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Assessment of the Quality of Agricultural Soils in Manica Province (Mozambique)

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Abstract: Agriculture is the main economic activity of Mozambique and there is a lack of information about the quality of agricultural soils. In this paper, five soils from the Manica and Sussundenga districts (Manica province) sampled in the years 2021/2022 and 2022/2023 (before and after the rainy seasons) were subjected to an agronomical and environmental chemical analysis to assess their quality, from the fertility and environmental contamination points of view. Standard analytical methodologies from external certified laboratories and local X-ray fluorescence measurements were used. All the studied soils were acidic (pH ranging from 4.5 to 5.4), had no salinity problems (conductivity ranging from 4.2 to 11.8 mS/m), and had a low amount of soil organic matter (0.90% to 1.81%). Soils from the Sussundenga district had a very low cation exchange capacity (CEC) (average of 3.33 $cmol_c/kg$), while that of those from the Manica district ranged from very low to average CEC (3.59 to 13.11 $cmol_c/kg$). Sussundenga soils also had a phosphorous deficiency (values ranging from <20 to 38.5 mg/kg) and there were deficiencies and/or excesses of some macro and micronutrients in all soil samples. Manica soils were contaminated, apparently from geogenic origin, with Cr (280 to 1400 mg/kg), Co (80 mg/kg), Ni (78 to 680 mg/kg) and V (86 mg/kg). Agricultural soil monitoring must be fostered in Mozambique in order to improve food quality and quantity to ensure economic and environmental sustainability.

Keywords: agricultural soils; chemical soil properties; soil fertility; metallic soil pollutants

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1. Introduction

The quality of agricultural soils is a critical factor for the environmental and socioeconomic sustainability of a rural region. Environmental agricultural soils' quality should meet regulations defined by governmental agencies to ensure ecological equilibrium and reduce human health risks, without compromising the yield of food production. Moreover, in this context, countries and organizations must stay in tune with the United Nations Objectives for Sustainable Development 2 (zero hunger), 12 (responsible consumption and production) and 15 (life on land). This is particularly important for Mozambique, which is one of the poorest countries in the world, where the majority of the population depends on subsistence farming, and sustainable management of soil is mandatory for the future generations to continue to rely on the soil for food production.

Toxic heavy metal soil contamination has been the subject of much research, and it is an increasing concern [1]. It is a severe problem in many regions in the world [2], especially in terms of environmental health safety [2–5], because of the potential threat to food contamination and its harmful effects on humans and animals [5]. These substances are considered pollutants due to their resistance to biodegradation, their toxic effects, and because they persist for long periods in soil [1–5]. Heavy metals are introduced into soils by natural sources [6,7] and also increasingly by anthropogenic sources [6,7] [8]. Activities such as agriculture with intensive use of chemical products [6–8], irrigation using polluted water [6–8], and industrial activities such as mining are good examples of environmental stressors affecting agricultural soils.

Agriculture is practiced by the majority of the Mozambican population [9,10], with the country having approximately 36 million hectares of arable land, but only 9 million are actually in use, most of which are occupied by family farming [10]. Nevertheless, information about the soils in Mozambique is very scarce, although there is a consensus on the poor fertility of these soils [11–14].

In this paper, the results of the analysis of soils from five farms in the province of Manica, and in the Manica and Sussundenga districts (Mozambique), are presented and discussed. Firstly, the agronomical chemical characteristics of the soils are discussed, based on the following parameters: extractable K, Mg, Ca, Fe, Mn, Zn, Cu and B; exchangeable Na, K, Ca, Mg and Al; cation exchange capacity (CEC); pH; extractable P; soil organic carbon and organic matter; total Kjeldahl nitrogen and inorganic nitrogen; conductivity, and texture. Secondly, the environmental quality of the soils is discussed. Some elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) (As, Sb, Ba, Be, Cd, Cr, Co, Cu, Hg, Pb, Mo, Ni, Se, Sn, V and Zn), and another set of elements was analyzed by a portable X-ray fluorescence instrument (XRF) (K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Sr, Zr, Ba, Ta and Pb). The soils under investigation were assessed from agronomical and environmental perspectives.

2. Materials and Methods

2.1. Study Area

The area of study focused on two districts in the Manica province (center of Mozambique), namely the Manica and Sussundenga districts (Figure 1).

The Manica district [15] is characterized by a dry-winter subtropical climate (Cw in the Köppen–Geiger classification) with two well-defined seasons (rainy and dry). The rainy season begins in November and it ends in the month of April. The annual average temperature is 21.2 °C with extreme maximum values in October (30.9 °C) (summer) and July (24.4 °C) (winter) and with extreme minimum values in February (18.5 °C) (summer) and in July (7.3 °C) (winter). The Revué river and its effluents drain the Manica region. Soils are developed on materials from Precambrian acidic rocks, such as granite and gneiss. The Manica district is characterized by its oxic red or reddish-brown clay soils [15].

The Sussundenga district [15] is characterized by a tropical rainy savanna climate (Aw in the Köppen–Geiger classification) with two well-defined seasons (rainy and dry), similar to the Manica district. The annual average temperature is 23.0 °C, with average maximum and minimum values of 29.5 and 17.6 °C, respectively. The Sussundenga district has four main rivers: Revué, Munhinga, Mussapa and Lucite. The geomorphology of the Sussundenga district is part of the vast gneisso-granitic complex of the Mozambique belt where the post-Karroo intrusive rocks stand out in the form of inselbergs [15]. The Sussundenga district has different soil groups such as red clay soils, red sandy soils, medium-textured red soils and lithic soils [15].

2.2. Soil Sampling

Soils were sampled from agricultural farms in the Manica province; two samples were taken in the Manica district (Fields **C1** and **C2**) and three samples in the Sussundenga district (Fields **C3**, **C4** and **C5**) (Figure 1). The areas of the five farms and their agricultural productions were:

C1—7 ha: corn, green beans, banana, lettuce, cucumber, strawberries and okra;
C2—2 ha; corn, tomatoes and beans;
C3—1.5 ha: corn and sesame;
C4—1 ha: corn and beans;
C5—1 ha: corn and beans.

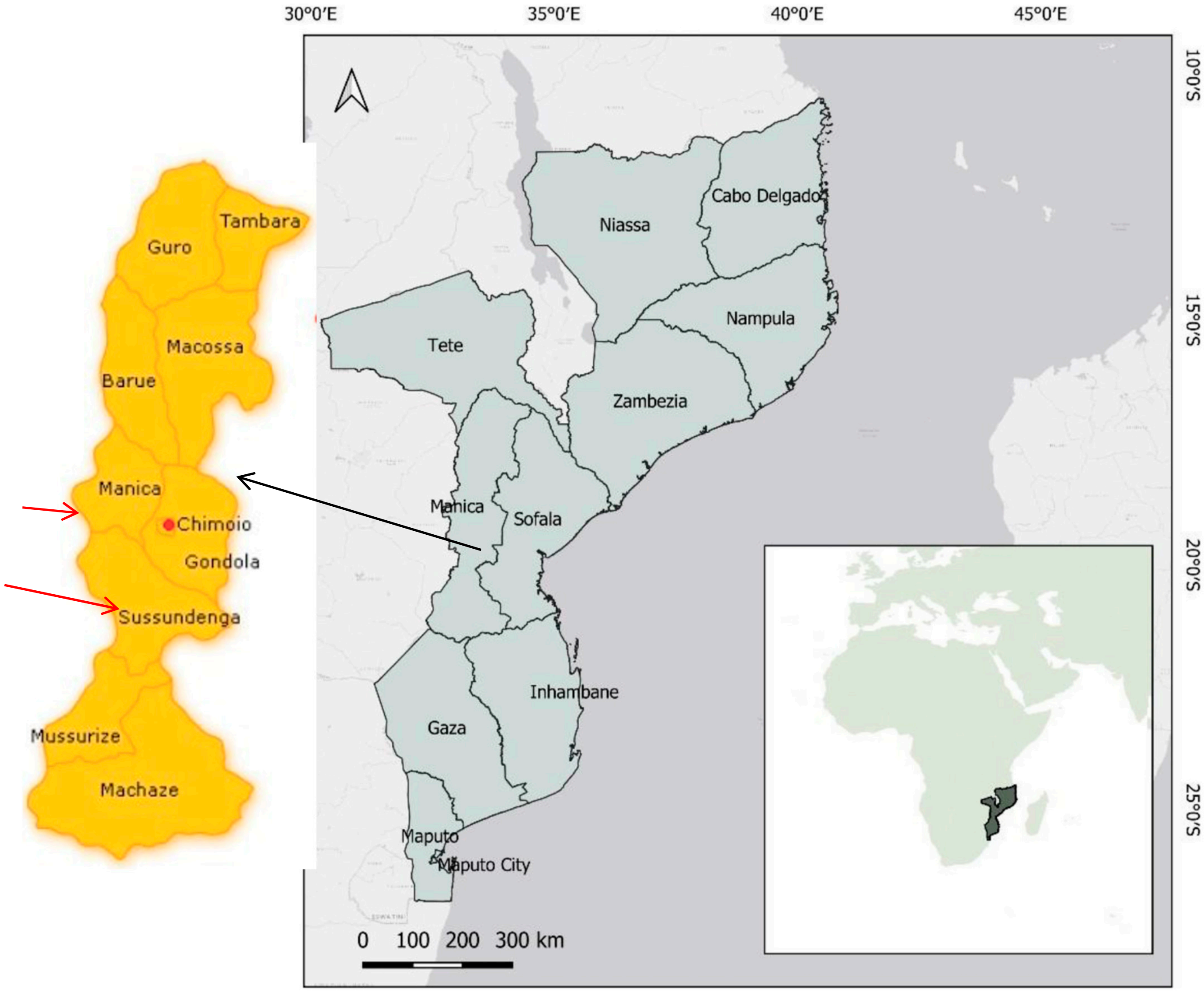

Figure 1. The map of Mozambique (with its provinces) with the Manica province highlighted with its districts. The red arrows indicate the areas where soil samples were collected. Adapted from reference [16].

Fertilizers and pesticides were used in these farms to improve the fertility of the soil and control pests.

Samples were collected in two campaigns (2021/2022 and 2022/2023), and in each of them samples were obtained before and after the rainy season, in the following periods (Table S1): the 2021/2022 campaign—September and October 2021 (before the rainy season) and April 2022 (after the rainy season; the 2022/2023 campaign—September 2022 (before the rainy season) and April 2023 (after the rainy season).

For each agricultural field, a sample was collected that was made up of a determined number of subsamples, which varied between 15 and 20. Subsamples of soil in each field were collected randomly and in a zigzag manner, in order to cover the entire area. The depth considered for the soil sampling was from 0 and down to 20 cm, and involved the use of a manual auger, two plastic buckets and plastic bags. Table S1 shows the date of the samplings and the coordinates of all the subsamples. After collection of the subsamples, they were mixed manually to homogenize them, and about 1 kg of the mixture was kept in a plastic bag, placed inside a cooler to be transported and conserved in a freezer.

2.3. Preparation of Soil Samples

The preparation of the soils consisted in the following procedure: (i) soils were dried at room temperature; (ii) fine soil fraction, for further analysis, was separated from coarser elements using a 2 mm sieve; and, (iii) fine soil fractions were kept inside glass beakers, in desiccators, until sent to analysis.

For the agronomical chemical analysis, ten soil samples were prepared, one from each farm in the two campaigns, 2021/2022 and 2022/2023—the samples collected before and after the rainy season were mixed. For the environmental chemical analysis by ICP-MS, only the samples from the 2022/2023 campaign were the subject of analysis, and five soil samples were prepared, one from each farm, by mixing the soils collected before and after the rainy season. For the XRF soil analysis, the ten samples collected in the 2022/2023 campaign, one from each farm and before and after the rainy season, were analyzed.

2.4. Analysis of the Soils

Agronomical chemical analysis was performed at Eurofins Agro Testing (Lagra, Beja, Portugal), according to the IPac Accreditation L0728 ISO/IEC 17025. The following methods were used: extractable K (K_2O)—Egner–Riehm method; extractable Mg and Ca—extracted with ammonium acetate; extractable Fe, Mn, Zn and Cu—Lakanen method; extractable B—extracted with boiling water; exchangeable Na, K, Ca and Mg—extracted with ammonium acetate; exchangeable Al—extracted with KCl; extracted phosphorous (P_2O_5)—Egner–Riehm method; organic carbon and organic matter—Walkley–Black method; nitrate—extraction with $CuSO_4$/potentiometry (N-NO_3); sand (USDA)—sieving; clay (USDA)—pipet method/gravimetry.

Metals were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) at Eurofins Analytico B.V., according to the reference method NEN-EN-ISO 17294-2 with aqua regia as the soil digestion solution (within the scope of NEN EN ISO/IEC 17025: 2017, RvA L010).

A X-MET 7000 handheld energy dispersive X-ray fluorescence (EDXRF) (Oxford Instruments, Abingdon, Oxfordshire, UK) was used for chemical elemental soil quantification. Soil samples were individually packed into cylindrical plastic boxes and coupled to the XRF for measurements. For each soil sample, three consecutive readings were registered and the average and standard deviations calculated.

3. Results and Discussion

3.1. Agronomical Chemical Analysis of the Soils

Table 1 shows the results of the agronomical chemical analysis of the five soils sampled in 2021/2022 and 2022/2023. The analysis of this table shows that all the soils were extremely to strongly acidic (pH ranging from 4.5 to 5.4, with an average of 5.0 $\pm$ 0.3) and had no salinity problems (conductivity ranging from 4.2 to 11.8 mS/m). The difference in pH values determined in water and in KCl 1M was about 0.8, suggesting that these soils had a negative charge and were cation exchangers [7]. All soils were characterized by a low amount of soil organic matter (SOM) ranging from 0.90% to 1.81%. The soils from the Sussundenga district (**C3** to **C5**) had a very low CEC (average and standard deviation of 3.33 $\pm$ 0.99 $cmol_c$/kg) while that of those from the Manica district (**C1** and **C2**) ranged from low to average CEC (**C1**, 7.30 and 13.11 $cmol_c$/kg) and very low to low CEC (**C2**, 3.59 to 9.74 $cmol_c$/kg). This analysis showed that these soils need liming, for pH correction, and incorporation of organic correctives to increase organic matter and improve CEC in order to improve fertility. Additionally, the Sussundenga district soils had a phosphorous deficiency (values ranging from <20 to 38.5 mg/kg) while the Manica district soils usually had a relatively high amount of phosphorous (with a concentration ranging from 106 to 174 mg/kg), with the exception of the sample **C1** from the year 2022 (44.8 mg/kg). These results show that the samples of the Sussundenga district soils have marked fertility problems.

Table 1. Characteristics of the five soil samples in 2021/2022 (first row) and 2022/2023 (second row).

Property	C1	C2	C3	C4	C5
Extractable K (K_2O), mg/kg	157 149	251 124	157 110	40.1 45.0	49.3 37.9
Extractable Mg, mg/kg	268 622	386 102	128 121	46.4 47	75.8 40.1
Extractable Ca, mg/kg	916 1474	1191 458	512 641	448 516	424 270
Extractable Fe, mg/kg	183 88.9	230 170	117 81	49.3 50.9	107 74.3
Extractable Mn, mg/kg	263 301	307 163	180 153	45.6 51.8	22.6 14.2
Extractable Zn, mg/kg	1.9 1.4	1.9 1.6	0.95 0.86	2.0 1.3	3.0 2.7
Extractable Cu, mg/kg	3.5 2.2	3.6 3.2	2.0 1.4	0.45 0.42	0.60 0.38
Extractable B, mg/kg	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2
Exchangeable Na, cmol(+)/kg	0.10 0.17	0.15 0.04	0.11 0.07	0.04 0.05	0.05 0.04
Exchangeable K, cmol(+)/kg	0.33 0.39	0.44 0.31	0.39 0.33	0.14 0.15	0.16 0.12
Exchangeable Ca, cmol(+)/kg	4.6 7.4	5.9 2.3	2.6 3.2	2.2 2.6	2.1 1.3
Exchangeable Mg, cmol(+)/kg	2.2 5.1	3.2 0.84	1.0 0.99	0.38 0.39	0.62 0.33
Exchangeable Al, cmol(+)/kg	<0.025 <0.025	<0.025 <0.025	<0.025 <0.025	<0.025 <0.025	<0.025 <0.03
CEC, cmol(+)/kg	7.30 13.11	9.74 3.59	4.22 4.67	2.83 3.26	3.08 1.91
pH(KCl) 1:5	5.2 5.2	5.4 4.5	4.8 5.1	5.2 5.3	4.6 4.5
pH(H_2O) 1:5	6.0 6.2	6.1 5.4	5.7 6.0	5.8 5.9	5.4 5.2
Extractable P (P_2O_5), mg/kg	132 44.8	106 174	36.4 <20	37.1 38.5	37.9 37.3
Organic Carbon (%)	0.63 1.0	0.77 0.52	1.0 0.76	0.60 0.64	0.78 0.66
Organic Matter (%)	1.09 1.77	1.33 0.90	1.81 1.31	1.04 1.10	1.34 1.14
Nitrogen Kjeldahl, g/kg	0.94 1.24	1.23 0.78	1.10 0.68	0.59 0.66	0.80 0.68
Nitrate (N-NO_3), mg/kg	18.5 19.8	23.2 14.5	7.0 4.7	12.0 14.3	16.9 20.1
Conductivity, mS/m	10.1 6.3	11.8 5.7	7.8 4.2	6.6 4.9	6.9 5.3
Sand, Clay, Silt (USDA) (%)	62.7, 21.7, 15.6 34.0, 32.3, 33.7	55.2, 26.3, 18.5 71.0, 17.0, 12.0	67.9, 20.3, 11.8 66.4, 19.2, 14.4	77.4, 10.2, 12.4 85.9, 9.7, 4.4	79.4, 13.0, 7.6 78.5, 10.5, 11.0
Texture (USDA)	sandy clay loam clay loam	sandy clay loam sandy loam	sandy clay loam sandy loam	sandy loam loamy sand	sandy loam sandy loam

A study about Mozambique soil fertility published in 2006 concluded that, in general, they can be classified as having low to moderate fertility [11]. Indeed, the median CEC was low, with an average of 5.0 $cmol_c/kg$, ranging from 0.4 to 14.5 $cmol_c/kg$, and 75% of the samples had less than 7.5 $cmol_c/kg$, which is considered the minimum adequate CEC [11]. The soils under analysis from Sussundenga had a particularly low CEC value (3.33 ± 0.99 $cmol_c/kg$). Mozambique soils have a median pH of 6.0 ± 0.53, and range between 4.4 and 7.8, and a SOM ranging from 0.4% to 5.0%, with a median of 2.1% [11]. The Manica and Sussundenga soils under analysis fell within these pH and SOM intervals, but were close to the lower values; i.e., more acidic and poor in organic matter.

Mozambique soils are relatively poor in the macronutrient phosphorous, and the following case studies demonstrate this problem:

(i) Maize is the highest crop in Mozambique [9,10]. Besides the well-known nitrogen fertilization in maize production, the availability of phosphorous is a critical factor for crop productivity, especially under Africa's acid soil conditions [17]. In a study on the Nacala corridor (Mozambique), it was suggested to fertilize soils with 32–74 kg P_2O_5 ha^{-1} [17].

(ii) Cassava is the second most produced crop in Mozambique [9,10]. Cassava is produced mainly by small-scale, resource-poor farmers, on nutrient-depleted soils [1]. Indeed, cassava can achieve reasonable yields in poor soils, where other crops would not thrive [18]. In Mozambique, about 75% of the economically active population is engaged in agriculture, and the majority in small farms with an average land area of 1.78 ha [18]. A soil of Milha-14 in the coastal Dondo district (Sofala province, Mozambique) was analyzed with the following results [19]: pH = 4.9; P, 6 mg/kg; K, 149 mg/kg; Ca, 215 mg/kg; Mg, 60 mg/kg; Na, 16 mg/kg; and SOM, 1.03%. The cassava tuber yield of this soil was 14.7 ± 2.6 ton/ha. The fertilization of this soil with 60 kg/ha N and with 60 kg/ha P_2O_5 yielded 27.7 tons/ha [18].

(iii) Soybean production is small, but it is growing in Mozambique, with a yield in the year 2020 of 1.67 t/ha [20]. Besides being used in human and animal nutrition, it is a legume crop that improves soil fertility [20]. The average soybean yield worldwide is 67.8% higher than that of Mozambique [19]. Fertilization with 20 to 30 kg P ha^{-1}, potassium and starter nitrogen, and inoculants, improves soybean yields [19].

The soils under analysis had somewhat different textures because the Manica soils had a higher percentage of clays when compared with the Sussundenga soils, with higher percentages of sand: Manica **C1** soil had a sandy clay loam/clay loam texture; Manica **C2** soil had a sandy-loam/sandy clay loam texture; **C3**, **C4** and **C5** Sussundenga soils had a loamy sand/sandy clay loam/sandy loam texture.

The Manica and Sussundenga soils had a similar texture to other Mozambique soils that fall in the loamy sand, sandy loam and sandy clay loam classes [11]. The typical minerals present in these soils were kaolinite, illite and the hydroxides, oxohydroxides and oxides of Fe and Al [11].

The following observations can be drawn about the macro and micronutrients in the Manica and Sussundenga soil samples:

(i) All the soils under analysis were deficient in boron, with an average concentration of extractable boron lower than 0.2 mg/kg;

(ii) Soils **C4** and **C5** from the Sussundenga district had calcium, magnesium and potassium deficiencies;

(iii) Soil **C3** from the Sussundenga district had calcium and zinc deficiencies;

(iv) Soil **C4** from Sussundenga district had copper and zinc deficiencies.

(v) Soil **C1** from the Manica district had an excess of magnesium, manganese and iron;

(vi) Soils **C2** from Manica district, and **C3** from Sussundenga district, had an excess of manganese and iron.

These results show that corrections are required in the concentration of the soil macro/micronutrients to achieve increased yields of Mozambique crops. However, before defining a correction scheme, soils must be analyzed to confirm their main deficiencies to allow a sustainable agro-environmental management of food production.

3.2. ICP-MS Elemental Concentrations

Table 2 shows the total concentrations of the elements present in the five mixtures of the soils sampled before and after the rainy season in the 2022/2023 campaign. The following elements were not detected: As, Sb, Be, Cd, Hg, Mo, Se and Sn.

Table 2. ICP-MS results (in mg/kg) of the analysis of the five soil samples collected in 2022/2023.

Element	C1	C2	C3	C4	C5	Reference Value [1]
As	-	-	-	-	-	
Sb	-	-	-	-	-	
Ba	67	32	51	19	17	210
Be	-	-	-	-	-	
Cd	-	-	-	-	-	
Cr	**1400**	**280**	34	-	4.1	67
Co	**80**	17	7	-	-	19
Cu	32	13	9.1	-	-	62
Hg	-	-	-	-	-	
Pb	8.8	6.4	13	4.3	5.1	45
Mo	-	-	-	-	-	
Ni	**680**	**78**	11	-	-	37
Se	-	-	-	-	-	
Sn	-	-	-	-	-	
V	**86**	36	30	3.0	5.1	86
Zn	30	17	15	-	13	290

[1] Reference values for agriculture soils according to the Portuguese Environmental Agency [21].

The reference values for agriculture soils accordingly to the Portuguese Environmental Agency [20] are included in Table 2. The comparison of the results with the reference values showed that soil samples **C1** and **C2** from the Manica district had severe contamination with the following elements: **C1**, Cr (1400 mg/kg), Co (80 mg/kg), Ni (680 mg/kg) and V (86 mg/kg); **C2**, Cr (280 mg/kg) and Ni (78 mg/kg). The soils from the Sussundenga district showed no contamination with the measured chemical elements.

The presence of the elements Cr, Co, V and Ni in the agricultural soils is of geogenic origin [21]. In a study of the top soils from Beira city (Mozambique), the following concentrations of these elements was found [21]: Cr, 11.0 to 3930 mg/kg (with an average of 89 mg/kg); Co, below the detection limit to 56.0 mg/kg (with an average of 3.00 mg/kg); and Ni, 1 to 120 mg/kg (with an average of 7.00 mg/kg); and, V, 2.00 to 87.0 mg/kg (with an average of 17.0 mg/kg). Soil pollution with elements of an anthropogenic origin, namely Cu, Pb and Zn, was not detected. Moreover, taking into consideration that the Manica district area under investigation has illegal artisanal gold mining [22–24], it was notable that no Hg contamination was detected in the studied soils.

Comparing the contamination of the **C1** and **C2** Manica soils with that of other agricultural soils from around the world, we can conclude that these results are outliers, due to the relatively high concentration levels of pollutants. For example, the contamination compares with that of Iranian agricultural soils that had an average (minimum/maximum) concentration of Cr, Co, Ni and V, respectively, 101 (5.67/633), 27.9 (6.80/519), 68.0 (2.79/770) and 101 (20.3/1202) mg/kg [25]. In a review of Indian agricultural soils, values for metals Co, Cr, Ni and V were mostly lower than the values found in this work [26]. Additionally, analysis of the agricultural soils from the Shanghai region found an average Cr value of 41.00 mg/kg [27] and showed that although this region is highly industrialized, the heavy metal levels in agricultural soils were within safe ranges according to the Chinese environmental regulations.

Due to the absolutely and relatively abnormal concentrations of some elements in samples **C1** and **C2**, these two soils were subject to a detailed chemical analysis of organic pollutants, and the following were detected: **C1**—p-isopropyltoluene (0.06 mg/kg), ethyl chlorpyrifos (0.03 mg/kg), diethylhexyl phthalate (0.3 mg/kg) and total petroleum hydrocarbons (C30–C35) (7.6 mg/kg); **C2**—diethylhexyl phthalate (0.4 mg/kg). The presence of these organic pollutants suggests that, besides the geogenic origin of the pollutants in these two soils, there was an unknown anthropogenic contribution to the pollution that will be the subject of further research.

Nevertheless, no conclusion can be drawn about the toxicity of those elements in the soils under analysis. Indeed, the obtained results correspond to total concentrations, and if they are chemically bounded in soil-stable minerals they probably are not bioavailable and, consequently, will show no immediate toxicity towards crops or animals. Further research is necessary to measure the bioavailability amount of those elements in the Manica soils.

3.3. XRF Elemental Concentrations

Table 3 shows the concentrations of the elements present in the soils under analysis for the years 2022 and 2023. This table only shows the elements that were detected by XRF.

Table 3. XRF results (mg/kg) of the analysis of the five soil samples in 2022/2023, before (first row) and after (second row) the rainy season (averages and standard deviation of three independent measurements).

Element	C1	C2	C3	C4	C5	Reference Value [1]
K	5591 (101)	14,013 (696)	15,344 (2062)	40,165 (3925)	22,545 (1113)	
	6841 (161)	13,877 (620)	15,772 (524)	23,067 (3136)	22,609 (511)	
Ca	7186 (1327)	6432 (478)	2170 (167)	3703 (659)	4360 (258)	
	8335 (1046)	6585(113)	2450 (1131)	3057(403)	3034 (146)	
Ti	3833 (72)	5814 (849)	5243 (779)	2242 (690)	2073 (65)	
	3798 (159)	5284 (228)	4840 (308)	1353 (29)	2018 (217)	
V	**132 (20)**	**97 (27)**	-	-	-	86
	112 (10)	24 (42)	-	-	-	
Cr	**2675 (308)**	**803 (67)**	60 (13)	-	-	67
	2543 (119)	**700 (8)**	52 (54)	-	-	
Mn	1429 (238)	783 (174)	690 (111)	318 (34)	167 (18)	
	1423 (159)	799 (23)	686 (115)	268 (60)	126 (5)	
Fe	83,114 (6083)	29,774 (2118)	22,247 (2373)	4412 (530)	5109 (95)	
	75,161 (2541)	28,393 (960)	25,610 (3308)	4048 (553)	4871 (141)	
Co	**44 (38)**	11 (18)	-	-	-	19
	49 (46)	-	11 (20)	-	-	
Ni	**823 (70)**	**154 (13)**	23 (6)	4 (8)	4 (7)	37
	684 (42)	**158 (2)**	25 (5)	-	-	
Cu	26 (4)	14 (1)	-	-	-	62
	25 (6)	17 (3)	4 (8)	-	-	
Zn	39 (3)	19 (2)	16 (1)	-	4 (6)	290
	36 (5)	22 (3)	20 (6)	-	-	
Rb	47 (8)	53 (8)	91 (4)	202 (30)	101 (2)	
	45 (1)	53 (2)	84 (3)	106 (20)	98 (5)	

Table 3. *Cont.*

Element	C1	C2	C3	C4	C5	Reference Value [1]
Sr	48 (9) 55 (4)	59 (5) 63 (4)	49 (2) 38 (5)	91 (14) 49 (8)	88 (3) 96 (2)	
Zr	164 (24) 199 (66)	261 (52) 294 (23)	393 (53) 292 (18)	169 (34) 158 (2)	196 (65) 165 (8)	
Ba	- -	**256 (3)** **256 (22)**	**-** **-**	**414 (71)** **294 (19)**	**299 (25)** **293 (30)**	210
Ta	29 (4) 10 (18)	- 7 (13)	- 12 (11)	- -	- -	
Pb	3 (6) 3 (6)	7 (6) 5 (5)	22 (3) 19 (2)	30 (10) 17 (2)	18 (2) 19 (2)	45

[1] Reference values for agriculture soils according to the Portuguese Environmental Agency [21].

The analysis of Table 3 confirms the results obtained by ICP-MS, showing that the soil sample **C1** from the Manica district was severely contaminated with V, Cr, Co and Ni and that the contamination was observed both in the samples collected before and after the rainy season. Sample **C2** was also contaminated with V, Cr and Ni. Comparing the results obtained before and after the rainy season, we found that the elemental concentration remained in the same order of magnitude, and it demonstrated that the rain that washed the soil in the summer months had no effect in the attenuation of the contamination. A probable cause for this observation is the geogenic origin of the most concentrated elements, whose minerals are not soluble in water.

The comparison of the ICP-MS and XRF concentration estimations showed that the results obtained by XRF were usually higher than those obtained by ICP-MS for the elements Ba and Cr, which were the elements with the highest concentrations in the soils under analysis. For the others, the XRF estimates were in the same order of magnitude of ICP-MS—the plot of the two sets of results resulted in a linear plot with a slope of 1.1 and an intercept of 7. These results support the use of portable XRF equipment for screening on-site and straightforward estimation of the concentration of chemical elements in soils, allowing the identification of potential contaminations that are above the regulated threshold values.

4. Conclusions

The Manica and Sussundenga district soils under analysis in this paper confirmed the low fertility of Mozambique soils, mainly due to macro and/or micronutrient deficiencies, low CEC and low SOM. These results emphasize the need to implement local soil analysis facilities in Mozambique, to support the management of agricultural production in a sustainable manner and with increased agricultural yields. Moreover, technical support to farmers and infrastructure to allow easy access to markets are also mandatory.

In addition to the fertility issues of the Mozambique soils, their environmental chemical quality must be assessed. The soils of the Manica district revealed a worrying situation because the agricultural soils where food is produced showed high levels of contamination with toxic metals such as chromium, cobalt, nickel and vanadium. This raises human health risks and deserves further investigation. In the case of the Sussundenga district soils, no chemical contamination with toxic substances was detected.

Mozambique is experiencing economic growth and projections forecast a rise in gross domestic product (GDP) from agriculture and other economic activities. This scenario opens the opportunity for the implementation of sustainable agricultural practices, and agro-environmental management that ensures that the quality of the agricultural soils is improved for future generations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments11040067/s1, GPS coordinates and date of the soil sampling.

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References

1. Zhao, H.; Wu, Y.; Lan, X.; Yang, Y.; Wu, X.; Du, L. Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution level page range. *Sci. Rep.* **2022**, *12*, 3552. [CrossRef] [PubMed]
2. Rashid, A.; Schutte, B.J.; Ulery, A.; Deyholos, M.K.; Sanogo, S.; Lehnhoff, E.A.; Beck, L. Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health. *Agronomy* **2023**, *13*, 1521. [CrossRef]
3. Mitra, S.; Chakraborty, J.C.; Tareq, A.M.; Emran, T.B.; Nainu, F.; Khusro, A.; Idris, A.M.; Khandaker, M.U.; Osman, H.; Alhumaydhi, F.A.; et al. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *J. King Saud Univ. Sci.* **2022**, *34*, 101865. [CrossRef]
4. Yanga, S.; Suna, L.; Suna, Y.; Songa, K.; Qina, Q.; Zhu, Z.; Xue, Y. Towards an integrated health risk assessment framework of soil heavy metals pollution: Theoretical basis, conceptual model, and perspectives. *Environ. Pollut.* **2013**, *316*, 120596. [CrossRef] [PubMed]
5. Sarker, A.; Kim, J.E.; Islam, A.; Bilal, M.; Rakib, R.; Nandi, R.; Rahman, M.M.; Islam, T. Heavy metals contamination and associated health risks in food webs—A review focuses on food safety and environmental sustainability in Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 3230–3245. [CrossRef] [PubMed]
6. Priya, A.K.; Muruganandam, M.; Ali, S.S.; Kornaros, M. Clean-Up of Heavy Metals from Contaminated Soil by Phytoremediation: A Multidisciplinary and Eco-Friendly Approach. *Toxics* **2023**, *11*, 422. [CrossRef] [PubMed]
7. Wuana, R.A.; Okieimen, F.E. Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecol.* **2011**, *2011*, 402647. [CrossRef]
8. Xin, X.; Shentu, J.; Zhang, T.; Yang, X.; Baligar, V.C.; He, Z. Sources, Indicators, and Assessment of Soil Contamination by Potentially Toxic Metals. *Sustainability* **2022**, *14*, 15878. [CrossRef]
9. Government of Mozambique. *Voluntary National Review of Agenda 2030 for Sustainable Development*; Government of Mozambique: Maputo, Mozambique, 2020.
10. Marassiro, M.J.; Romarco de Oliveira, M.L.; Pereira, G.P. Family farming in Mozambique: Characteristics and challenges. *Res. Soc. Dev.* **2021**, *10*, e22110615682. [CrossRef]
11. Maria, R.M.; Yost, R. A Survey of Soil Fertility Status of Four Agroecological Zones of Mozambique. *Soil Sci.* **2006**, *171*, 902–914. [CrossRef]
12. Chichongue, O.; van Tol, J.; Ceronio, G.; Preez, C.D. Effects of Tillage Systems and Cropping Patterns on Soil Physical Properties in Mozambique. *Agriculture* **2020**, *10*, 448. [CrossRef]
13. Serrani, D.; Cocco, S.; Cardelli, V.; D'Ottavio, P.; Rafael, R.B.A.; Feniasse, D.; Vilanculos, A.; Fernández-Marcos, M.L.; Giosué, C.; Tittarelli, F.; et al. Soil fertility in slash and burn agricultural systems in central Mozambique. *J. Environ. Manag.* **2022**, *322*, 116031. [CrossRef] [PubMed]
14. Folmer, E.C.R.; Geurts, P.M.H.; Francisco, J.R. Assessment of soil fertility depletion in Mozambique. *Agric. Ecosyst. Environ.* **1998**, *71*, 159–167. [CrossRef]
15. República de Moçambique, Ministério de Administração Estatal, Perfil do distrito de Manica-Província de Manica. 2005. Available online: www.portaldogoverno.gov.mz (accessed on 31 January 2024).
16. Cianciullo, S.; Attorre, F.; Trezza, F.R.; Rezende, M.; Ntumi, C.; Campira, J.; Munjovo, E.T.; Timane, R.D.; Riccardi, T.; Malatesta, L. Analysis of land cover dynamics in Mozambique (2001–2016). *Rend. Lincei. Sci. Fis. Nat.* **2023**, *34*, 81–92. [CrossRef]
17. Nasukaw, H.; Tajima, R.; Muacha, B.; Pereira, M.; Naruo, K.; Nakamura, S.; Fukuda, M.; Ito, T.; Homma, K. Analyzing soil-available phosphorus by the Mehlich-3 extraction method to recommend a phosphorus fertilizer application rate for maize production in northern Mozambique. *Plant Prod. Sci.* **2019**, *22*, 211–214. [CrossRef]
18. Cuvaca, I.B.; Eash, N.S.; Lambert, D.M.; Walker, F.R.; Rustrick, W. Nitrogen, phosphorus, and potassium fertilizer effects on cassava tuber yield in the coastal district of Dondo, Mozambique. *Afr. J. Agric. Res.* **2017**, *12*, 3112–3119. [CrossRef]
19. Omondi, J.; Mkuhlani, S.; Mugo, J.; Chibeba, A.; Chiduwa, M.; Chigeza, G.; Kyei-Boahen, S.; Masikati, P.; Nyagumbo, I. Closing the yield gap of soybean (*Glycine max* (L.) Merril) in Southern Africa: A case of Malawi, Zambia, and Mozambique. *Front. Agron.* **2023**, *5*, 1219490. [CrossRef]

20. Contaminated Soils-Technical Guide, REFERENCE VALUES, To the ground, Amadora, January 2019, (Review 3-September 2022), Portuguese Environment Agency (APA). Solos Contaminados–Guia Técnico, VALORES DE REFERÊNCIA, PARA O SOLO, AMADORA, JANEIRO DE 2019, (REVISÃO 3–SETEMBRO DE 2022), Agencia Portuguesa do Ambiente (APA). Available online: https://sniambgeoviewer.apambiente.pt/GeoDocs/geoportaldocs/AtQualSolos/Guia_Tecnico_Valores%20de%20Referencia_2019_01.pdf (accessed on 31 January 2024).
21. Batista, M.J.; Quentala, L.; Dias, R.; Ramalho, E.; Fernandes, J.; Milisse, D.; Manhiça, V.; Ussene, U.; Cune, G.R.; Daudi, E.X.; et al. Geochemical characterisation of soil of Beira city, Mozambique: Geogenic origin and relation with land cover. *J. Geochem. Explor.* **2018**, *187*, 184–200. [CrossRef]
22. Raso, E.F.; Savaio, S.S.; Mulima, E.P. Impact of artisanal gold mining on agricultural soils: Case of the district of Manica, Mozambique. *Rev. Verde Agroecol. Desenvolv. Sustentável* **2022**, *17*, 44–50. [CrossRef]
23. Leuenberger, A.; Winkler, M.S.; Cambaco, O.; Cossa, H.; Kihwele, F.; Lyatuu, I.; Zabre, H.R.; Farnham, A.; Macete, E.; Munguambe, K. Health impacts of industrial mining on surrounding communities: Local perspectives from three sub-Saharan African countries. *PLoS ONE* **2021**, *16*, e0252433. [CrossRef]
24. Dondeyne, S.; Ndunguru, E.; Rafael, P.; Bannerman, J. Artisanal mining in central Mozambique: Policy and environmental issues of concern. *Resour. Policy* **2009**, *34*, 45–50. [CrossRef]
25. Shahbazi, K.; Marzi, M.; Rezaei, H. Heavy metal concentration in the agricultural soils under the different climatic regions: A case study of Iran. *Environ. Earth Sci.* **2020**, *79*, 324. [CrossRef]
26. Daulta, R.; Prakash, M.; Goyal, S. Metal content in soils of Northern India and crop response: A review. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 4521–4548. [CrossRef]
27. Li, R.; Wang, J.; Zhou, Y.; Zhang, W.; Feng, D.; Su, X. Heavy metal contamination in Shanghai agricultural soil. *Heliyon* **2023**, *9*, e22824. [CrossRef] [PubMed]