detailed in Table 7. Cd in the XC region is regarded as a moderate risk. The E_h^j values for the remaining areas were all below 40, indicating a lower ecological risk. Further analysis revealed that the PERI values for the 0–20 cm soil layer in the CLZ, BP, XC, and GLT regions were 125.34, 166.51, 154.42, and 11.58, respectively, while the PERI values for the 20–40 cm soil layer were 112.97, 164.86, 153.40, and 112.50, respectively. The PERI values for the XC and BP regions are categorized as medium risk, while the other regions are classified as low risk. These assessment results enable a profound understanding of the status of heavy metal pollution in tea garden soils, offering a scientific basis for developing corresponding risk management and mitigation measures.

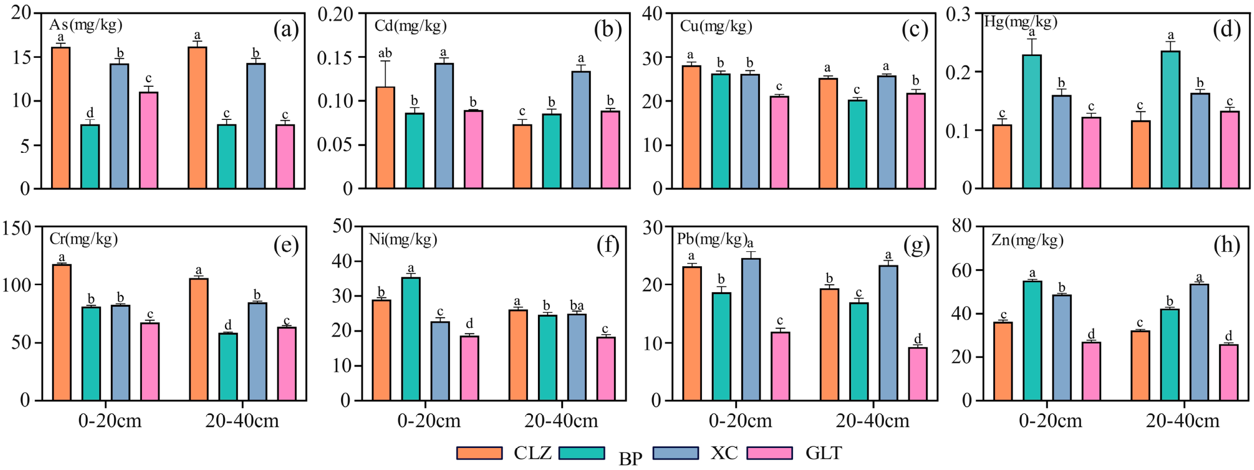

Figure 5. Heavy metal element distribution analysis of four research regions soil layers including topsoil (0–20 cm, top) and subsoil (20–40 cm, sub). Soil heavy metal elements included As, Cu, Hg, Cd, Cr, Ni, Pb, and Zn. Note: Significant differences are indicated by different letters at the 0.05 level. In (**a**): Heavy metal As content in the 0–20cm and 20–40cm soil layers of four regions; In (**b**): Heavy metal Cd content in the 0–20cm and 20–40cm soil layers of four regions; In (**c**): Heavy metal Cu content in the 0–20cm and 20–40cm soil layers of four regions; In (**d**): Heavy metal Hg content in the 0–20cm and 20–40cm soil layers of four regions; In (**e**): Heavy metal Cr content in the 0–20cm and 20–40cm soil layers of four regions; In (**f**): Heavy metal Ni content in the 0–20cm and 20–40cm soil layers of four regions; In (**g**): Heavy metal Pb content in the 0–20cm and 20–40cm soil layers of four regions; In (**h**): Heavy metal Zn content in the 0–20cm and 20–40cm soil layers of four regions.

Table 7. The potential ecological hazard index (E_h^j) of each heavy metal and PERI values in the 0–20 cm and 20–40 cm soil layers of tea gardens at four research regions.

Sampling Site		E_h^j								**PERI**
		Cd	**Pb**	**Cr**	**Ni**	**Zn**	**Cu**	**As**	**Hg**	
CLZ	0–20 cm	36.08	4.51	3.86	5.39	0.49	6.23	14.47	54.32	125.34
	20–40 cm	22.68	3.79	3.49	4.87	0.44	5.60	14.50	57.61	112.97
BP	0–20 cm	26.80	3.76	2.64	6.60	0.74	5.81	6.57	113.58	166.51
	20–40 cm	26.49	3.32	1.92	4.60	0.57	4.49	6.59	116.87	164.86
XC	0–20 cm	44.33	4.92	2.71	4.23	0.66	5.80	12.76	79.01	154.42
	20–40 cm	41.55	4.54	2.78	4.65	0.72	5.72	12.79	80.66	153.40
GLT	0–20 cm	27.73	2.33	2.23	3.48	0.37	4.68	9.85	60.91	111.58
	20–40 cm	27.53	1.86	2.10	3.42	0.35	4.83	6.57	65.84	112.50

3.5. Correlation Coefficient Analysis Between Tea and Soil

To further investigate the relationships among various soil chemical properties and tea quality parameters, PCA was conducted. The PCA plot (Figure 6a) illustrates the first two principal components for the 0–20 cm soil layer, which together accounted for 75.5% of the total variance in the data. Figure 6b presents the first two principal components for the 20–40 cm soil layer, explaining 80.2% of the total variance. The plots revealed strong correlations between certain soil chemical properties and tea quality parameters, highlighting the most significant factors influencing tea quality.

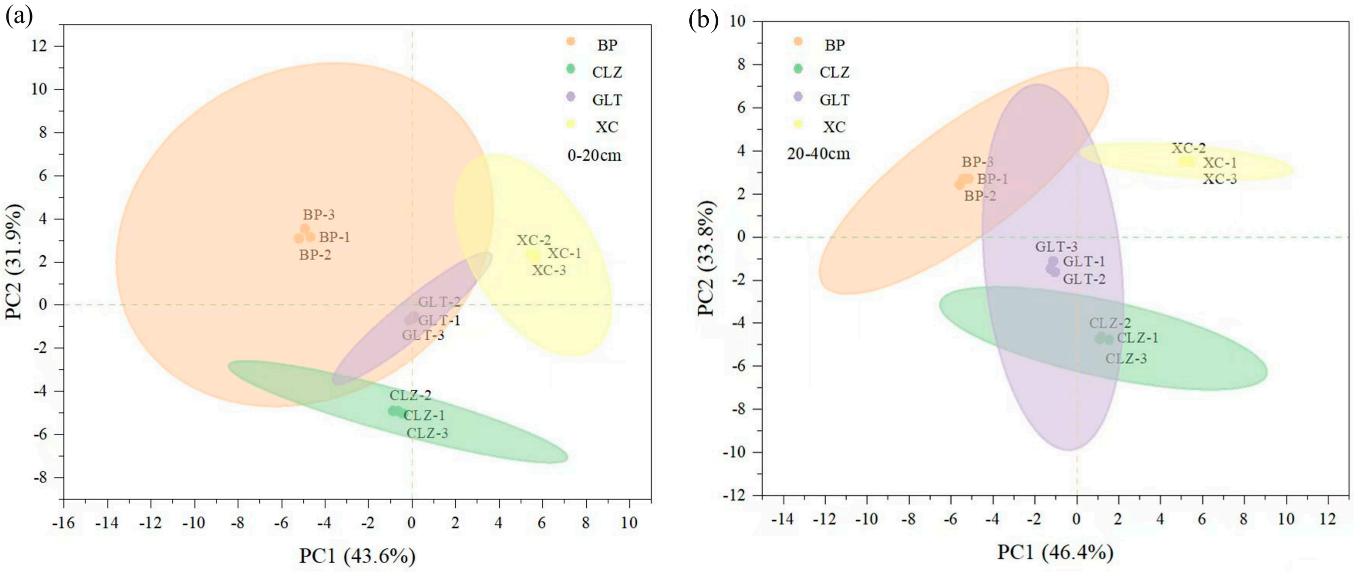

Figure 6. PCA of soil properties and tea quality parameters across different soil layers. In (**a**): Principal component analysis of soil chemical properties and tea quality parameters in the 0–20 cm layer across four research regions; In (**b**): Principal component analysis of soil chemical properties and tea quality parameters in the 20–40 cm layer across four research regions.

To further understand the association between tea garden soil characteristics and tea components, we conducted a correlation analysis on soil chemical properties and heavy metal elements in the 0–20 cm and 20–40 cm soil layers across four research regions and their relationship with tea quality components. From the analysis (Table 8), 10 important tea component factors were selected for attention, which included tea polyphenols, free amino acids, soluble sugars, flavonoid glycosides, C, CG, EC, EGC, GC, and GCG. Additionally, eight important soil chemical properties factors were identified, namely OM, CEC, TN, TS, AK, Cd, and Hg. The results, as shown in Table 8, indicate that TN, TS, and AK in the soil exhibited negative correlations with CG in the tea leaves, with correlation coefficients of −0.143, −0.058, and −0.647, respectively. Moreover, AK also showed a negative correlation with tea polyphenols (−0.227). Apart from these, other soil chemical properties components were positively correlated with the tea components. Notably, Cd in the soil was negatively correlated with tea polyphenols and CG, but positively correlated with the other tea components. The Hg was positively correlated with C and ECG, but negatively correlated with the other tea components. These findings provide new insights into how soil chemical properties can influence the quality of tea and offer a scientific basis for optimizing tea garden management to enhance the quality and safety of tea.

Table 8. Correlation analysis between tea and soil.

Tea Components	Soil Properties																			
	pH	**OM**	**CEC**	**TN**	**TK**	**TP**	**TS**	**AK**	**AN**	**AP**	**Mg**	**FL**	**Cd**	**Pb**	**Cr**	**Ni**	**Zn**	**Cu**	**As**	**Hg**
WE	0.712 **	−0.295	−0.103	0.068	0.270	−0.483	−0.190	0.620 *	−0.609 *	−0.343	0.557	0.414	0.558	0.183	−0.593 *	−0.060	0.664 *	−0.177	−0.355	0.537
TPL	−0.286	0.743 **	0.492	0.316	−0.843 **	0.918 **	0.301	−0.227	0.269	−0.313	−0.949 **	0.293	−0.052	−0.257	0.474	−0.564	−0.822 **	0.112	0.545	−0.961 **
AA	0.854 **	0.717 **	0.766 **	0.839 **	−0.710 **	0.254	0.532	0.864 **	−0.179	−0.979 **	−0.449	0.893 **	0.894 **	0.411	0.101	−0.506	0.206	0.351	0.528	−0.382
SS	0.863 **	0.763 **	0.861 **	0.946 **	−0.664 *	0.113	0.714 **	0.909 **	0.065	−0.913 **	−0.447	0.735 **	0.923 **	0.639 *	0.316	−0.278	0.338	0.589 *	0.690 *	−0.341
CA	−0.233	−0.990 **	−0.902 **	−0.811 **	0.941 **	−0.649 *	−0.750 **	−0.336	−0.424	0.658 *	0.940 **	−0.515	−0.454	−0.313	−0.685 *	0.386	0.344	−0.564	−0.886 **	0.868 **
FLA	0.967 **	0.423	0.541	0.678 *	−0.424	−0.026	0.332	0.935 **	−0.397	−0.904 **	−0.101	0.850 **	0.895 **	0.404	−0.175	−0.405	0.453	0.207	0.260	−0.036
PAR	−0.977 **	−0.187	−0.384	−0.561	0.135	0.321	−0.269	−0.941 **	0.383	0.726 **	−0.184	−0.674 *	−0.861 **	−0.504	0.246	0.156	−0.689 *	−0.213	−0.116	−0.244
C	0.865 **	0.059	0.166	0.325	−0.141	−0.127	−0.060	0.776 **	−0.700 *	−0.716 **	0.207	0.782 **	0.711 **	0.133	−0.547	−0.429	0.463	−0.160	−0.152	0.237
CG	−0.685 *	0.334	0.048	−0.143	−0.457	0.806 **	−0.058	−0.647 *	0.265	0.169	−0.670 *	−0.128	−0.450	−0.511	0.331	−0.360	−0.906 **	−0.159	0.196	−0.692 *
EC	0.857 **	0.639 *	0.669 *	0.751 **	−0.680 *	0.278	0.397	0.841 **	−0.330	−0.989 **	−0.393	0.938 **	0.852 **	0.293	−0.047	−0.596 *	0.176	0.208	0.403	−0.327
ECG	0.690 *	−0.346	−0.217	−0.035	0.251	−0.380	−0.353	0.566	−0.810 **	−0.387	0.565	0.494	0.452	−0.010	−0.776 **	−0.242	0.555	−0.372	−0.497	0.560
EGC	0.581 *	0.686 *	0.582 *	0.589 *	−0.831 **	0.623 *	0.230	0.550	−0.399	−0.934 **	−0.600 *	0.954 **	0.613 *	−0.054	−0.088	−0.849 **	−0.229	−0.015	0.339	-0.572
EGCG	−0.436	−0.982 **	−0.979 **	−0.938 **	0.867 **	−0.434	−0.870 **	−0.545	−0.460	0.725 **	0.824 **	−0.521	−0.634 *	−0.542	−0.712 **	0.248	0.080	−0.724 **	−0.946 **	0.730 **
GC	0.937 **	0.522	0.610 *	0.731 **	−0.527	0.087	0.384	0.917 **	−0.347	−0.945 **	−0.218	0.878 **	0.904 **	0.391	−0.101	−0.466	0.366	0.235	0.335	−0.142
GCG	0.200	0.743 **	0.838 **	0.794 **	−0.484	0.051	0.961 **	0.360	0.848 **	−0.279	−0.575	0.011	0.424	0.772 **	0.945 **	0.314	0.132	0.939 **	0.951 **	−0.475

Note: PAR—polyphenols/amino acids ratio. ** represents the correlation was significant at the 0.01 level ($p < 0.01$); * represents the correlation was significant at the 0.05 level ($p < 0.05$).

4. Discussion

Tea polyphenols, free amino acids, soluble sugars, and flavonoid glycosides are the principal biochemical constituents of tea. They are not only key to the flavor profile and health benefits of tea but also crucial indicators for assessing tea quality [44]. The growth of tea plants relies on fertile soil, which provides the essential material basis for the plants. The nutritional supply in the soil, especially the availability of carbon (C), nitrogen (N), and phosphorus (P), directly affects the tea plant's absorption and utilization efficiency of these nutrients, thereby determining the formation of the main quality components in tea [10,45,46]. Nutrients such as N, P, and sulfur (S) are crucial for the growth of tea plants and the formation of tea quality [47]. These elements directly affect the synthesis of biochemical components in tea by participating in the metabolic pathways of tea plants. For instance, nitrogen is an essential element for the biosynthesis of tea polyphenols [48], while phosphorus and sulfur are involved in energy metabolism and the synthesis of secondary metabolites [49].

Therefore, using Pearson correlation analysis to reveal the connection between soil properties components and tea quality components is of paramount importance for a profound understanding of the impact of soil on the formation of tea quality. The ideal pH range for tea garden soil is 4.5 to 5.5 [50], which is considered the optimal environment for the growth of tea plants. Research results indicate that the soil pH values in the study area ranged from 4.9 to 6.17, all of which are suitable for the growth of tea plants, but higher than those of other studied regions [27,28], a characteristic that may significantly affect the availability of phosphorus in our soil. The present work showed extremely low available phosphorus in soils. Previous studies have shown that under higher pH conditions, phosphorus is more likely to form insoluble phosphates with calcium and magnesium and other cations in the soil [51,52], thereby reducing the bioavailability of phosphorus, which requires timely attention in subsequent tea garden management.

Notably, the content of tea polyphenols was significantly positively correlated with OM and TP in the soil, indicating that the direct supply of these nutrients in the soil has a significant positive impact on the formation of tea polyphenols. Free amino acids, as key factors affecting the freshness of tea, directly influence the taste and overall quality of tea [53]; soluble sugars in tea, as important active components, possess functions such as reducing blood lipids and glucose, inflammation, and the effects of radiation. Free amino acids and soluble sugars are significantly positively correlated with OM, CEC, TN, TS, and AK. These factors play a crucial role in the formation of free amino acids and soluble sugars. These findings underscore the close link between the availability of soil nutrients and the content of tea plant quality components, providing a scientific basis for the management of tea garden soil and the enhancement of tea quality.

The primary secondary metabolites in tea are catechins, and relevant studies have indicated that the biosynthesis of catechins is a part of the C metabolism in tea plants [54]. An enhancement of soil carbon can stimulate the carbon metabolism of tea plants, thereby increasing the accumulation of catechins [55]. By conducting a correlation analysis using Pearson correlation coefficients, the connection between catechin components in tea and soil properties components was explored. The four significant catechin components selected, EC, EGC, GC, and GCG, were found to be positively correlated with soil properties components such as OM, CEC, TN, TS, and AK, with most showing significant positive correlations, with the exception of CG, which showed a negative correlation with TN, TS, and AK. This was consistent with the findings of researchers such as Yang et al. [56]. It suggests that the five property components in the soil are significant factors affecting the synthesis of catechins in the metabolic pathway, and the underlying mechanisms warrant further investigation.

Under heavy metal stress, plants exude a variety of low-molecular-weight compounds, such as amino acids, organic acids, sugars, phenolics, and other secondary metabolites [57]. Heavy metals in the soil, such as Cd and Hg, affect tea quality by disrupting the normal metabolic pathways of tea plants. The stress of heavy metals may lead to the production of more antioxidants, such as tea polyphenols, to combat the toxicity of heavy metals, but excessively high levels of heavy metals can also be toxic to tea plants, affecting the quality and safety of tea. Soil organic matter plays an essential role in the plant–soil system regarding the availability of heavy metals by inducing changes in soil physicochemical properties and through its metal chelation capacity [58,59]. The mobility and bioavailability of heavy metals like Cd, Cu, Pb, and Zn are modulated by the solubilizing action of OM and the concomitant formation of organometallic complexes [60]. Additionally, soil-borne heavy metals are critical determinants of the principal quality constituents in tea [61]. This study primarily focuses on the influence of Cd and Hg on the key quality components of tea, with Cd impacting the tea polyphenols and CG, and Hg affecting the concentrations of EC, GC, GCG, tea polyphenols, free amino acids, soluble sugars, and flavonoid glycosides. The underlying mechanisms of these interactions warrant further exploration. The research findings indicate variations in the extent of heavy metal contamination across the four research regions, with XC and BP exhibiting the highest levels of pollution. In the XC region, the risk of Cd contamination was considered moderate, while the other three regions were classified as low risk. In another study, Cd was identified as a primary source of pollution from phosphate fertilizers [62]. This could be attributed to the proximity of XC and BP to residential living areas.

Our research findings reveal a complex relationship between soil nutrients and tea quality. Wen and Liu et al. [63,64] reported positive correlations between soil N and P contents and the levels of tea polyphenols in tea leaves, but our results present a more nuanced picture. Specifically, we observed significant negative correlations between AP and the polyphenolic compounds EC, EGC, GC, and FLA, with no significant correlation between AP and TPL. For nitrogen, the relationships were more intricate, showing significant negative correlations between TN and EGCG, and AN and ECG, but positive correlations between TN and EC, EGC, GC, and GCG, and between AN and GCG. There were no significant correlations between TN and AN with TPL. Additionally, our study discovered a significant correlation between soil heavy metal contamination and tea quality parameters, a finding that echoes the results of Zhang et al. [65], both of which highlight the potential risks of soil heavy metal pollution to the quality and safety of tea. However, while our study explores the relationship between soil chemical properties and tea quality, it also considers the impact of soil heavy metal pollution, which has been less addressed in previous studies. Our results emphasize that in addition to focusing on the supply of soil nutrients in tea garden soil management, it is also necessary to pay attention to the control of heavy metal pollution to ensure the quality and safety of tea.

5. Conclusions

This study has unveiled the significant impact of soil properties on the formation of tea quality, identifying that OM, CEC, TN, TS, and AK significantly influence the content of key components in tea, such as free amino acids, tea polyphenols, caffeine, and catechins. An assessment of heavy metals in tea garden soils revealed that Hg has a particularly high pollution index, indicating a high to moderate ecological risk. Cd in the XC region is classified as a moderate risk. The PERI for the XC and BP regions suggests a moderate risk, while other regions are considered to be at low risk. Cd and Hg are likely the heavy metals that require the most monitoring, with BP and XC being more severely polluted due to their proximity to residential areas. The study also evaluated the soil IFI across four research regions, identifying OM, CEC, TN, TS, and AK as significant factors affecting soil fertility in local tea gardens. By properly controlling the supply of AN and OM, along with scientific fertilization and soil amelioration measures, soil fertility can be effectively enhanced, ensuring adequate supply of key nutrients, thereby promoting the improvement of tea quality. Monitoring and managing heavy metal content in the soil are also crucial for ensuring the safety and quality of tea. Future research should further explore the mechanisms of heavy metals in soil–plant systems and how to more effectively control heavy metal pollution through soil management measures to ensure the quality and safety of tea products. This will not only promote the sustainable development of the tea industry but also provide consumers with safer and higher-quality tea products.

While this study provides valuable insights into the relationship between soil properties and tea quality in ancient tea gardens, it is not without limitations. The sample size was restricted to specific regions in Yunnan, and the study did not account for soil physical and biological properties, which may also significantly influence tea quality. Future research should aim for a broader and more diverse sample set, and consider incorporating additional soil characteristics to enhance the comprehensiveness of the findings.

Author Contributions: All authors contributed to the study conception and design. The initial drafting of the paper, determination of physicochemical components, and data analysis were carried out by H.W. The preparation of materials and data collection were the responsibility of W.Y., Q.W. and Y.X. was in charge of the data analysis. The investigation was conducted by W.C., H.L. and G.P., W.H. and B.W. were responsible for manuscript review, editing, and grant application. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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