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Research Article

Physicochemical Properties and Fertility Assessment of Soils in Foumban (West Cameroon)

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Foumban is located in the West Cameroon Highlands, precisely in the Noun Valley. Given the low productivity recorded in this locality, this study aims to assess the state of soil fertility in this locality in order to redefine the major agro-ecological complexes in Cameroon. In order to achieve this objective, ninety (90) soil samples of this area were studied in order to determine their physicochemical parameters, namely, soil organic carbon (OC), total nitrogen (N), available P, total P, exchangeable cations (Ca, Mg, K, and Na), cation exchange capacity (CEC), and pH of water. The results obtained showed that the soils of Foumban present three classes of fertility, namely: class one (01) includes soils with a good level of fertility that are plaggic hortic NITISOLS (arenic) (NIpha), the chernic arenic UMBRISOLS (UMca), umbric arenic FERRALSOLS (Flua), mollic fragic NITISOL (hortic) (NImfh), the cambic hortic FERRALSOLS (plaggic) (FLchp) on basalts, umbric pisoplinthic PLINTHOSOLS (haplic) (PLuph), nitic CHERNOSOLS (pretic) (CHnp), and cambic FRAGISOLS (plaggic) (FGcp) with an area of about 528.71 Km^2. Class two (02) includes soils with an average level of fertility that are the pretic UMBRISOLS (UMp) only, on an area of about 226.14 Km^2. Class three (03) includes soils with a poor level of fertility that are the hortic FERRALSOLS (plaggic) (FLchp) on trachytes and the cambic FRAGISOLS (plaggic) (FGcp) with an area of about 38.47 Km^2. Principal component analysis (PCA) has revealed that the parameters that control fertility in Foumban soils are C/N, pHeau, Ca, CEC, OM, P, and Mg. An amendment of these soils in organic fertilizer (fluent, compost, and manure) would facilitate the formation of the clay-humus complex; thus, allowing good retention of water in the soil.

1. Introduction

Soil is a dynamic natural system containing minerals and organic constituents that provide an environment conducive to plant growth [1]. It has physical, chemical, and biological properties that enable it to provide nutrients in quantity and quality in an appropriate balance for plant growth [2–6], especially for sub-Saharan African countries [7]. It is the backbone on which all high-input production systems can be built. In most sub-Saharan African countries, soils have low fertility, and exported nutrients are not adequately replaced. As a result, yields are relatively low and land productivity is consequently decreasing [8, 9]. Population growth in sub-Saharan Africa has led to an increase in food demand. The practice of long-term fallowing is tending to disappear, giving way to short-term fallowing and sedentary agriculture [8, 10].

In Cameroon, more than ten million people (about 45.62%) live in rural areas and therefore depend exclusively on agricultural income [11]. Agriculture is a pillar of the country's economic development, and GDP growth has always been above 20%. Agricultural GDP growth has been driven by food crops, which have grown at an average annual rate of 4.9%, compared to 1.6% for industrial crops [12]. In addition, the increasing population growth in Cameroon, 2.50% in 2014 [13], has led to an increasing demand for land for agricultural production. However, specific information on the state of soil fertility in Cameroon remains scarce and highly localized [14–17]. Cameroonian farmers need up-to-date information on soil fertility to guide their management decisions.

According to RADEC-MINEPAT/Ouest in Reference [18], agriculture in Foumban has many problems related to productivity. Yet, it remains the main economic activity and source of livelihood for the population. The assessment of soil fertility is therefore fundamental to propose optimal conditions for plant growth [19]. Thus, this study proposes to assess the fertility of the soils of Foumban and its surroundings in order to propose alternative solutions for sustainable and efficient management of arable land. To this end, the physical and chemical properties of the soil groups defined by the WRB [20] will be studied, as well as the associated fertility parameters, in order to assess the state of fertility. This will enable the prediction of good soil resource management practices that can preserve soil fertility, and thus improve large-scale sustainable agricultural production in Cameroon, particularly in the Foumban locality.

2. Location

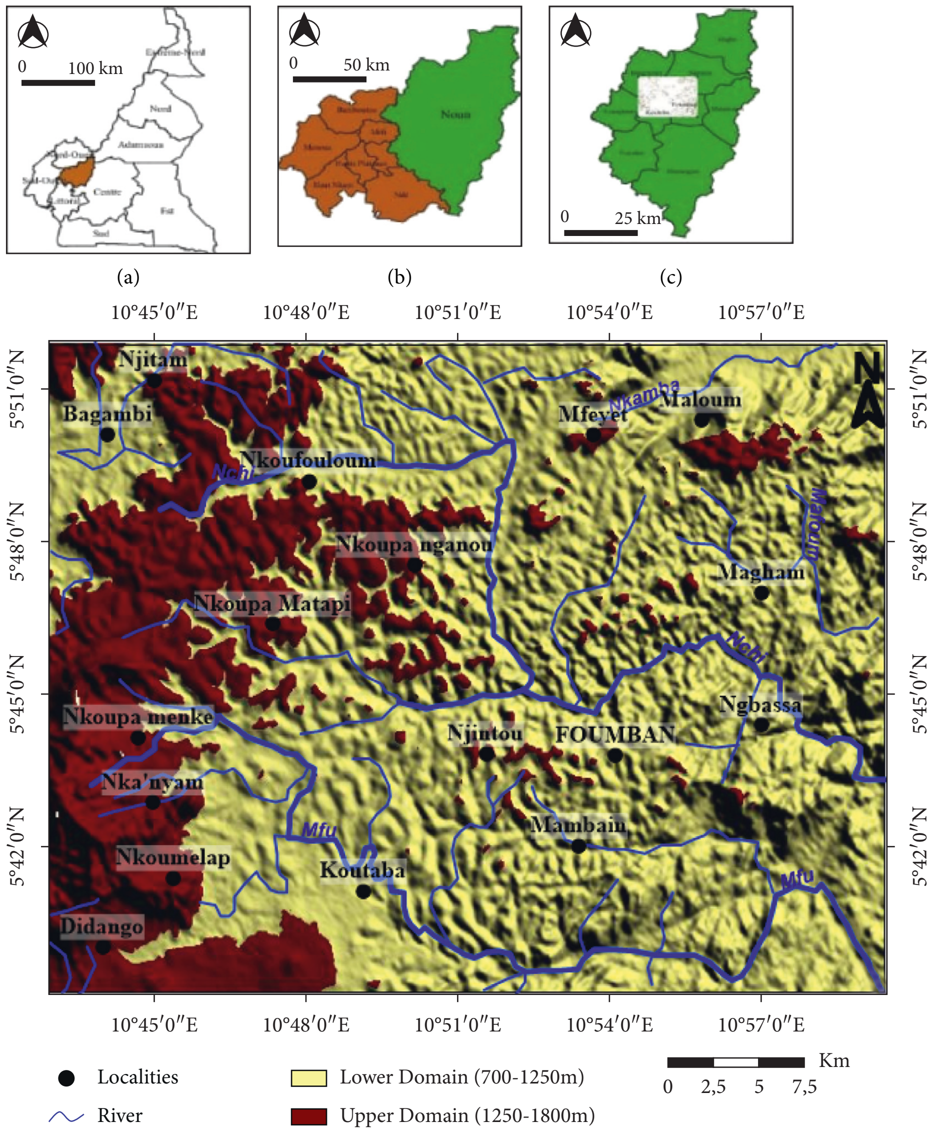
The study area that extends between the north parallels 5°39′ and 5°52′ north latitude and the east meridians 10°42′ to 11°00′ east longitude with an area of 793.27 km^2 (Figure 1) is located in the central part of the Noun Valley. In the study area, there is a tropical humid climate of altitude. The total annual rainfall reaches 1994.2 mm with a temperature between 22°C and 24°C. It is drained by two large watersheds, namely: the Mfu basin and the Nchi basin. Both show a subparallel-type hydrographic network.

Geologically, the study area consists of volcanic, plutonic, and metamorphic rocks [21, 22]. Volcanic rocks are represented by basalts and trachytes while metamorphic rocks are made up of migmatites and finally gneissic plutonic rocks consisting mainly of granites (Figure 2(a)). Ten soil groups have been differentiated using the WRB [20]. The ten soil groups are cambic FRAGISOLS (plaggic) (19.37 km^2), plaggic hortic NITISOLS (arenic) (129.06 km^2), chernic arenic UMBRISOLS (174.23 km^2), umbric arenic FERRALSOLS (108.03 km^2), mollic fragic NITISOLS (hortic) (50.53 km^2), cambic hortic FERRALSOLS (plaggic) on basalts (137.29 km^2), umbric pisoplinthic PLINTHOSOLS (haplic) (72.42 km^2), nitic CHERNOSOLS (pretic) (55.60 km^2), cambic hortic FERRALSOLS (plaggic) on trachytes (16.10 km^2), and pretic UMBRISOLS (40.43 km^2) (Figure 2(b)). According to RADEC-MINEPAT/Ouest in [18], human action on the vegetation cover has transformed the forest into a grassy steppe. Some patches of forest remain along the swampy areas.

3. Study Methods

The field campaign consisted of a soil survey on pits with a thickness varying from 0 to 40 cm on the A horizon only. Then, soil samples were taken from the walls of these pits along a cultural profile. Samples were collected by soil group using the soil map drawn up by Lotse et al. [24] from the WRB [20]. These samples were taken by taking into account the lithology (parent material), morphology, and surface area of each soil group. A total of ninety (90) soil samples were collected by the random method from all soil groups (Figure 3). That is, three on cambic FRAGISOLS (plaggic), sixteen on plaggic hortic NITISOLS (arenic), twenty-one on chernic arenic UMBRISOLS, seven on the umbric arenic FERRALSOLS, four on the mollic fragic NITISOLS, sixteen on the cambic hortic FERRALSOLS (plaggic) on basalts, ten on the umbric pisoplinthic PLINTHOSOLS (haplic), four on the nitic CHERNOSOLS (pretic), three on the cambic hortic FERRALSOLS (plaggic) on trachytes, and six on the pretic UMBRISOLS. It should be noted that the amount of samples taken per soil group is a function of the surface area of the soil group, accessibility, and land use (housing, vegetation, and other). Once the sample was taken, it was transported to the laboratory where the physicochemical analyses were carried out.

Chemical analyses included the following: soil organic carbon (OC), total nitrogen (N), available P, total P, exchangeable cations (Ca, Mg, K, and Na), cation exchange capacity (CEC), and pH of water. OC was extracted by oxidation with potassium dichromate in a highly acidic solution and quantified using a TOC-5000A analyzer. The total N was determined by the Kjeldahl method [25]. The available P and total P was determined by using the Bray II method [26], and exchangeable cations are extracted by ammonium acetate (C2H3O2NH4) buffered at pH 7 and quantified using an atomic absorption spectrophotometer. CEC at pH 7 was determined using the ammonium acetate method. The soil pH was determined in a 1 : 2.5 soil suspension with demineralized water. Physical analyses performed were bulk density (bd) and particle size distribution. The bulk density (bd) was obtained using the Koppeki cylinder method. With regard to the particle size distribution, the coarse sand and part of the fine sand fractions were separated by wet sieving with a sieve of 80 μm, then kiln dried at 105°C, and weighed on the remaining part of the fine sand, and the silt and clay fractions were determined by laser diffraction after the dispersion of the particles in a sodium hexametaphosphate solution. The fertility parameters concerned consist of the following: sum of exchangeable cations (S) (S < 2méq/100 g indicates a very low content; 2 < S (méq/100 g) < 5 indicates a low content; 5 < S (méq/100 g) < 10 indicates an average content; 10 < S (méq/100 g) < 15 indicates a high content; and 15 > Sméq/100 g indicates a very high content [27]; cation exchange capacity (CEC) (CEC < 5 meq/100g indicates a very low content; 5 < CEC (meq/100 g) < 10 indicates a low content; 10 < CEC (méq/100 g) < 25 indicates a medium content; 25 < CEC (méq/100 g) < 40 indicates a high content; and 40 > CECméq/100 g indicates a very high content [27]. S is obtained by adding the exchangeable cations, which are the following: Ca, Mg, K, and Na. The cation equilibrium score (Ca/Mg/K) is the relative abundance of Ca^{2+}, Mg^{2+}, and K^{+} in the soil qualifying the competition between the above nutrients during plant absorption.



(d)

Figure 1: Study area. (a) Map of Cameroon, (b) western region, (c) Noun Department, and (d) location and morphology of the study area.

The ISS (Structural Stability Index) is a physical parameter that determines the degree of degradability and erodibility of a soil [3]. It is defined by Pieri [28] according to the report:

$$\mathrm{ISS} = \frac{(1.724 \times \mathrm{OC})}{((\mathrm{L} + \mathrm{A})) \times 100}; \quad 0 \leq \mathrm{ISS} \leq \infty. \tag{1}$$

With, MO: soil organic matter content, A: clay content in the soil. L: Silt content in the soil. ISS >9% indicates soils with a stable structure; 7% < ISS ≤ 9% indicates soils with a low risk of structural degradation; 5% < ISS ≤ 7% indicates soils with a high risk of structural degradation; and 5% < ISS indicates soils with a degraded structure.

The beat index (IB) indicates the risk of erosion in compaction of one. Rémy et al. [29] formula for estimating the risks of beating is written as follows:

$$\mathrm{IB} = \frac{(1.5 \times Lf) + (0.75 \times LG)}{(A - 10OM)} - C, \tag{2}$$

with $C = 0.2 * (\mathrm{pH} - 7)$, LF = fine silt, LG = coarse silt, A = clay, and Om = organic matter. IB < 1.4% indicates nonbeating soils, 1.4% < IB ≤ 1.6% indicates low-beating soils, 1.6% < IB ≤ 1.8% indicates beating soils, and IB > 1.8% indicates very beating soils.

The Forestier index indicates on the reserve in bases exchangeable in the ground. It is given by the formula of Forestier [30]:

$$\mathrm{IF} = \frac{S^2}{(A + Lf)}. \tag{3}$$

When this index is above 1.5 (IF > 1.5), the reserve in exchangeable bases is good, and when IF < 1.5 the reserve in base is low.

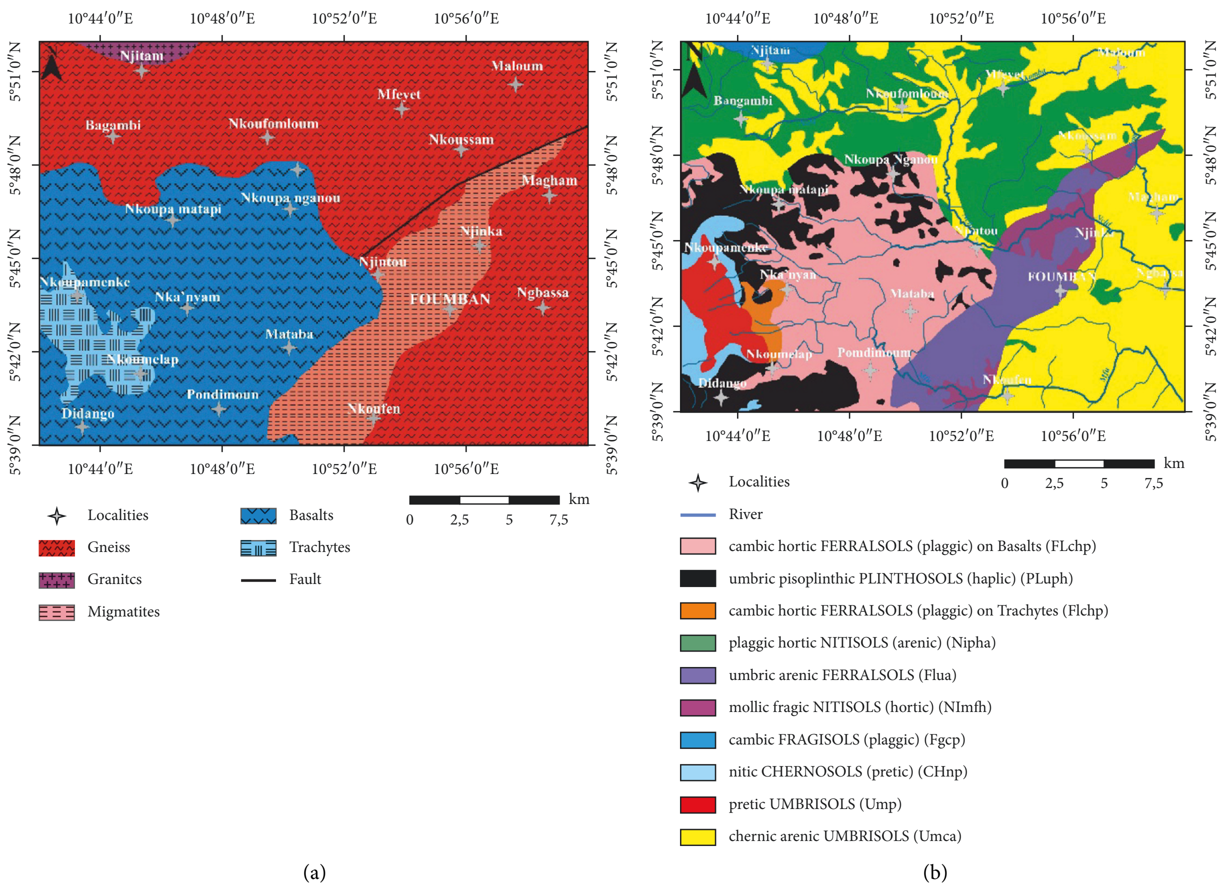


Figure 2: Geological sketch map and soil map of the study area. (a) Geological map of Foumban (after) [23]; and (b) map of the distribution of soil groups in the study area.

Aluminum toxicity is defined by the Kamprath index [31], to determine the degree of exchangeable aluminum toxicity. It is given by the following formula:

$$m = Al^{3+} \times \frac{100}{S + Al^{3+}}. \quad (4)$$

Al^{3+}: exchangeable aluminum (meq/100 g) and S: sum of exchangeable bases (meq/100 g). $m < 20\%$ indicates soils with normal aluminic toxicity, $20 < m\ (\%) \leq 50$ indicates soils with high aluminic toxicity, and $m > 50\%$ indicates soils with very high aluminic toxicity.

The balances between certain physicochemical properties have been established and reported on the diagrams according to the models used by other authors such as FAO-ISRIC [20], Forestier [30], Dabin [32], and Martin [33]. The different textural classes are given from the FAO textural diagram; thus, characterizing the different groups of soils of Foumban and its surroundings on the agropedological level. The Ca-Mg-K ternary fertility diagram after Dabin [32] highlights the thresholds of deficiency and relative deficiency in a given cation in the equilibrium of the cationic balance. Dabin's [32] diagram on the N-pH equilibrium highlights the nitrogen contents carried on the abscissa and the pH water carried in the ordinate. The limitations are defined by the water pH values carried in ordinate which define horizontal lines and show only the influence of the pH water on the total nitrogen reserve. It defines four levels of chemical fertility (low, poor, medium, and good) of soils according to their degree of acidity. The Dabin's diagram [32] makes it possible to highlight this antagonism or synergy between K-Mg cations in the soil. The Ca/K diagram relating to the binary fertility diagram of Martin [33] establishes the balance between calcium and potassium in soils.

The data obtained after analysis of the samples in the laboratory were processed using Excel 2016 and IBM SPSS Statistic 20 software. A descriptive statistical analysis of 24 variables was used to compare mean and standard deviations by soil group in the study area. Principal component analysis (PCA) determined the parameters that control fertility in Foumban soils.

4. Results and Discussion

4.1. Variation of Physical Properties in Soil Groups. The results presented in Table 1 show significant variability between the different soil groups. The battiness index (BI) shows that with the exception of Cambic hortic FERRALSOLS (plaggic) (FLch) on trachytes and Cambic FRAGISOLS (plaggic) (FGcp), which are highly battable soils (BI > 1. 8), i.e. have a surface battance crust increasing the cohesion of the soil, and thus its resistance to loosening. In theory, this should reduce the rate of erosion. However, even

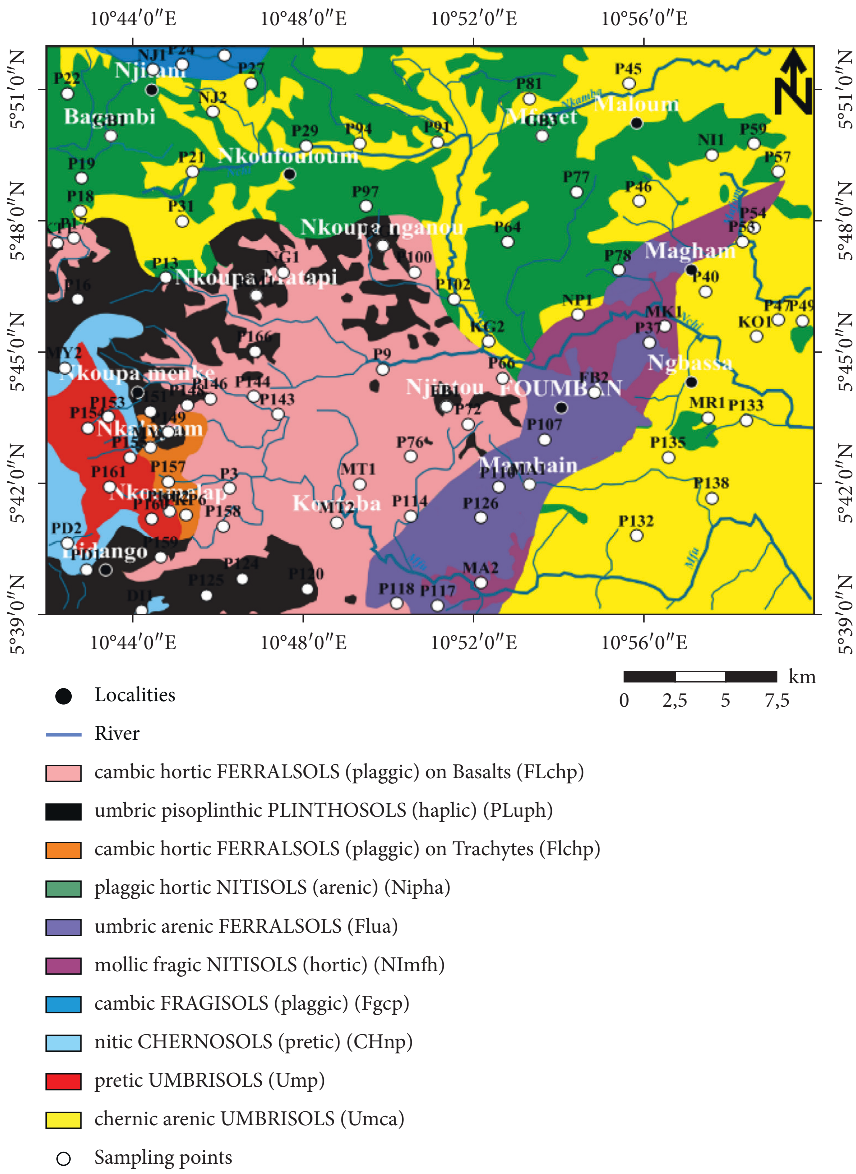


Figure 3: Sampling map with the distribution of soil groups.

Table 1: Statistical study of the physical properties of Foumban soil groups.

Soil group	Number of values	%S		%L		%A		pHeau		Da (g/cm3)		IB (%)		ISS (%)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nipha	13	64.1	5.4	16.5	5.1	19.3	6.5	5.1	0.6	1.0	0.05	−7.3	17.9	12.2	17.9
Umca	20	59.4	8.3	16.5	4.3	24.2	7.8	5.1	0.6	1.0	0.08	−5.6	10.6	14.7	10.6
Flua	10	55.2	15.9	15.7	4.8	29.2	15.2	4.9	0.4	1.0	0.05	−1.0	2.1	12.9	2.1
Nimfh	4	50.1	3.4	20.9	4.7	29.0	5.5	4.9	0.6	1.0	0.05	−2.1	0.6	9.9	0.6
FLchp B	17	52.3	7.7	18.2	6.0	30.1	9.8	5.0	0.6	1.0	0.07	−0.3	1.5	13.0	1.5
Pluph	14	44.8	7.4	18.0	6.3	37.4	10.3	4.8	0.6	0.9	0.08	−0.5	6.0	9.8	6.0
CHnp	2	37.7	2.3	29.0	3.0	33.3	0.8	5.4	0.8	0.9	0.07	−4.2	3.4	12.0	3.4
Ump	4	42.7	5.3	28.4	3.9	28.9	4.2	5.1	0.2	1.5	0.85	−3.9	1.0	7.7	1.0
FLchp T	3	35.3	5.2	29.5	5.6	35.2	2.0	5.1	0.5	1.0	0.03	16.5	58.7	6.5	58.7
FGcp	3	45.7	2.8	19.3	0.6	35.0	2.3	4.9	0.8	1.1	0.04	13.2	28.2	6.2	28.2

Plaggic hortic NITISOLS (arenic) = NIpha, Chernic arenic UMBRISOLS = UMca, Umbric arenic FERRALSOLS = Flua, Mollic fragic NITISOL (hortic) = NImfh, Cambic hortic FERRALSOLS (plaggic) = FLchp on Basalts, Umbric pisoplinthic PLINTHOSOLS (haplic) = PLuph, Nitic CHERNOSOLS (pretic) = CHnp, Cambic hortic FERRALSOLS (plaggic) = FLchp on Trachytes, pretic UMBRISOLS = UMp, and cambic FRAGISOLS (plaggic) = FGcp.

Table 2: Statistical study of the chemical properties of Foumban soil groups.

Soil group	Number of values	OM (%)		N (%)		C/N		S (méq/100)		CEC (méq/100)		P (mg/kg)		IF		(Ca + Mg)/K		m (%)	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Nipha	13	4.29	2.33	0.14	0.06	20.04	11.14	12.33	5.51	20.54	5.70	13.29	15.31	5.39	4.77	48.06	41.73	5.11	3.78
Umca	20	5.67	2.13	0.10	0.05	37.52	20.63	11.00	6.64	20.33	6.36	9.54	2.12	4.20	6.25	58.24	141.30	11.58	5.39
Flua	10	4.72	1.73	0.09	0.04	34.76	16.52	10.78	4.78	20.82	5.07	10.47	2.23	3.29	2.54	19.66	14.01	11.39	3.86
NImfh	4	4.90	0.31	0.09	0.02	32.75	8.98	15.20	9.29	24.33	9.41	8.89	0.80	5.71	6.14	22.42	24.93	7.87	5.26
FLchp B	17	6.00	2.54	0.11	0.03	32.69	11.94	10.87	4.63	22.40	5.46	9.21	3.39	2.64	1.85	130.57	327.56	8.45	5.67
Pluph	14	5.38	1.76	0.10	0.04	35.66	18.72	8.67	5.58	18.25	6.99	8.85	5.00	2.00	3.14	43.17	29.46	11.81	19.48
CHnp	2	7.60	3.48	0.13	0.06	32.08	1.56	17.11	4.41	29.76	3.68	38.40	22.82	4.93	2.25	27.98	23.57	6.26	1.62
Ump	4	4.42	0.36	0.13	0.05	21.34	7.50	5.92	5.26	17.67	14.65	7.76	5.96	1.00	1.20	22.80	26.13	31.47	39.26
FLchp T	3	4.19	0.78	0.12	0.03	21.31	4.15	6.91	4.06	16.23	8.58	6.51	4.40	0.96	0.64	19.05	12.88	23.39	36.33
FGcp	3	3.39	0.71	0.07	0.01	29.00	9.35	7.96	3.09	16.00	2.81	5.44	1.53	1.25	0.92	37.13	31.01	7.07	6.00

though this increases the soil's resistance to loosening, it significantly decreases the rate of water infiltration and increases the rate of runoff [34]. The other soil groups do not have a crust and therefore do not offer any mechanical resistance to root growth and stem expansion.

The sloughing crust of these soils can present mechanical resistance to root growth and stem expansion. It thus creates anaerobic conditions for the roots [34]. This beating crust is due to the high presence of the clay fraction in the soil. The other groups of soils are nonthreshing (IB < 1.4). Nonhammering soils do not have a crust and therefore do not offer any mechanical resistance to root growth and stem expansion. They are aerated and facilitate the exchange of CO2 and O2 with the atmosphere. They increase the rate of water infiltration and consequently the water reserve [34].

With the exception of Cambic hortic FERRALSOLS (plaggic) (FLch) on trachytes, Cambic FRAGISOLS (plaggic) (FGcp) and Pretic UMBRISOLS (UMp), which are at high risk of structural degradation (5% < SSI < 7%) due to the very low organic matter content of these soils and their high clay content, the other groups of soils have structurally stable soils (SSI > 9). Soils with a high risk of structural degradability have a high fertility probability of erodibility. They reduce the rate of water infiltration, which determines water availability for plants [34]. Structurally stable soils have a high capacity for internal cohesion of aggregates. These aggregates are not easily carried away by runoff or wind, and therefore less susceptible to any form of erosion [35]. According to Hubert and–Schaub [36]; soils rich in organic matter have physical phases favorable to plant development because organic matter plays a physical role in the soil for cohesion, structure, porosity, water retention, or storage. All soil groups in the Foumban locality have an acidic pH, below 5.5 (Table 1). pH is a key element of the chemical composition of the soil and determines the availability of nutrients for plants and soil microorganisms [37, 38].

4.2. Variation of Chemical Properties in Soil Groups. S (sun of exchangeable bases), Sd (standard deviation), m = Kramprath index, C/N = mineralization rate; Chemically, with the exception of the cambic hortic FERRALSOLS (plaggic) (FLch) on trachytes and pretic UMBRISOLS (UMp) which show a Forest Index (FI) below 1.5 due to the low levels of exchangeable bases in their soils, the rest of the soil groups have a FI above 1.5 (Table 2); this suggests that these soils have a good reserve of exchangeable bases and therefore good chemical fertility [39]. CEC is a relative indicator of the fertility capacity of a soil (OMAFRA. 2006). According to Chapman [40], CEC depends on the organic matter and clay content of the soil. Soils with a high CEC can hold more cations and have a high capacity to exchange them than soils with a low CEC. This is the case for the nitic CHERNOSOLS (pretic)(CHnp) which have a high CEC (29.76 ± 3.68 meq/100 g). This is due to the very high organic matter content (7.6 ± 3.48%) in this soil group. The presence of organic matter in the soil significantly increases the CEC of the soil (e.g. 1% organic matter adds 2meq/100g CEC to the soil) [41]. Due to the low presence of organic matter in the other

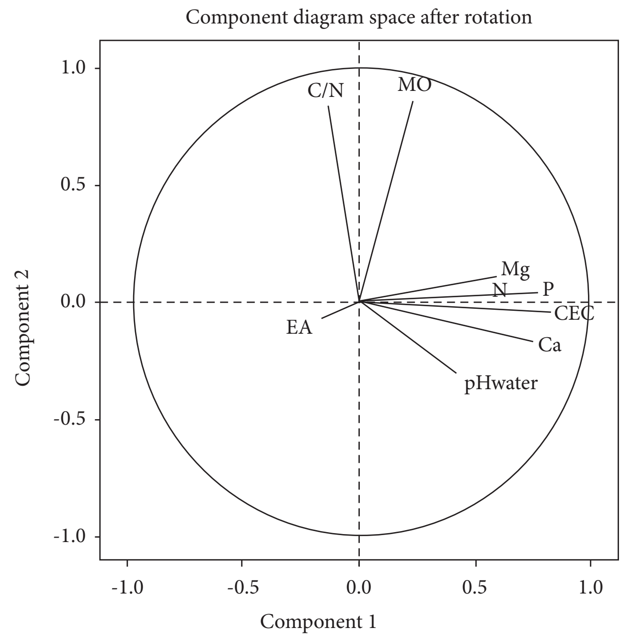


Figure 4: Diagram of components in the ACP area: analysis of partial components; OM: organic matter, C/N: mineralization rate, EA: exchangeable aluminum, pHeau, N: nitrogen, Mg: magnesium, CEC: cation exchange capacity, Ca: calcium, and K: potassium.

soil groups, their CEC remains average. They do not have a very good retention and cation exchange capacity. The aluminium toxicity index or Kramprath index (m) is low in almost all soil groups in Foumban ($m < 12\%$). This is due to the high presence of Ca relative to other exchangeable bases in these soils, which on the other hand, acts as an antagonist to aluminium and displaces the Al3+ ion from the absorbing complex and then neutralises the acidity formed [42]. cambic hortic FERRALSOLS (plaggic) (FLch) on trachytes and pretic UMBRISOLS (UMp) show a high aluminium toxicity (respectively m±23.39±36.33% and m±31.47 ± 39.26%). This would be the consequence of a water pH below 5.5 and the low calcium content of this soil [43]. The sum of exchangeable bases (S) is very high in nitic CHERNOSOLS (pretic) (CHnp) (S: 17.11 ± 4.41 meq/100g) and mollic fragic NITISOL (hortic) (NImfh) (S: 15.20 ± 9.29 meq/100g). This reflects a very high exchangeable cation content in these soils. For the other soil groups, exchangeable cations are medium to high. The high exchangeable cation content is related to the humus-clay complex, which is rich in organic matter and thus humus [43].

Biochemically, all soil groups in the study area have high to very high levels of organic matter (OM) in the soil. This justifies the nutrient richness of these soils [44]. Organic matter is really abundant in the nitic CHERNOSOLS (Pretic) (OM: 7.60 ± 3.48%); this may be due to its higher position (altitude above 1500 m) than the other soil groups [45] and the dominant vegetation cover. As clay and organic matter are the bases of the clay-humus complex, their deficiency would largely contribute to the degradation of the fertility of these soils [43, 46]. Nitrogen levels vary from low to medium in all these soil groups. The C/N mineralization rate is above

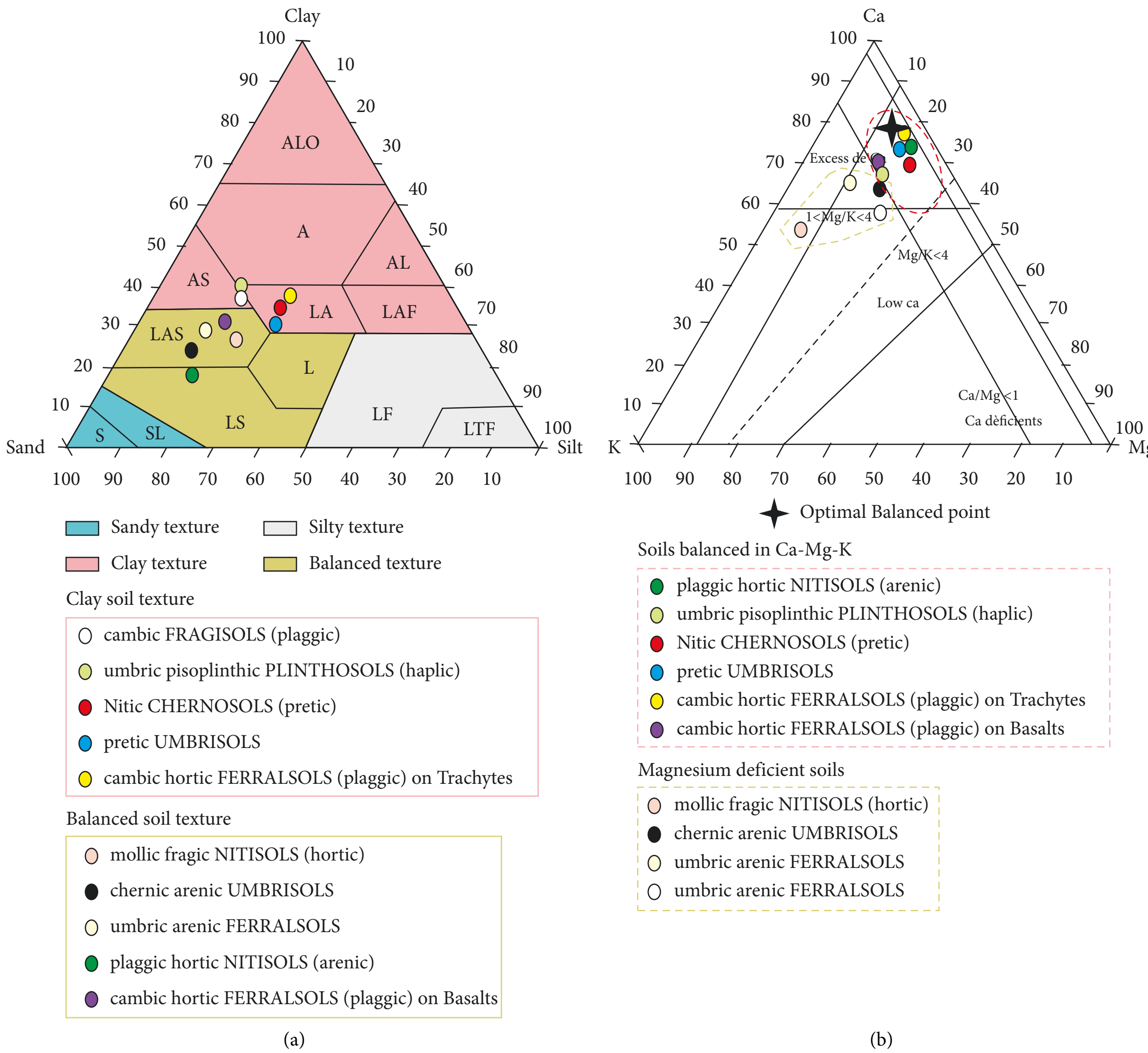


Figure 5: Textural and chemical classification of Foumban soils. (a) Textural diagram [53] and (b) global equilibrium Ca-Mg-K [32].

20 for all soil groups. This reflects very low mineralization rates caused by the low total N content. Therefore, mineralization is slow in all soil groups and only allows a small amount of mineral N to be added to the soil [47]; Ballot C.S.A. et al., [48]. P content is medium in the nitic CHERNOSOLS (Pretic) and low in all other soil groups. This reflects a level that is not high enough to ensure good plant nutrition [49]. Phosphorus deficiency in this soil group is influenced by the high fixation capacity of the soils due to the presence of iron oxides and hydroxides [50].

(See Figure 4), subdivided into two axes, the figure shows that there is a correlation between the fertility indicators and the physicochemical parameters of the soil samples studied. Axis (1) component 1 and component 2 show, respectively, 27.88% and 44.28% affinity between soil chemical characteristics. Variables such as exchangeable cations, $Ca2+$, $Mg2+$, $K+$, P, total N, pH water, and CEC are well represented in the correlation circle and are close to axis 1 (component 1), with a positive coordinate. Variables such as the C/N ratio and organic matter (OM) are very close to axis 2 (component 2). Finally, the variable Al3+, although in the circle, is negatively correlated with the soil fertility components (Figure 3).

Agronomically, the physicochemical properties that control soil fertility in Foumban as shown in Figure 3 are C/N, pH water, Ca, CEC, OM, Mg, and P. Almost similar results for soil fertility indicators were obtained by Pypers et al. [51] and Ballot C.S.A. et al [48]. Organic restitutions through long-term fallows restore fertility to soils depleted by several years of successive cropping [52].

According to the FAO textural diagram (Figure 5(a)), the soils of Foumban are grouped into two categories: clay-textured soils are represented by cambic FRAGISOLS (plaggic), umbric pisoplinthic PLINTHOSOLS (haplic), nitic CHERNOSOLS (pretic), cambic hortic FERRALSOLS (plaggic) on trachytes, and pretic CAMBISOLS.

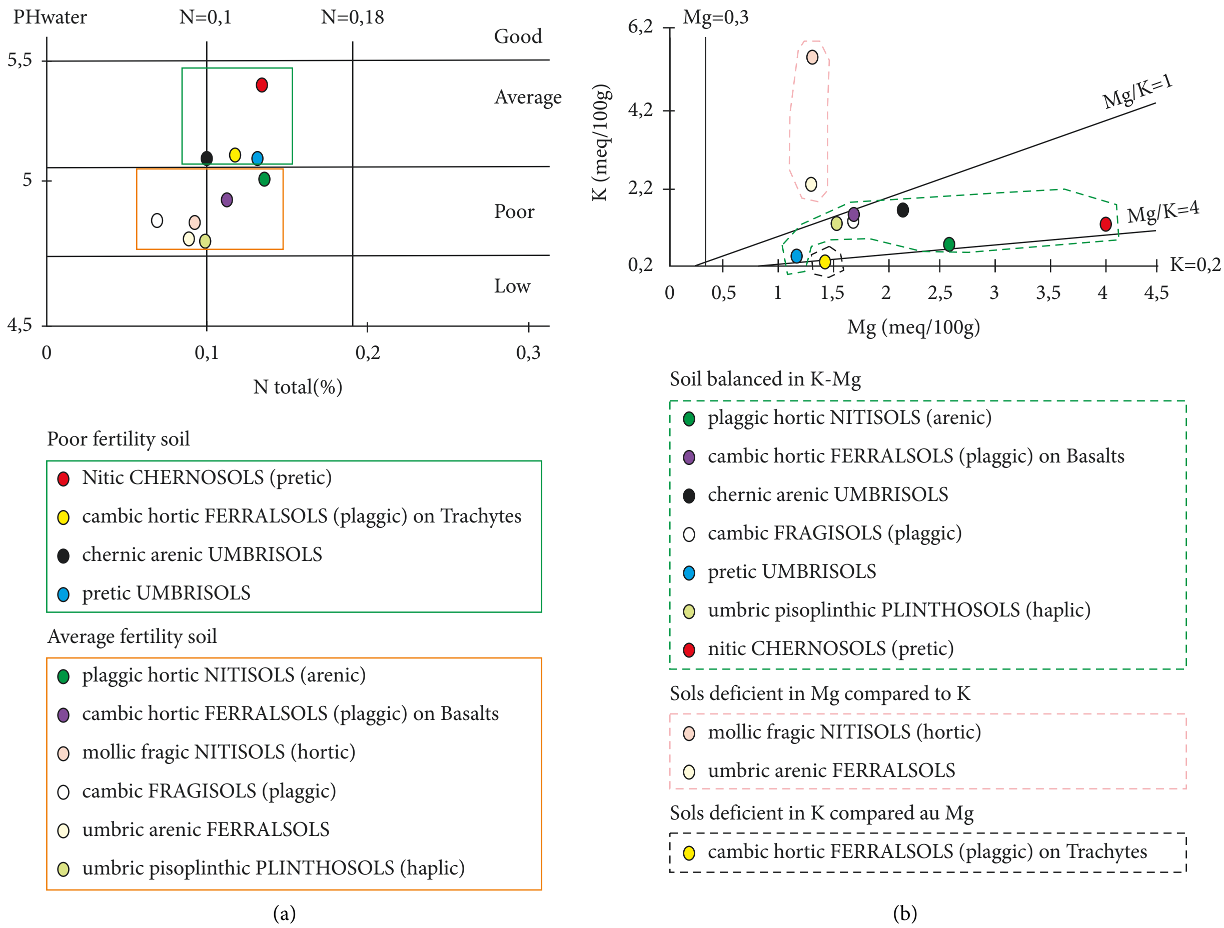


Figure 6: Classification of Foumban soils in function of the fertility and K-Mg. (a) N-pH balance [32] and (b) figure: K-Mg balance after Dabin [32].

They are not very permeable and poorly aerated, preventing good penetration by roots and soil microorganisms. The high clay content of the soils conditions the fixation of mineral elements on the adsorbent complex [43]. The developed balanced textured soils are represented by plagic hortic NITISOLS (arenic), chernic arenic UMBRISOLS, umbric arenic FERRALSOLS, mollic fragic NITISOLS (hortic), and cambic hortic FERRALSOLS (plaggic) on basalts. They lend themselves very well to development because they are very permeable and easy to work [54] and are therefore ideal for growing maize and rice [14]. According to the work of Giguère [55], Buol et al. [56], and Pypers et al. [51] balanced textured soils are excellent and suitable for most crops.

The calculation of the Ca/Mg/K cation balance (Figure 5(b)) of the Foumban soils shows that the plagic hortic NITISOLS (arenic), the cambic hortic FERRALSOLS (plagic) on basalts, the umbric pisoplinthic PLINTHOSOLS (haplic), the nitic CHERNOSOLS (pretic), the cambic hortic FERRALSOLS (plagic) on trachytes, and the pretic CAMBISOLS are close to the optimum balance. This indicates a balance of absorption and good assimilation by the plant roots [15, 57]. Cambic FRAGISOLS (plaggic), chernic arenic UMBRISOLS, umbric arenic FERRALSOLS, and mollic fragic NITISOLS (hortic) have potassium and magnesium deficits. This means that the clay-humus complex is essentially dominated by calcium. This richness of the clay-humus complex in calcium may explain the low acidity of these soil groups [43].

This binary fertility diagram or N-pH diagram of Dabin [32] (Figure 6(a)) divides the soils of Foumban and its surroundings into two fertility classes: low fertility soils and medium fertility soils The cambic FRAGISOLS (plaggic), the plagic hortic NITISOLS (arenic), the umbric arenic FERRALSOLS, the mollic fragic NITISOLS (hortic), the cambic hortic FERRALSOLS (hortic) on basalts, and the umbric pisoplinthic PLINTHOSOLS (haplic) represent the low-fertility soil groups. The limitation of these low fertility soils is due to acidity levels between 4.75 and 5.1. They are characterized by low-to-medium exchangeable base reserves. Chernic arenic UMBRISOLS, nitic (pretic) CHERNOSOLS, cambic (plaggic) hortic FERRALSOLS on trachytes, and pretic CAMBISOLS are groups of soils with medium fertility. The limitation of these medium-fertility soils is due to acidity levels between 5.1 and 5.5. They are characterized by medium-to-high exchangeable base reserves. pH values below 6 indicate the presence of Al^{3+} ions in the soil absorption complex [58].

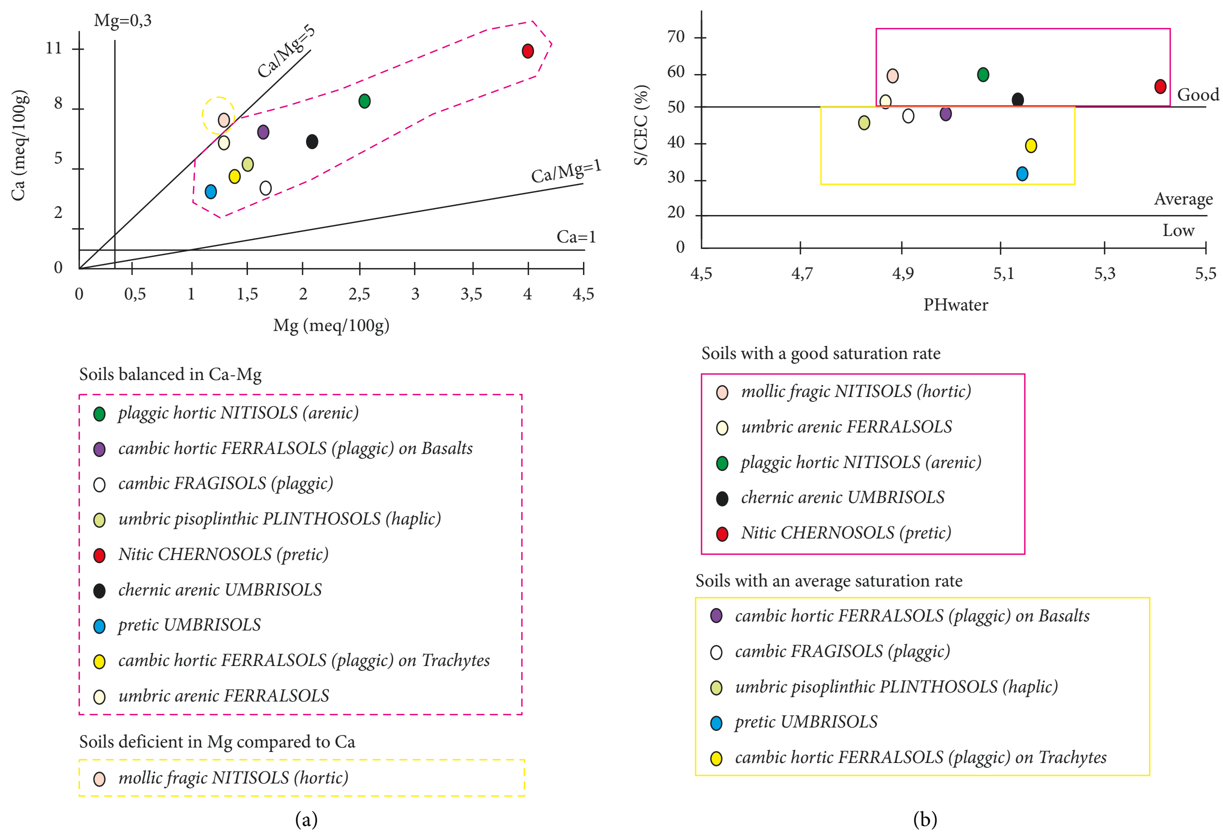


FIGURE 7: Nutritional balance of Foumban soils in Ca and Mg and saturation rate and pH. (a) Ca-Mg balance according to Martin [33] and (b) S/CEC-pH balance.

The K/Mg diagram of Dabin [32] (Figure 6(b)) shows that all soils in the study area are above the potassium and magnesium deficiency thresholds. Most of them have a good K-Mg balance ($1 < Mg/K < 4$). This reflects a nutritional balance between Mg and K. The mollic fragic NITISOLS (hortic) and the umbric arenic FERRALSOLS are found above the ratio $Mg/K = 1$, resulting in a nutritional imbalance between K and Mg. This translates into an excess of Mg uptake in the soil by the plant roots compared to K. This imbalance is also observed in cambic hortic FERRALSOLS (plaggic) on trachytes, where there is an excess of K assimilation by the plants compared to Mg. Too high K/Mg ratio in balanced soils leads to magnesium deficiency and thus to lower yields, while in clay soils, too low K^+/Mg^{2+} ratio slows down the rate of potassium uptake, thus limiting yields [47, 51].

According to this Ca/Mg binary diagram (Figure 7(a)), all soils in Foumban are above the deficiency and deficit thresholds for magnesium ($Mg = 0.3$ meq/100g) and calcium ($Ca = 1$ meq/100g). According to the work of Kambiré [59], Kawano [60], and Ballot C.S.A. [48], the decrease in calcium and magnesium in a nutrient solution would be due to the increase in potassium contents. With the exception of the mollic fragic NITISOLS (hortic) which show a deficiency of Mg in relation to Ca ($Ca/Mg > 5$) and therefore a nutritional imbalance indicating an excess of Ca in the soil in relation to Mg, the rest of the soils in the study area show a perfect Ca-Mg balance ($1 < Ca/Mg < 5$). This means that these soils are satisfactory and reflect a nutritional balance between Ca and Mg [38].

The balance between saturation rate and pH (Figure 7(b)) shows the influence of pH on the evolution of exchangeable bases in the soil. In the Foumban locality, soils with a good saturation rate ($S/CEC > 50\%$) include plagic hortic NITISOLS (arenic), chernic arenic UMBRISOLS, umbric arenic FERRALSOLS, mollic fragic NITISOLS (hortic), and nitic CHERNOSOLS (pretic). This reflects a low level of acidity in these soils. Soils with medium saturation are cambic FRAGISOLS (plagic), cambic hortic FERRALSOLS (plagic) on basalts, umbric pisoplinthic PLINTHOSOLS (haplic), cambic hortic FERRALSOLS (plagic) on trachytes, and pretic UMBRISOLS. This means that these soils are moderately ($5.3 < pH < 6$) acidic with average exchangeable cation contents. The pH-water values showing moderately acidic soils are a limiting factor for plant nutrition [61].

4.3. Criteria for Assessing the Fertility of Foumban Soils. The statistical analysis of the fertility parameters as well as the balances between these parameters made it possible to assess the current fertility status of the Foumban soils. Then, they were grouped into fertility classes according to Quemada and Cabrera [62] modified by Guemezi et al., [63]. This made it possible to define four levels of fertility for Foumban soils (Table 3).

Table 3: Criterion for assessing soil fertility classes [62] modified by Reference [63].

Characteristic	Level I (no limitation)	Level II (moderate limitation)	Level III (severe limitation)	Level IV (very severe limitation)
OM (%)	>2	100-2	0.5-1	<0.5
N (%)	>0.08	0.045-0.08	0.03-0.045	<0.03
P (ppm)	>20	10-20	5-10	<5
K (méq/100 g)	>0.4	0.2-0.4	0.1-0.2	<0. 1
S (méq/100 g)	>10	5-10	2-5	<2
S/CEC (%)	>60	40-60	15-40	<15
CEC (méq/100 g)	>25	10-25	5-10	<5
pHe	>5.5	5.1-5.5	4.75-5.1	<4.75
IB	≤1.4	1.6-1.4	1.8-1.6	≥1.8
IF	>1.5	—	—	<1.5
ISS	>9	7-9	5-7	<5
M (%)	<20	20-40	40-60	>60

Table 4: Foumban soil fertility assessment.

Soil group	pHeau	OM (%)	N (%)	K (méq/100)	SBE (méq/100)	CEC (méq/100)	P (ppm)	S/ CEC	IB (%)	ISS (%)	IF	m (%)	Fertility class	Limiting factor
Nipha	II	I	I	I	I	II	II	II	I	I	I	I	Good	pHe and P
Umca	III	I	I	I	I	II	II	II	I	I	I	I	Good	pHe and P
Flua	III	I	I	I	I	II	II	II	I	I	I	I	Good	pHe and P
Nimfh	III	I	I	I	I	II	III	I	I	I	I	I	Good	pHe and P
FLchp sur basalts	III	I	I	I	I	II	III	II	I	I	I	I	Average	pHe, P, CEC, and S/CEC
Pluph	III	I	I	I	II	II	III	II	I	I	I	I	Average	pHe, P, CEC, and S/CEC
CHnp	II	I	I	II	I	I	I	II	I	I	I	I	Good	pHe and K
Ump	II	I	I	II	II	II	III	III	I	II	IV	II	Average	IF, P, S/CEC, and pHe
FLchp sur trachytes	II	I	I	II	II	II	III	III	IV	III	IV	II	Poor	IF, ISS, IB, P, pHe, and S/ CEC
FGcp	III	I	II	I	II	II	III	II	IV	III	IV	I	Poor	IF, ISS, IB, P, pHe and, S/ CEC

(i) Level I: soils with no or low limitations.

(ii) Level II: soils with no more than three moderate limitations associated with low limitations.

(iii) Level III: soils with more than three moderate limitations associated with severe limitations.

(iv) Level IV: soils with more than one severe limitation.

According to the evaluation of soil fertility in Foumban (Table 4), three (03) classes of soil fertility can be differentiated.

(i) Class one (01) includes soils with a good level of fertility such as plaggic hortic NITISOLS (arenic) (NIpha), chernic arenic UMBRISOLS (UMca), umbric arenic FERRALSOLS (Flua), mollic fragic NITISOLS (hortic) (NImfh), and nitic CHERNOSOLS (pretic) (CHnp). They have medium-to-severe limitations in terms of water and phosphorus pH, except for the nitic CHERNOSOLS (pretic) (CHnp), which have rather average limitations in potassium and water pH. This means that these soils necessarily need an addition of CaO to improve their acidity.

(ii) Class two (02) includes soils with a medium level of fertility, such as pretic UMBRISOLS (UMp), cambic hortic FERRALSOLS (plaggic) (FLchp) on basalts, and umbric pisoplinthic PLINTHOSOLS (haplic) (PLuph). These soils have moderate-to-severe limitations in IF, S/CEC, pH-water, and CEC and moderate limitations in phosphorus. It is necessary to provide these soils with agricultural inputs rich in phosphate fertilizers, as well as fallowing for a long period of time, in order to allow for a reconstitution of the soil properties.

(iii) Class three (03) includes soils with a low level of fertility, such as cambic hortic FERRALSOLS (plaggic) (FLchp) on trachytes and cambic FRAGISOLS (plaggic) (FGcp). They have severe-to-very severe limitations in IF, ISS, IB, pHe, and S/CEC and moderate-to-severe limitations in P. This means that these soils need organic fertilizer inputs to repair the apparently very poor physical properties in order to facilitate good soil aeration and sufficient retention of infiltration water. Fallowing for a long

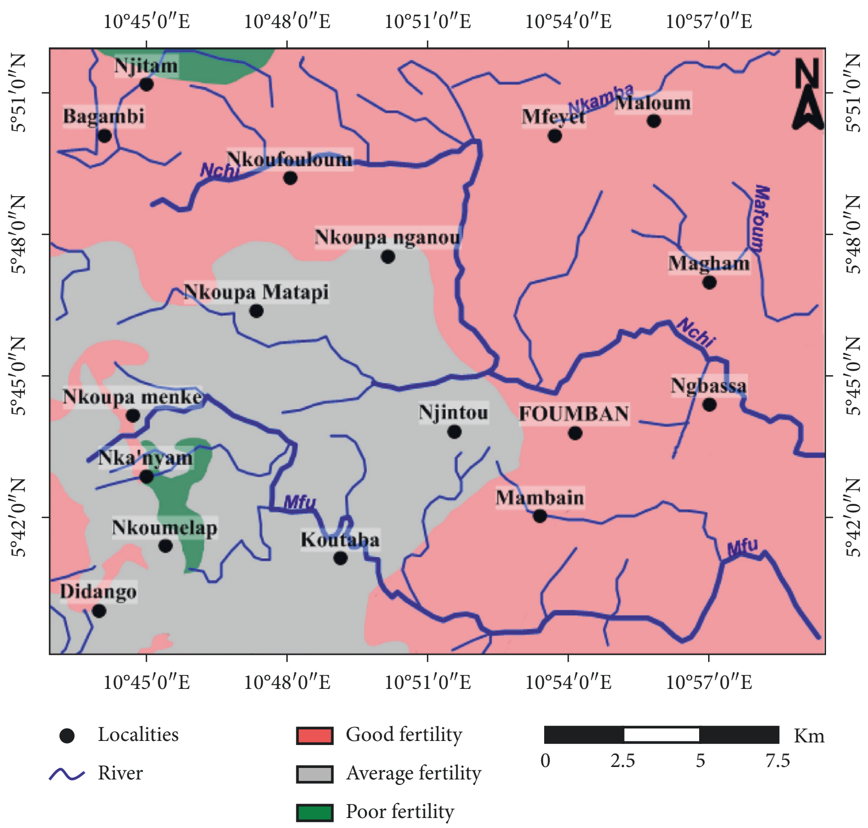


Figure 8: Foumban soil fertility map.

period is essential for good fertility of these soils. Lime is important to improve the acidity of these soils, which are at high risk of toxicity. A calcium amendment would favor the availability of P and Mg for the plant, which would facilitate root establishment.

4.4. Spatial Distribution of Fertility of Foumban Soils. The Foumban soil fertility spatial distribution map (Figure 8) shows that poorly fertile soils are located to the north and west of the study area. They cover 4.84% of the study area, or an area of about 38.47 Km^2. Average fertility soils are located to the west of the study area. They cover 28.50% of the study area, or an area of about 226.14 Km^2. Soils with good fertility are spread over the entire study area. They cover 66.65% of the study area, or an area of about 528.71 Km^2.

5. Conclusion

The objective of this study was to assess the fertility of Foumban soils based on physicochemical properties and fertility parameters. The data obtained in the laboratory were processed by the statistical method using the SPSS software, and it appears that Foumban soils have three fertility classes, namely: the class of soils with good fertility with an area of about 528.71 Km^2, the class of soils with average fertility with an area of about 226.14 Km^2, and the classes of soils with poor fertility with an area of about 38.47 Km^2. Principal component analysis (PCA) has revealed that the parameters that control fertility in Foumban soils are C/N, pHeau, Ca, CEC, MO, P, and Mg. The fertility assessment makes it possible to understand that the major problems of the soils in the study area are the risk of high acidity and phosphorus. To overcome this major problem, it would be wise for farmers to use lime (CaO) to reduce the risk of toxicity overall and to use calcium fertilizers that would promote the availability of P and Mg to plants. Soils with medium and poor fertility have a poor physical phase. An amendment of these soils in organic fertilizer (fluent, compost, and manure) would facilitate the formation of the clay-humus complex; thus, allowing good retention of water in the soil. Finally, an amendment in mineral fertilizer would correct the CEC and would bring a high rate of exchangeable cations to the soils; thus, increasing the sum of the bases. [64].

Data Availability

The (numerical type (numerical values)) data used to support the results of this study are included in the article.

Conflicts of Interest

The authors declare that they have no financial or nonfinancial conflicts of interest to disclose.

Authors' Contributions

All the authors contributed to the conception and design. Material preparation, data collection, and analysis were carried out by Vivien Piercy, Lotse Tedontsah, Michel Bertrand Mbog, and Robert Christel Edzoa. The principal component analysis (PCA) was carried out and interpreted by Jacque Etame. The first version of the manuscript was written by Bernard Tassongwa and revised by Gilbert Ngon Ngon and Dieudonné Bitom. The authors commented on the valuable versions of the manuscript. Finally, all authors read and approved the final manuscript.

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