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Determination of Soil Fertility Characteristics and Heavy Metal Health Risks Using the *Camellia oleifera* Planting Base in Guizhou Province, China

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Abstract: To clarify the soil nutrient status and identify the safety risks of heavy metals in *Camellia oleifera* planting regions, the integrated soil fertility status was assessed using the improved Nemero composite index method, weighted average method, and coefficient of variation (CV) method, and the impact of heavy metals in the soil on human health was evaluated with a health risk assessment model using the Qianyu *C. oleifera* planting base in Yuping County, Guizhou Province, as the study object. The results showed the following: (1) The soil pH levels were 4.12–6.17, with CV values of 0.04–0.66, and no significant differences were observed among the plots. The soil was rich in organic matter, alkali-hydrolyzed nitrogen, and available phosphorus, with a high total potassium content, total phosphorus content, and rapidly available potassium, indicating a high level of comprehensive soil fertility. (2) The total carcinogenic risk (CR) index of the arsenic (As), cadmium (Cd), and chromium (Cr) in the soil was 1.92×10^{-7}, and among these elements, the CR index of the As was the highest ($1.3–8.0 \times 10^{-7}$), but all were below the highest acceptable level (10^{-6}) recommended by the United States Environmental Protection Agency (USEPA). (3) The redundancy analysis (RDA) between the soil fertility and trace elements revealed that the soil organic matter content was positively correlated with the contents of lead (Pb), manganese (Mn), and Cr and negatively correlated with the contents of zinc (Zn), iron (Fe), Cd, mercury (Hg), As, and copper (Cu). The soil pH was positively correlated with the contents of Cr, Fe, and Cu and negatively correlated with the contents of Mn, Pb, Zn, Cd, Hg, and As. In the study area, the soil was slightly acidic with overall high fertility without any CR. The quality of the *C. oleifera* was degraded by soil acidification, but the slightly acidic soil facilitated the absorption of trace elements by *C. oleifera*. Soil acidification could be relieved by taking appropriate measures, such as the addition of biochar or $CaCO_3$. This study determined the soil fertility of the Qianyu *C. oleifera* planting base and assessed the health risk of heavy metals in the soil, providing a theoretical reference for enhancing *C. oleifera* quality, preventing the excessive accumulation of soil heavy metals, and improving the soil in this planting base.

Keywords: *Camellia oleifera*; soil fertility; Nemero composite index method; heavy metal; health risk assessment

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1. Introduction

The increasingly severe heavy metal pollution of soils in recent years is a serious threat to plant growth. Because they are nondegradable, heavy metals in soils have been described as "chemical time bombs" that can lead to long-term irreversible soil pollution [1], and this has recently become an active area of research in the planting industry [2,3]. Soil-derived factors limiting plant growth and development can be identified by evaluating comprehensive soil fertility and health risks. Moreover, such research is conducive to reasonable soil improvements and can indirectly prevent plants from triggering carcinogenic risks (CRs) to humans via food chains [4]. At present, the main health risk assessment methods for soil heavy metals include the single-factor quality index method [5], improved Nemero composite index method [6], geometric mean-based composite assessment model, and fuzzy mathematical method [7].

China has the largest *C. oleifera* planting area in the world. The healthy and sustainable development of this industry can be enhanced by investigating the soil fertility of the tea grove and assessing the health risks of the heavy metals present in the soils. Yuping County in Guizhou Province, which is one of the main regions that produce *C. oleifera*, has a reputation as being the home of *C. oleifera* in China. In 2020, the total planting area of *C. oleifera* reached approximately 14,667 acres in Yuping County, and with 10,267 acres in production, the annual output was 16,000 tons of fresh *C. oleifera* fruit and 4000 tons of *C. oleifera* seeds, which were converted into an annual output of 1000 tons of *C. oleifera* oil and an output value of RMB 200,000,000. However, this *C. oleifera* planting base is subject to a variety of problems, e.g., an unstable yield of tea oil, no scientific evaluations of the soil's texture, and deficient breeding for improved varieties, all of which restrict the high quality and sustainable development of this industry. Appropriate soil conditions are necessary for producing high-quality *C. oleifera*. A critical factor affecting the fruiting rate of *C. oleifera* and the quality of the tea oil is the soil's fertility. Moreover, healthy soil is the basis for the development of high-quality *C. oleifera*. However, few studies have been conducted regarding the status of the soil's fertility and heavy metal risks in this planting base. In this study, therefore, weighted values were calculated using the correlation analysis method and the coefficient of variation (CV) method. Next, the soil fertility characteristics and content differences in the planting base were analyzed using the improved Nemero composite index method. Simultaneously, the health risks of the soil's heavy metals were assessed in an effort to evaluate the soil nutrient status and identify the safety risks related to the heavy metals in the planting base. Moreover, the soil fertility status and heavy metal contents in the *C. oleifera* grove were analyzed, and the health risks of the soil's heavy metals were assessed. Thus, the soil fertility characteristics and potential heavy metal risks were determined, generating a theoretical basis for the scientific improvement of soil properties in the *C. oleifera* grove and its reasonable operation. This study will provide considerable guiding significance for the sustainable development of the *C. oleifera* industry.

2. Materials and Methods

2.1. Overview of the Study Area

Guizhou Yuping Dong Autonomous County is located at 108°34′–109°09′ E and 27°28′–27°31′ N. Yuping County is adjacent to Xinhuang, Hunan Province, in the southeast, and it is adjacent to Zhenyuan and Cengong in the west and borders Tongren City and Wanshan Special District in the north, with an east–west distance of 36 km, a south–north distance of 42 km, and a total area of 523.78 km^2. With a subtropical monsoon humid climate, Yuping County is free from the excessive cold of winter and intense heat of summer, and it has abundant rainfall, with heat and precipitation accumulating during the same period. In addition, the annual average relative humidity, annual precipitation, and annual sunlight hours are 79%, 1174.1 mm, and 1206.7 h, respectively. Yuping County is located in the transitional zone between the Yunnan-Guizhou Plateau to the hills in western Hunan and consists of flat lands between low mountains and hills, with a typical elevation of 400–600 m. The study area is located within the *C. oleifera* planting base in Yuping County in the transitional zone from the Yunnan-Guizhou Plateau to the hills of western Hunan (Figure 1).

In addition, according to the first edition of the World Reference Base for Soil Resources (WRB), which was officially adopted by the International Union of Soil Science (IUSS) in 2001, we classified soil types within the site (Figure 1).

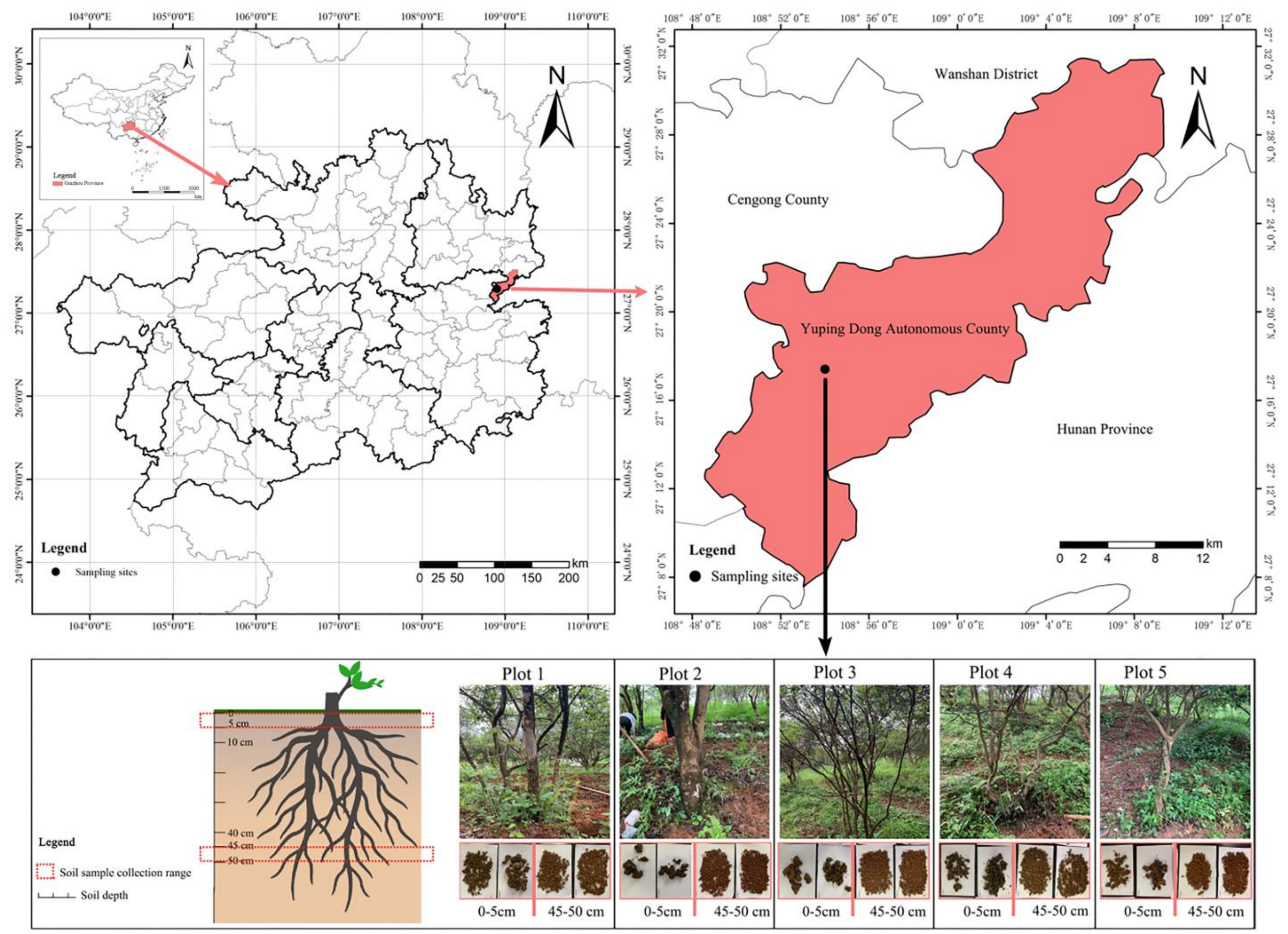

Figure 1. Detailed schematic diagram of the sample plots.

2.2. Sample Plots and Determination of Related Indexes

Referring to the standards of the State Environmental Protection Administration of China [8], the five-point sampling method was used for the soil sampling. A 40 m × 40 m sample was set up in the study area, and 51 m × 1 m sample points were set up at the 4 corners and in the middle of the sample for sampling. In each sample point, 2 soil samples were collected at depths of 0–5 cm, and 2 samples were collected at depths of 45–50 cm. A total of 20 clean samples (1 kg) were collected and numbered from the 5 plots, and the GPS coordinates of the sample plots were recorded (Table 1 and Figure 1). The following 8 physiochemical indexes were determined in this study: alkali-hydrolyzed nitrogen, organic matter, total nitrogen, available phosphorus, total phosphorus, rapidly available potassium, total potassium, and pH. For both determination and digestion, a standard addition test and a blank control trial were conducted. All volumetric flasks and beakers were soaked in a 5% (v/v) nitric acid solution for over 48 h. The physiochemical indexes of the soils were determined by methods referenced in the literature [9,10]. Specifically, the total quantities of lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) were determined through digestion with HNO_3-$HClO_4$-HF (3:1:1, V-V), and the total quantities of mercury (Hg) and arsenic (As) were detected through digestion with HNO_3-HCl (1:3, V-V). The concentrations of Pb, Cd, Cu, and Zn in the soil samples were measured via inductively coupled plasma-atomic emission spectrometry (ICP-AES). The contents of Hg and As were determined using an atomic fluorescence spectrophotometer (AFS-2100, Beijing Haiguang). Based on the soil distribution characteristics of Guizhou Province, carbonate, ferric oxide/manganite, organic matter-binding heavy metals, and heavy metal residues were extracted using methods referenced in the literature in accordance with the China Standard Substance in Soil [GBW07408 (GSS-8) [11]. A blank control and three repeated experiments were used to guarantee the method's precision. The accuracy and precision of the material testing methods and results were examined by referring to a certification standard purchased from the State Bureau of Quality and Technical Supervision. Recycling research was performed using certified standard reference materials, and the recovery rate of the heavy metals in the soil samples was 93.2% (reference value: 103.6%). The linear correlation coefficients of all heavy metals were greater than 0.999, with the relative standard deviations (*n* = 3) ranging from 1.0% to 6.2%. The soil nutrient contents were divided into six levels: extremely abundant, abundant, ideal, appropriate, deficient, and extremely deficient, as well as into three levels (high, medium, and low). The statistics, evaluation, and analysis of the soil's nutrient status were conducted by referring to the grading standard in the second national soil survey and the second Guizhou provincial soil survey [12,13].

Table 1. Information about the soil sample plots.

Sample Plot	Sample No.	Sampling Depths (cm)	Altitude (m)	Longitude and Latitude
1	1-A-1	0–5	527.987 ± 5.9	108.90 E, 27.29 N
	1-A-2	0–5	527.987 ± 5.9	108.90 E, 27.29 N
	1-B-1	45–50	527.987 ± 5.9	108.90 E,27.29 N
	1-B-2	45–50	527.987 ± 5.9	108.90 E, 27.29 N
2	2-A-1	0–5	528.478 ± 9.6	108.90 E, 27.29 N
	2-A-2	0–5	528.478 ± 9.6	108.90 E, 27.29 N
	2-B-1	45–50	528.478 ± 9.6	108.90 E, 27.29 N
	2-B-2	45–50	528.478 ± 9.6	108.90 E,27.29 N
3	3-A-1	0–5	527.103 ± 10.4	108.90 E, 27.29 N
	3-A-2	0–5	527.103 ± 10.4	108.90 E, 27.29 N
	3-B-1	45–50	527.103 ± 10.4	108.90 E, 27.29 N
	3-B-2	45–50	527.103 ± 10.4	108.90 E, 27.29 N
4	4-A-1	0–5	708.457 ± 4.0	108.72 E, 27.79 N
	4-A-2	0–5	708.457 ± 4.0	108.72 E, 27.79 N
	4-B-1	45–50	708.457 ± 4.0	108.72 E, 27.79 N
	4-B-2	45–50	708.457 ± 4.0	108.72 E, 27.79 N
5	5-A-1	0–5	527.987 ± 5.13	108.72 E, 27.79 N
	5-A-2	0–5	527.987 ± 5.13	108.72 E, 27.79 N
	5-B-1	45–50	527.987 ± 5.13	108.72 E, 27.79 N
	5-B-2	45–50	527.987 ± 5.13	108.72 E, 27.79 N

2.3. Evaluation Method for the Comprehensive Soil Fertility Index

The data were standardized before calculating the comprehensive soil fertility index. In this study, the soil fertility indicators (i.e., organic matter, alkali-hydrolyzed nitrogen, total nitrogen, available phosphorus, total phosphorus, rapidly available potassium, total potassium, and pH) were calculated with membership functions. The correlation analysis method, CV method, and weighted average method were then combined to calculate the weights of the soil fertility factors, which avoided the problem of poor comparability that is associated with common methods such as the standardization of the mean, range, standard deviation, and initial value, as follows:

$$q_i = \begin{cases} \frac{c_i}{c_s c_i} \leq x_a \\ 1 + \frac{(c_i - x_a)}{(x_c - x_a)x_a} < c_i \leq x_c \\ 2 + \frac{(c_i - x_c)}{(x_p - x_c)x_c} < c_i < x_p \\ 3c_i \geq x_p \end{cases}, \quad (1)$$

$$W_i = \frac{\frac{c_i}{s_i}}{\sum_{i=1}^{n} \frac{c_i}{s_i}}, \quad (2)$$

$$P = \sqrt{\frac{(P_{iaver})^2 + (P_{imin})^2}{2}} \times \frac{(n-1)}{n}, \text{ and} \tag{3}$$

$$P_i = q_i \times W_i \times n, \tag{4}$$

where q_i, c_i, and x_i represent the soil fertility index, the measured value of the soil nutrient index, and the classification index, respectively. The national soil survey standard was used to grade the standards of the soil property values (x_a, x_c, and x_p). The variables W_i, n, and C_i represent the weight of factor i, the number of participatory evaluation factors, and the measured values of the participatory evaluation factors, respectively. S_i denotes the mean value of the total sum of the grading standards for the soil properties corresponding to factor i, as follows: $S_i = (x_a + x_c + x_p)/3$. The variables P, P_{iaver}, P_{imin}, W, and n are the comprehensive soil fertility index, the mean value of the single soil fertility index coefficients, the minimum value among the single fertility coefficients, the weight of the soil fertility factor i, and the number of participatory evaluation factors, respectively. The grading standard for the soil fertility was described as follows: very fertile ($P \geq 2.12$), fertile ($1.42 < P < 2.12$), ordinary ($0.72 < P < 1.24$), infertile ($0.47 < P < 0.72$), and extremely infertile ($P \leq 0.47$).

2.4. Health Risk Assessment Method for the Heavy Metals

In this study, the risks posed by the soil's heavy metals on human health were assessed using the health risk assessment model developed by the United States Environmental Protection Agency (USEPA). The non-CR index (hazard index, *HI*) is a noncarcinogenic substance prediction model proposed by the USEPA that is specific to the health risk assessment criteria for chemical element mixtures [14]. The *HI* consists of the hazard quotient (*HQ*) and chronic daily ingestion (*CDI*), which are expressed by the following formulas:

$$CDI = \frac{CF \times IR \times EF \times ED}{BW \times AT}, \tag{5}$$

$$HQ = \frac{CDI}{RfD_o}, \text{ and} \tag{6}$$

$$HI = \sum HQ, \tag{7}$$

where *CDI* is the quantity of a substance for which a unit of weight is exposed for a unit of time (mg/kg/d), *CF* denotes the heavy metal contents in the plants (mg/kg), and the variables *IR*, *EF*, *ED*, *BW*, and *AT* represent the unit of ingestion (kg/d), exposure frequency (365 d/year), exposure duration (70 years for adults and 6 years for children), average body weight (61.6 kg for adults and 18.6 kg for children), and noncarcinogenic average exposure duration ($ED \times 365$ d/year), respectively. *HQ* is the calculated result of the non-CR of a single heavy metal, and the potential exposure is based on the proportion of substances and the expected degree of influence. If the *HQ* value is less than 1, it is estimated that the contact was subjected to no potential risk. RfD_o represents the reference dose (0.0003, 0.0371, and 0.3 mg/kg/d for Hg, Cu, and Zn, respectively). If $HI > 1$, potential impacts are posed to human health, and there is no potential risk when $HI < 1$ [15]. In this study, a health risk assessment model developed by the USEPA was used to assess the effects of heavy metal exposure from soil and on human health. *TCR* is the total carcinogenic risk index of the carcinogenic heavy metals through the three pathways. *CR* is a single health risk index for carcinogenic heavy metals. In general, it is acceptable if *CR* and *TCR* values are less than 10^{-6}. The CR triggered by each exposure to heavy metals could be estimated by the method in [16], as follows:

$$CR = CDI \times SF \tag{8}$$

and

$$TCR = \sum CR, \quad (9)$$

where SF stands for the cancer slope factors (mg/kg/d), which are 0.0085, 6.3, and 1.5 mg/kg/d for Pb, Cd, and As, respectively. If $TCR < 1 \times 10^{-6}$, the impact is negligible, but human health will be significantly impacted when $TCR > 1 \times 10^{-4}$. If $1 \times 10^{-4} > TCR > 1 \times 10^{-6}$, then the CR of heavy metals is within an acceptable range [17]. The definition and value of the parameters are listed in Tables 2–4. The formulas are summarized in Table 2.

Table 2. Formulas for the health risk assessment models.

Exposure Pathway	Formula
Soil ingestion ($CDI_{ingetstion-soil}$)	$CDI_{ingestion-soil} = \frac{C_i \times IR_{soil} \times CF \times EF \times ED}{BW \times AT}$
Skin contact ($CDI_{demal-soil}$)	$CDI_{dermal-soil} = \frac{C_i \times CF \times SA \times AF \times ABS_d \times EF \times ED}{BW \times AT}$
Soil inhalation ($CDI_{inhale-soil}$)	$CDI_{inhale-soil} = \frac{C_i \times IR_{air} \times EF \times ED}{BW \times AT \times PEF}$
Eating crops ($CDI_{inhale-soil}$)	$CDI_{inhale-soil} = \frac{C_i \times IR_{crop} \times EF \times ED}{BW \times AT}$
CR	$CR = CDI \times SF$ $TCR = \sum CR$
Non-CR	$HQ = \frac{CDI}{RfD_o}$ $HI = \sum HQ$

Table 3. Exposure parameters in the health risk assessment.

Variable	Definition	Adults	Children	Citation
BW	Weight/kg	56.8	19.2	[17]
IR_{soil}	Soil ingestion rate/(mg/d)	100	200	[17]
IR_{air}	Soil inhalation rate/(m^3/d)	20	10	[17]
IR_{crop}	Crop ingestion rate/(g/d)	301.4	231.5	[18]
ED	Exposure time/a	25	6	[19]
EF	Exposure frequency/(d/a)	350	350	[19]
AF	Soil adhesion factor to skin/(mg·cm^2)	0.07	0.2	[19]
CF	Conversion factor/(kg/mg)	10^{-6}	10^{-6}	[19]
SA	Skin region to contact soil/(cm^2/d)	5700	2800	[17]
PEF	Particle emission factor/(m^3/kg)	1.13×10^9	1.13×10^9	[17]
$ABSd$	Dermal absorption factor	0.001	0.001	[17]
AT	Average time (CR)/d	70 × 365	70 × 365	[19]
	Average time (non-CR)/d	ED × 365	ED × 365	[19]

Table 4. RfD and SF values of the model's parameters.

Route	Variable	Cd	Cu	Hg	Zn	Pb	As	Cr
Skin contact	RfD	1×10^{-3}	1.9×10^{-3}	2.10×10^{-5}	6.00×10^{-3}	3.52×10^{-3}	3.00×10^{-4}	7.5×10^{-5}
	SF	6.1					1.5	2.0
Soil ingestion	RfD	1×10^{-3}	3.7×10^{-2}	3.00×10^{-3}	3.0×10^{-1}	3.50×10^{-3}	3.00×10^{-4}	3.0×10^{-3}
	SF	6.1					1.5	20
Soil inhalation	RfD	1×10^{-3}	4.2×10^{-2}	8.57×10^{-5}	3.0×10^{-1}	5.25×10^{-3}	1.23×10^{-4}	2.55×10^{-5}

3. Results and Analysis

3.1. Contents of the Soil Physiochemical Indexes

The five sample plots had pH values of between 4.12 and 6.17, high total nitrogen contents (0.85–1.89 mg/kg) with low variability, and average organic contents of 20.56 g/kg, 21.75 g/kg, 22.06 g/kg, 24.53 g/kg, and 21.20 g/kg, respectively. In addition, the plots were relatively rich (at the ideal and medium levels) in organic matter, alkali-hydrolyzed nitrogen, and available phosphorus. The total potassium, total phosphorus, and rapidly available potassium were all at medium to high levels and were favorable for plant growth. These results revealed that this soil has high fertility and promotes the growth of *C. oleifera*. The soil physiochemical properties are listed in Table 5.

Table 5. Contents of the soil's physiochemical indexes.

Plot	Statistic	Organic Matter (g/kg)	Alkali-Hydrolyzed Nitrogen (mg/kg)	Total Nitrogen (g/kg)	Available Phosphorus (mg/kg)	Total Phosphorus (g/kg)	Rapidly Available Potassium (mg/kg)	Total Potassium (g/kg)	pH
Plot 1	Mean	20.56	95.16	1.08	17.04	2.30	98.48	50.75	5.15
	CV	4.41	5.39	0.18	2.54	0.28	4.50	6.26	0.04
	Maximum	27.03	102.19	1.25	19.28	2.71	102.56	57.28	5.18
	Minimum	17.34	89.06	0.85	14.49	2.08	94.45	42.80	5.10
Plot 2	Mean	21.75	96.44	1.50	16.19	3.07	103.00	48.12	4.70
	CV	4.01	6.94	0.17	2.45	0.31	15.53	4.25	0.62
	Maximum	25.73	101.18	1.74	18.50	3.41	120.87	52.14	5.47
	Minimum	17.60	86.25	1.35	13.28	2.71	89.40	42.73	4.12
Plot 3	Mean	22.06	91.27	1.43	14.73	2.78	97.90	53.68	4.73
	CV	3.81	8.79	0.06	1.89	0.39	2.15	4.53	0.31
	Maximum	26.61	101.89	1.47	17.28	3.12	101.09	58.25	5.05
	Minimum	18.16	82.77	1.34	13.18	2.22	96.49	47.72	4.38
Plot 4	Mean	24.53	88.68	1.54	16.86	3.01	107.17	53.20	4.93
	CV	3.61	3.86	0.26	2.03	0.13	4.08	8.22	0.61
	Maximum	27.78	92.23	1.89	18.83	3.18	111.74	61.36	5.72
	Minimum	19.45	85.17	1.28	14.17	2.90	101.89	42.16	4.29
Plot 5	Mean	21.20	84.84	1.35	15.61	2.86	108.87	53.95	5.37
	CV	5.98	4.51	0.17	5.04	0.07	9.25	4.93	0.66
	Maximum	27.28	91.59	1.48	20.28	2.93	115.01	59.72	6.17
	Minimum	15.74	82.36	1.12	10.16	2.78	95.37	47.69	4.62

3.2. Weights of the Soil Fertility Factors and the Soil Fertility Assessment

As shown in Figure 2a, the total potassium and total phosphorus were present in the highest proportions. Specifically, the total potassium was the most heavily weighted factor, whereas the available nitrogen and pH had the lowest weights. The results of the CV method showed that among the five sample plots, plot 2 had the greatest variability in available potassium, followed by the variability in alkali-hydrolyzed nitrogen in plot 3. Overall, the total nitrogen, total phosphorus, and pH showed little variation.

Based on the weighted average values and the CV shown in Figure 2b, the base had relatively high soil fertility. The q_i values of each index in the five plots are listed in Table 6.

Table 6. The q_i values of each index in the five plots.

Plot	Organic Matter	Alkali-Hydrolyzed Nitrogen (mg/kg)	Total Nitrogen	Available Phosphorus	Total Phosphorus	Rapidly Available Potassium	Total Potassium
Plot 1	2.06	2.09	2.17	2.70	3.00	1.97	3.00
Plot 2	2.18	2.11	3.00	2.62	3.00	2.06	3.00
Plot 3	2.21	2.02	2.85	2.47	3.00	1.96	3.00
Plot 4	2.45	1.96	3.00	2.69	3.00	2.14	3.00
Plot 5	2.12	1.83	2.69	2.56	3.00	2.18	3.00

As shown in Table 7, all the soil fertility index values of the base obtained from the correlation analysis method, the weighted average method, and the CV method, as well as the weighted average of the three methods, were relatively stable. Moreover, the comprehensive soil fertility index values of the five sample plots showed no large differences and were similar to the weighted average of the three methods. Overall, the soils from each sample plot were fertile. Specifically, the comprehensive soil fertility index values of the base of the *C. oleifera* grove obtained with the CV method, the correlation coefficient method, the weighted average method, and the weighted average of the three methods were 1.84, 1.76, 1.42, and 1.67, respectively. The soil fertility evaluation indicated that the soil was fertile (Table 8).

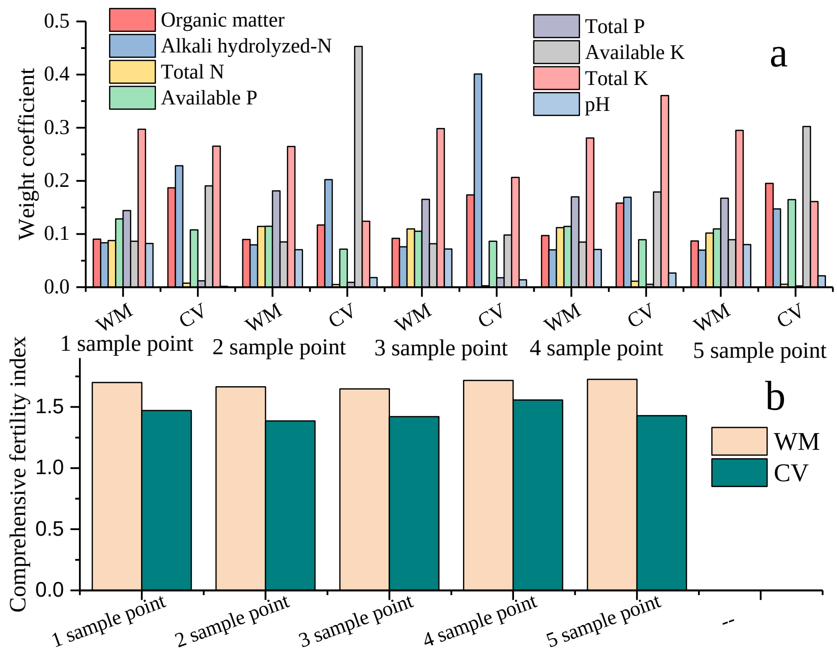

Figure 2. Weighted average coefficients and the comprehensive soil fertility index in the five sample plots. Note: (**a**) weight coefficient, and (**b**) comprehensive soil fertility index.

Table 7. Comprehensive soil fertility index for each plot.

Plot	Correlation Analysis Method	Weighted Average Method	CV Method	Weighted Average of the Three Methods	Soil Fertility Evaluation
Plot 1	1.80	1.77	1.44	1.44	Fertile
Plot 2	1.88	1.81	1.37	1.69	Fertile
Plot 3	1.82	1.77	1.40	1.66	Fertile
Plot 4	1.85	1.78	1.54	1.72	Fertile
Plot 5	1.75	1.72	1.41	1.62	Fertile

Table 8. Comprehensive soil fertility index for the Qianyu *C. oleifera* base.

	CV Method	Correlation Analysis Method	Weighted Average Method	Weighted Average of the Three Methods	Soil Fertility Evaluation
Soil of *C. oleifera*	1.84	1.76	1.42	1.67	Fertile

3.3. Health Risk Assessment of the Soil's Heavy Metals

3.3.1. Heavy Metal Contents in the Soil and the Assessment of Potential Risks

As shown in Figure 3, the Cu, As, Pb, and Cr contents were lower than the national threshold. The Zn content was high but within the standard range. In addition, the Cd contents in the soil were 0.18 ± 0.01 mg/kg, with a maximum value of 0.21 mg/kg, whereas the Hg contents were 0.13 ± 0.02 mg/kg, which was lower than the national threshold. Overall, the contents of the heavy metals in the base soil were lower than the national thresholds (GB 156182008).

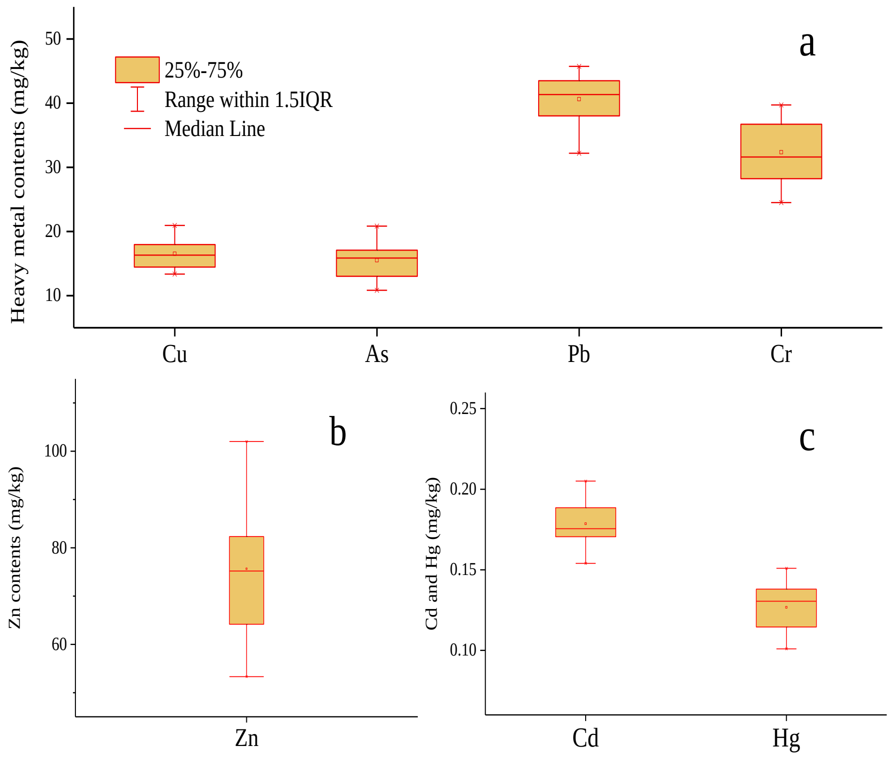

Figure 3. Boxplots of the heavy metal contents in the soil of the Qianyu *C. oleifera* base. Note: (**a**) Cu\As\Pb\Cr contents, (**b**) Zn content, and (**c**) Cd\Hg contents.

3.3.2. Non-CR Assessment

Based on the comparison of the single non-CR index HQ and the total non-CR index HI of the heavy metals present in adults and children exposed to oral, dermal, and respiratory contact, as shown in Table 9, plot 2 had HI values greater than 1 among the children, suggesting a greater risk of carcinogenic harm to children from the heavy metals. In contrast, the HI values of plot 1 and plot 4 among the children were close to 1, indicating a risk of harm to children's health from these two plots, as well. The overall HI values revealed essentially no CR for adults.

Table 9. Results of the non-CR index HQ and the total non-CR index HI.

Sample Plot	Age	HQ							HI
		As	Cd	Cr	Cu	Ni	Pb	Zn	
1	Adult	8.4×10^{-3}	2.84×10^{-5}	1.18×10^{-3}	7.96×10^{-5}	5.5×10^{-3}	1.9×10^{-3}	4.0×10^{-3}	0.017
	Children	0.0500	1.68×10^{-4}	6.8×10^{-3}	4.6×10^{-4}	0.029	0.011	2.3×10^{-4}	0.098
2	Adult	0.0100	3.16×10^{-5}	1.1×10^{-3}	7.6×10^{-5}	5.6×10^{-4}	2.1×10^{-3}	4.9×10^{-5}	0.018
	Children	0.0560	1.9×10^{-4}	6.2×10^{-3}	4.3×10^{-4}	0.030	0.012	2.8×10^{-4}	1.010
3	Adult	0.0087	3.3×10^{-5}	1.2×10^{-3}	7.8×10^{-5}	3.1×10^{-3}	2.0×10^{-3}	4.6×10^{-5}	0.150
	Children	0.0510	1.9×10^{-4}	7.0×10^{-3}	4.5×10^{-4}	0.016	0.011	2.7×10^{-4}	0.087
4	Adult	0.0081	2.9×10^{-5}	1.2×10^{-3}	9.4×10^{-5}	4.5×10^{-3}	2.1×10^{-3}	4.6×10^{-5}	0.016
	Children	0.0480	1.7×10^{-4}	7.0×10^{-3}	5.4×10^{-4}	0.024	0.012	2.7×10^{-4}	0.092
5	Adult	0.0090	3.0×10^{-5}	1.3×10^{-3}	8.3×10^{-3}	2.6×10^{-3}	1.8×10^{-3}	3.7×10^{-5}	0.015
	Children	0.0530	1.8×10^{-4}	7.2×10^{-3}	4.8×10^{-4}	0.014	0.011	2.2×10^{-4}	0.086

3.3.3. CR Assessment

The single CR indexes and the TCR indexes of the As, Cd, and Cr in the soil for adults and children are listed in Table 10. For both adults and children, the values of the CR index and the TCR indexes of As, Cd, and Cr in the base soil, which were obtained through the analysis of the risks of carcinogenic heavy metals to human health, were all lower than the highest acceptable level (10^{-6}) recommended by the USEPA [20].

Table 10. Results of the single CR indexes and the TCR indexes.

Sample Plot	Age	CR			TCR
		As	**Cd**	**Cr**	
1	Adult	1.3×10^{-7}	1.7×10^{-9}	1.2×10^{-8}	1.4×10^{-7}
	Children	7.5×10^{-7}	1.0×10^{-8}	6.8×10^{-8}	8.3×10^{-7}
2	Adult	1.4×10^{-7}	1.9×10^{-9}	1.1×10^{-8}	1.5×10^{-7}
	Children	8.4×10^{-7}	1.1×10^{-8}	6.2×10^{-8}	9.2×10^{-7}
3	Adult	1.3×10^{-7}	2.0×10^{-9}	1.2×10^{-8}	1.4×10^{-7}
	Children	7.7×10^{-7}	1.2×10^{-8}	6.9×10^{-8}	8.5×10^{-7}
4	Adult	1.2×10^{-7}	1.7×10^{-9}	1.2×10^{-8}	1.4×10^{-7}
	Children	7.2×10^{-7}	1.0×10^{-8}	7.0×10^{-8}	8.0×10^{-7}
5	Adult	1.4×10^{-7}	1.8×10^{-9}	1.3×10^{-8}	1.5×10^{-7}
	Children	8.0×10^{-7}	1.1×10^{-8}	7.3×10^{-8}	8.9×10^{-7}

3.3.4. Correlation Analysis of the Soil Fertility and Trace Elements

Based on the interpretation ratios of the first and second axes at 33.5% and 24.3%, respectively, the first two sequential axes of the 15 (soil plus trace elements) indicators explained 57.8% of the variation in the soil and the contents of the trace elements in the soil (Figure 4), which contained available information about the soil's environment and the trace elements therein. This figure also presents the correlations between the following factors: the positive correlations for the soil organic matter with Pb, Mn, and Cr, and the negative correlations for the soil organic matter with Zn, Fe, Cd, Hg, As, and Cu.

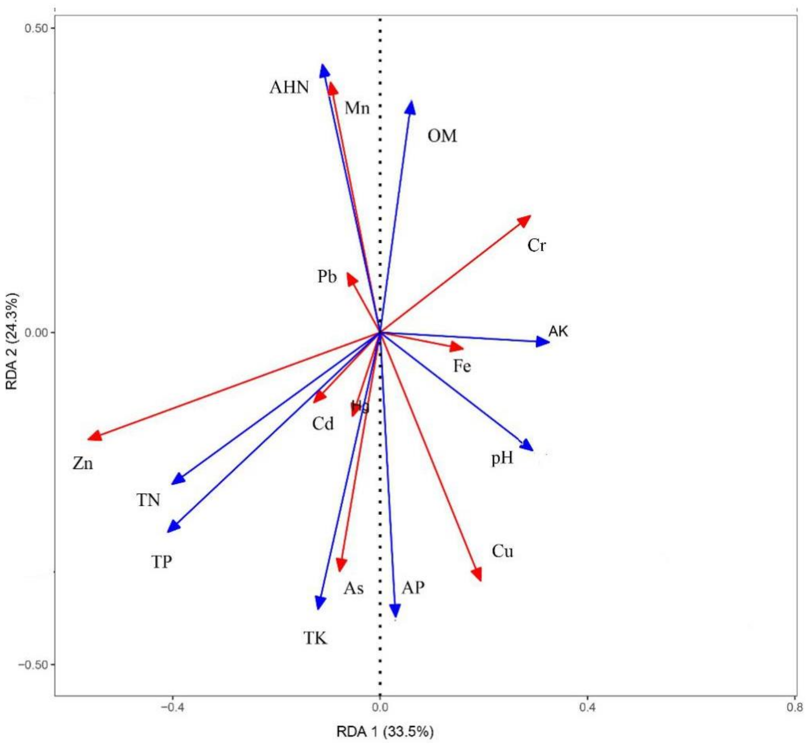

Figure 4. RDA between the soil fertility and the various trace elements in soil of the *C. oleifera* base.

4. Discussion

4.1. Soil Physiochemical Properties and Status of Soil Fertility

As has been demonstrated by extensive research, although *C. oleifera* has strong adaptability, good tolerance, and low requirements for its growth environment, the most suitable pH value of the soil is between 5 and 6. In particular, acidic or slightly acidic soil (i.e., 4.5–6.5) is favorable for the growth of *C. oleifera*. Our studies showed that the pH values of the soil ranged from 4.12 to 6.17, and overall, the soil was acidic in the Qianyu *C. oleifera* base. The total nitrogen content and alkali-hydrolyzed nitrogen were at high and medium levels, respectively. These contents are greatly affected by fertilization, and inappropriate fertilization may be mainly responsible for the high soil nitrogen contents in the base. Attention should be given to the balance between nitrogen preservation and supply. Specifically, an excessively high concentration of total nitrogen will make plants prone to falling and insect-induced damage. In addition, the base had medium mean contents of soil organic matter and nitrogen, and the soil organic matter may primarily have come from artificial applications of organic fertilizers, ground vegetation debris, and necrotic roots. Similarly, the contents of total phosphorus and rapidly available phosphorus in the base were at medium levels, as well. This sufficient phosphorus content may be attributed to fertilization. As described in the literature [21], organic fertilizers can activate soil phosphorus and reduce phosphorus adsorption by decomposing to generate organic acids and cover adsorption sites with carbohydrates, respectively. The contents of total potassium and rapidly available potassium are relatively low in most tropical and subtropical acidic soils. It was estimated that no less than one-third of the soil was subject to a potassium deficiency given the current yield. After the application of nitrogen fertilizers, yields increase, accelerating the consumption of other nutrients and then exacerbating the crop production problems that result from the low level of rapidly available potassium in the soil. For these reasons, it is essential to control the use of organic fertilizers within an appropriate range.

Based on the assessment results obtained using the improved Nemero composite index method, the weighted average method, and the CV method, the soil of the Qianyu *C. oleifera* base was relatively fertile. Soil fertility is mainly affected by total potassium contents. Moreover, the comprehensive soil fertility index of 1.44–1.72 indicated high fertility, suggesting that the soil was relatively suitable for planting *C. oleifera*. These values were all higher than those observed in previous studies [22–24].

4.2. Risk Assessment of the Heavy Metals in the Soil

In assessing the quality and safety of *C. oleifera*, the heavy metals content is a crucial indicator. The accumulation of heavy metals causes soil pollution, hinders the growth and development of *C. oleifera*, and threatens human health. However, the pollution of *C. oleifera* by heavy metals in soils has been rarely reported. In the present research, the CR indexes of the As, Cd, and Cr in the base were below the highest acceptable levels (10^{-6}) designated by the USEPA. Based on the results of the non-CR assessment, the overall HI value of the base showed no CR to adults but potential risks to children. Despite the insignificant influence of exposure to heavy metals in the soil of the Qianyu *C. oleifera* base on human health, importance should still be attached to the potential hazards of As and Hg.

4.3. Intrinsic Relationships between Soil Fertility and Trace Elements

Soil fertility and trace elements are inseparable. Major organic compounds such as carboxyls, hydroxyls, carbon, phenolic hydroxyls, methoxys, aldehydes, and ether amines in soil can produce high reactivity, thus reducing the toxicity of harmful substances through frequent interactions with metal ions in the environment. Most heavy metals exhibit low contents in soils because the chelates produced by the interactions between heavy metals and organic matter can be better absorbed by plants [25]. The organic matter of the soil in the base was negatively correlated with most heavy metals, whereas the soil's pH was positively correlated with Cr, Fe, Cu, As, Hg, and Cd and negatively correlated with Mn, Pb, and Zn, which was consistent with the results of previous studies [26]. In the present research, pH was significantly negatively correlated with the concentrations of exchangeable Cd, Zn, and Pb in the soil, whereas it was positively correlated with the Zn in the iron and manganese oxidation state and the Zn bound to organic matter; with the Cd, Zn, and Pb bound to carbonate and organic matter in the iron manganese oxidation state; and with the residual Cd, Zn, and Pb in the soil. Moreover, the availability of Cd is regulated by soil pH, to a large extent, and it will decrease with increases in soil pH, hindering its absorption by plants. Moreover, Cd in soil is easily absorbed by plants, and when pH values are lower, Cd contents in soil will be lower, showing a positive correlation between the two. In weakly acidic to alkali soil, the pH values mainly exist in the form of the residue state, iron and manganese oxidation states, and other stable states, whereas the ion exchange state can be less than 2%, which only results in minimal harm to an ecosystem. Additionally, the proportion of exchanged Pb ions in the total amount exhibits a linear increase with soil acidity, and it reaches approximately 20% at a pH of 5. The Fe transformation in soil mainly depends on the conditions of the environment in which the soil is located. Various substances such as carbohydrates and organic acids produced by the aggregation and decomposition of fallen leaves will cause direct changes in the pH values of wetland soils and provide dissolved groups, thus promoting the dissolution and migration of Fe, Mn, and other elements. For the base examined in this research, negative correlations were identified between the contents of Fe and Mn and the pH values of the soil. Specifically, more Fe and Mn were absorbed by *C. oleifera* under acidic soil conditions. Overall, acidic soils can contribute to the absorption of trace elements by Qianyu *C. oleifera*, whereas the quality of *C. oleifera* is degraded by soil acidification, which was consistent with the results of previous studies [27].

5. Conclusions

(1) The soil of the Qianyu *C. oleifera* base had pH values of between 4.12 and 6.17, indicating slightly acidic conditions. The soil was relatively fertile, which satisfied the growth requirements of *C. oleifera*.

(2) Based on the measurements and comparisons of the heavy metal contents in the soil of the Qianyu *C. oleifera* base, the CR indexes and TCR indexes of the As, Cd, and Cr in the soil were below the highest acceptable levels (10^{-6}) recommended by the USEPA. However, although the non-CR assessment results showed that the overall HI value of the soil in the base had no CR to adults, it did pose potential risks to children. Despite the minimal influence of exposure to heavy metals in the soil of the Qianyu *C. oleifera* base on human health, the potential risks of As and Hg are worth monitoring.

(3) The organic matter in the soil was positively correlated with Pb, Mn, and Cr and negatively correlated with Zn, Fe, Cd, Hg, As, and Cu. Soil acidification tends to degrade the quality of *C. oleifera*, whereas weakly acidic soil promotes the absorption of trace elements by *C. oleifera*. Soil acidification can be relieved by appropriate measures such as the application of biochar and $CaCO_3$.

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