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Physicochemical Parameters of Soils in the Poura Gold District: Mouhoun Sub-basin in Burkina Faso, West Africa

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Abstract: The physicochemical parameters of the soils made it possible to assess their fertility and pollution around the gold district of Poura. The 3-fraction granulometry indicates a dominance of sandy soils with a silty-sandy texture. The OM (Organic Matter) content is less than 1%, like most soils in Burkina Faso. The characterization of the fertility of the 26 composite soil samples indicates that 96.15% are of average fertility. The pollution assessment indicates that the measured pH values are between 5.5 and 8, therefore in accordance with the local reference standards in force, while the determination of the ratio of Al on the exchangeable bases and the low phosphorus contents express a very high aluminium toxicity. The electrical conductivities measured vary from 17.5 to 252 µS/cm, with a threshold limit of 2 µS/cm, expressing significant soil salinization. With the Pearson correlation matrix and the PC (Principal Component) analysis, the causes of pollution are attributable to the high contents of Al and exchangeable bases, linked to agricultural and mining activities. The analysis of the geological and pedological context indicates that the origin of Al and the exchangeable bases is natural, therefore pedo-geogenic, attributable to the destabilization of feldspars, ferromagnesian minerals and carbonates under supergene alteration.

Key words: Soils, fertility, pollution, salinization, Burkina Faso.

1. Introduction

Burkina Faso is a country located in the heart of West Africa where the main source of income for most of the population is agriculture [1-3]. It is one of the Sahel countries where food self-sufficiency constitutes a major challenge for the population. The loss of arable land is a recurring phenomenon in the Sahel, linked to climatic and anthropogenic activities [4, 5]. This situation is at the origin of the decline in agricultural productivity [6] undermining the economic health of the sector. Gold panning, which was once an off-season activity, has now become one of the country's main economic activities, given the low productivity of the soil. Gold panning employs more than 1.5% of the population with a production of 9.5 to 30 tonnes of gold per year [7, 8]. The gold mining district of Poura, which is the home to both the former industrial mine (SO.RE.MI.B.) operated from 1984 to 1999 and countless gold panning sites. It is also one of the areas

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with strong agricultural potential in Burkina Faso due to the favorable climatic context and irrigation by the Mouhoun River. The proliferation of artisanal mining and agricultural activities contributes to the deterioration of land quality [9-11]. This degradation could be physical, chemical or biological. Pollution, which is the consequence of natural or anthropogenic activities, constitutes a human and animal health problem [12-14]. The objective of the present study is to assess the physical and chemical characteristics of soils to not only determine their physical and chemical fertility, but also to diagnose the risk of pollution.

2. Materials and Methods

2.1 Study Area

The study area is 180 km southwest of Ouagadougou, the capital of Burkina Faso. It is located in the province of "Bales", Boucle du Mouhoun region, located between latitudes 11°20′ and 11°50′ North and longitudes 2°40′ and 2°55′ West (Fig. 1). The study area is drained by the Mouhoun River and its tributaries from the Lower Mouhoun sub-basin. It is known for its agricultural potential and belongs to the Sudano-Sahelian climatic zone, on the border with the Sudanian zone with an average rainfall of 892 mm/year and an average temperature of 28.8 ℃, recorded from 1991 to 2019 (Boromo synoptic station, 2020).

2.2 Methodology

The samples studied are composites of three to five sub-samples, at least 20 m apart. The sampling depth is 0 to 30 cm. Each sample is sieved with a standardized

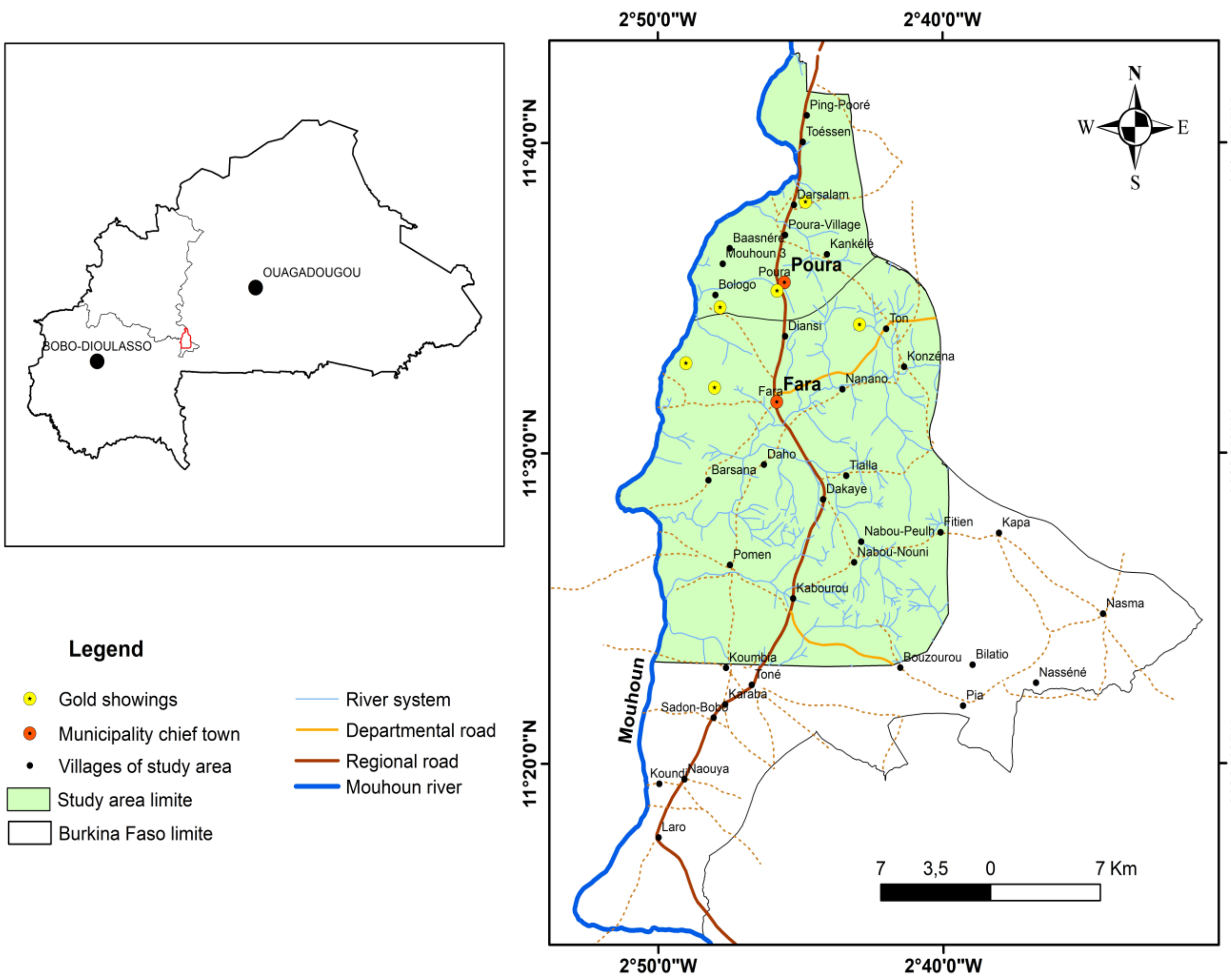


Fig. 1 Location of the study area.

(a) Depth measurement (b) Soil sampling for sieving

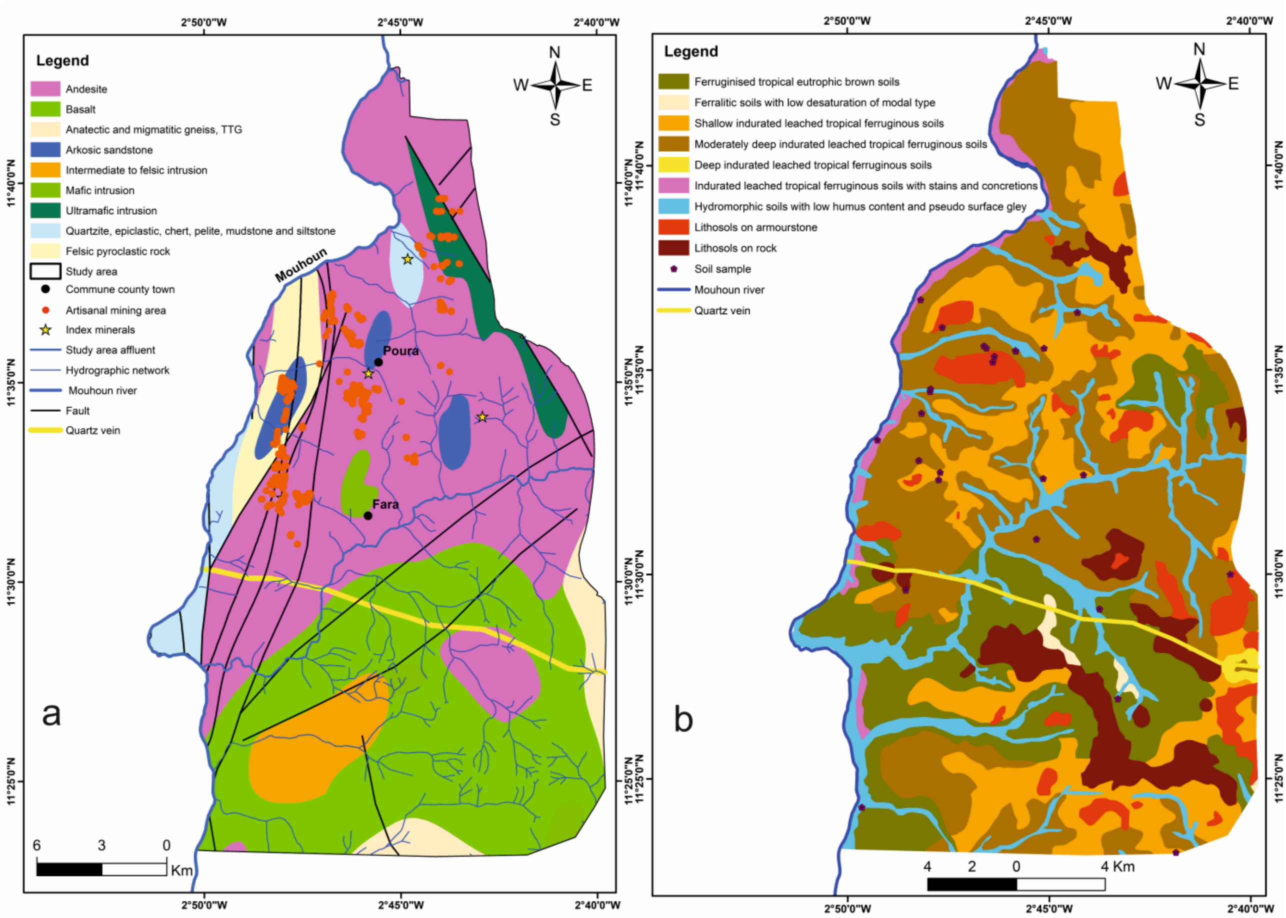
Fig. 2 Sampling method.

2 mm mesh sieve, brand "Anlysensieb ISO 3310-1", before being packaged in a sterile bag. Soil sampling was carried out using a crowbar, shovels and plastic dishes, previously decontaminated by rubbing it with the soil to be sampled. The sterile latex gloves used are changed at each point, to avoid contamination (Fig. 2). The mechanical preparation (drying, grinding and quartering) was carried out in the mineralurgy-metallurgy-environment laboratory of the BUMIGEB (Bureau of Mines and Geology of Burkina). The physicochemical analyses were carried out at the LEHSA (Water, Hydro-System and Agriculture) laboratory of the 2iE institute and at the analysis laboratory of the CID (Engineering Cabinet for Development) according to the required standards. The characterization of pollution was carried out by a comparative study between the results obtained and the reference standards of Burkina Faso of 2001, in accordance with the WHO (World Health Organization) prescription in terms of pollution and local standards [15].

3. Results and Discussions

3.1 Pedo-Geological Characterization of the Study Area

The geology of the study area is similar to that of the Boromo-Goren belt. The Birimian belt of the Poura sector comprises three types of formations: intrusive volcanic rocks, effusive and pyroclastic, volcano-sedimentary rocks and granitoid intrusions [16-18]. In the field, as in most Birimian formations of the West African craton, the rocks are covered by supergene alteration, and rarely outcrop [19-22]. The geological formations of the Poura gold district are characterized by andesites, basalts, migmatitic and anatectic gneisses, TTGs (Tonalites, Trondhjemites, Granodiorites), arkosic sandstones, felsic to intermediate intrusions, mafic and ultramafic intrusions, siltstones, argillites, pelites, cherts, epiclastites, quartzites and felsic volcanics (Fig. 3a). The few rare outcrops of rocks are highly metamorphosed and show evidence of polyphase deformation [16, 23-25]. All of these rocks are essentially composed of quartz, ferromagnesian minerals (muscovite, biotite, chlorite, amphibole, pyroxene) and generally calc-sodic feldspars (plagioclases). The soils resulting from the pedogenesis of these rocks are of nine (9) types: lithosols on rock, lithosols on cuirass, hydromorphic soils with little humus with pseudo gley surface, weakly desaturated ferralitic soils of typical modals, eutrophic tropical ferruginized brown soils, leached indurated tropical ferruginous soils with spots and concretions, medium-deep leached indurated tropical ferruginous soils, shallow leached indurated tropical ferruginous soils and deep leached indurated tropical ferruginous soils [26] (Fig. 3b). Their geochemical



(a) Geology (b) Pedology

Fig. 3 Geo-pedological maps of the Poura gold district.

composition is linked to the mineralogical nature of each rock material. The soils, which are mainly derived from meta-andesites and to a lesser extent from metabasalts, are rich in chemical elements such as Si^{4+}, Al^{3+}, Fe^{2+}, Fe^{3+}, Na^{+}, Ca^{2+}, K^{+} and Mg^{2+}, which would come from alteration minerals such as kaolinite, goethite, hematite, gibbsite, chlorite and oxyhydroxides [27, 28].

3.2 Evaluation of Soil Physicochemical Parameters

3.2.1 Granulometry and Texture

The particle size results indicate a heterogeneous particle distribution of sand, silt and clay in the samples (Fig. 4), with a dominant composition of sand, followed by silt and finally clay. The proportion of clay in the soils studied is between 5.88% and 39.22%, with an average of 15.91%. That of silt varies between 7.84% and 27.46%, with an average of 21.23%. The sand fraction is between 45.10% and 84.31% with an average of 62.86%. Studies carried out in North-Central Burkina Faso show similar results [4]. The projection of soils into the textural triangle allowed four textures to be identified: sandy silts (73%), sandy clay silts (15.38%), silty sands (7.69%) and sandy clays (3.85%) (Fig. 5). The dominance of coarse sandy-silty texture could negatively influence soil fertility with low retention capacity for OM (Organic Matter), nutrients and some TMEs (Trace Metal Elements) [3, 4, 29, 30].

3.2.2 pH

Hydrogen potential (pH) contributes to the determination of soil fertility, because it plays a major role in the balances of hydrolysis, precipitation, dissolution, oxidation-reduction, in the saturation of bases and the

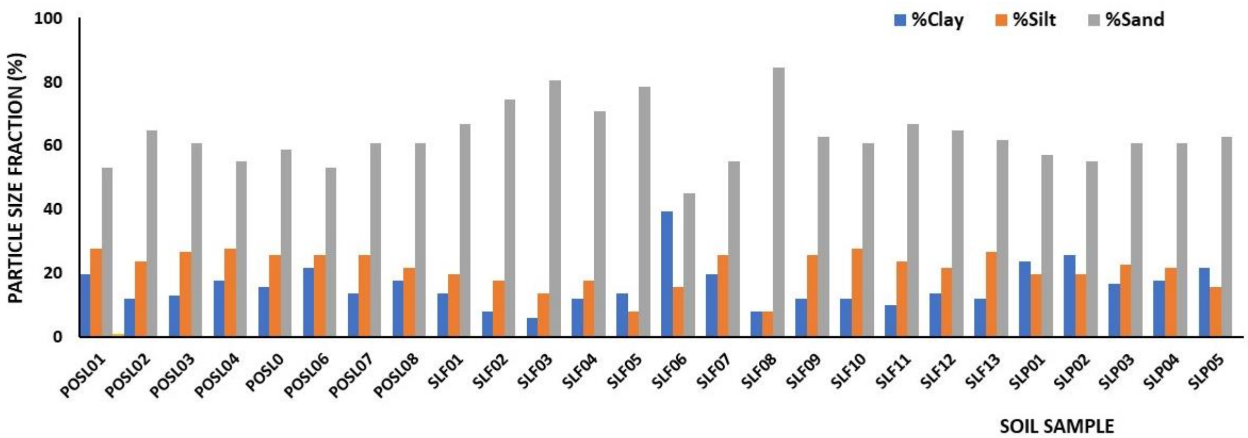


Fig. 4 Particle size distribution of soil samples.

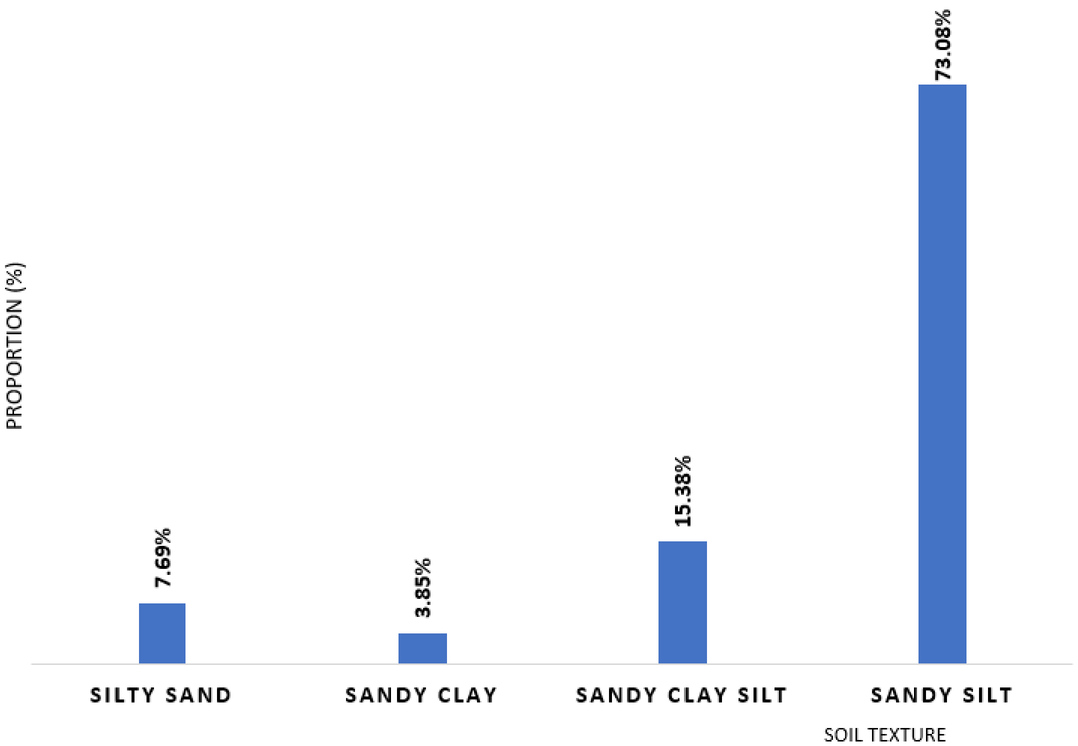


Fig. 5 Textural distribution of soils.

development of microorganisms [31]. The measured pH of the topsoil layers is between 6.17 and 8.03 with an average of 7.01. The pH of the soils studied varies from weakly acidic to strongly alkaline. These results corroborate those of some authors [31-33]. Based on pH, four soil types have been identified in the Poura gold district: weakly acidic soils (6.0 < pH < 6.6); neutral soils (6.6 < pH < 7.4); slightly alkaline soils (7.4 < pH < 7.9) and moderately alkaline soils (7.9 < pH < 8.5) (Fig. 6). Generally, pH between 5.5 and 6.5 indicates tropical ferruginous soils, pH between 6.5 and 6.8 indicates tropical red soils, and pH ranging from 6.5 to 8.0 corresponds to subarid soils including vertisols (6.7 to 8.5) [33].

3.2.3 Organic matter (OM)

The OM content of soils ranges from 0.42% to 0.96% with an average of 0.73%. The Burkina Faso land evaluation guide indicates that proportions below 0.5% are very low OM soils and those between 0.5% and 1% are low OM soils. Thus, the results show that 11.54% of

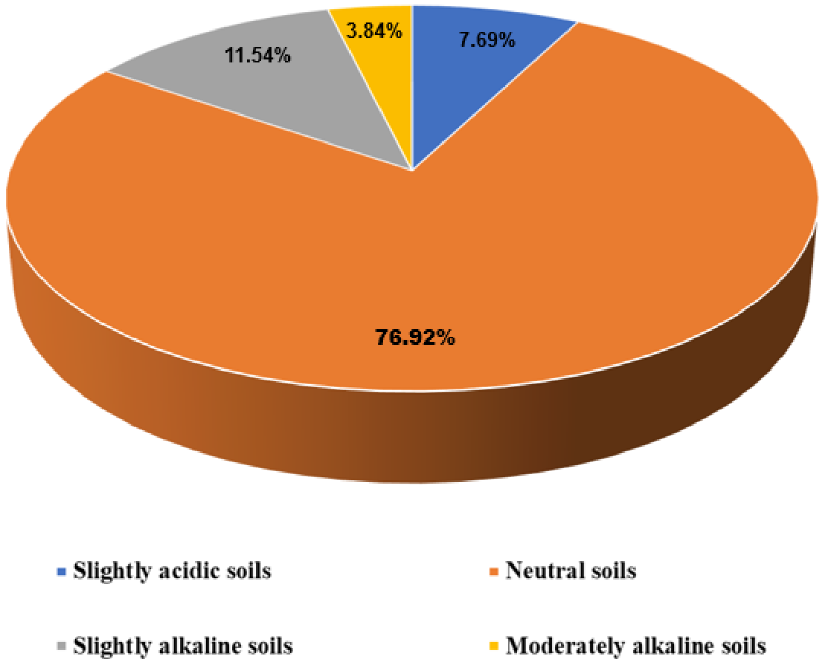


Fig. 6 Soil distribution according to pH.

the soils are very low OM, while 88.46% are low OM. These results are consistent with the trend observed in Burkina Faso with OM contents below 1% [34]. This observation could be explained either by soil leaching by runoff or by erosion towards watercourses [3, 32, 35], or by a migration of OM towards the subsoil in favor of the silty-sandy texture by infiltration or by percolation [3, 36]. The decrease in content may also be linked to a loss of plant cover through deforestation, due to anthropogenic pressures (agriculture and gold panning), low MO levels in the soil contribute to a decline in soil fertility and therefore impact on crop yields [37, 38].

3.2.4 Nitrogen Content

Soil nitrogen contents range from 0.03% to 0.08% with an average of 0.05%. Nitrogen contents are comparable to those of OM, with low concentrations. These contents are divided into two classes: low class (0.02% < N% < 0.06%) and medium class (0.06% < N% < 0.10%). Variation in nitrogen content is influenced by soil temperature, which affects microbial activity, through soil moisture, soil leaching or denitrification, cover crop destabilizing soil structure and promoting erosion, OM contents and soil properties [39-42].

3.2.5 C/N Ratio

The C/N ratio is a parameter that expresses the state of decomposition and quality of OM in the soil [3, 34]. It varies between 6.33 and 12.74, with an average of 8.91. The soils studied are divided into 3 classes: very low level soils (C/N < 8) which represent 50% of the samples, low level soils (8 < C/N < 10) corresponding to 3.85% and medium level soils (10 ≤ C/N ≤ 15) with a proportion of 46.15%. Soils with a C/N ratio < 10 correspond to exhausted soils, therefore with a low OM reserve. Medium level soils indicate soils with well decomposed OM and fairly stable humus [31, 34]. It could be deduced that the majority of the study area constitutes exhausted soil (54%) which would require the addition of agricultural fertilizers.

3.2.6 Phosphorus Content

Phosphorus concentrations range from 0.02 ppm to 16.90 ppm with an average of 2.50 ppm. There are also three classes based on their content: The very low class (P < 5 ppm), the low class (5 ppm < P < 10 ppm) and the medium class (10 ppm < P < 20 ppm). In general, a low phosphorus content is observed, similar to nitrogen and OM, indicating a depletion of soil nutrients.

3.2.7 Sum of Exchangeable Bases

The sum of exchangeable bases varies between 2.04 meq/100 g and 5.54 meq/100 g with an average of 3.40 meq/100 g. All soil samples studied indicate a low concentration of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+). The very low levels would indicate a nutrient depletion of the soils in the Poura gold district. Similar results were obtained in Madagascar and Gabon in acidic soils [43, 44]. As for the Cationic exchange capacity (CEC), it is between 2.9 and 6.9 meq/100 g, with an average of 5 meq/100 g. According to the characterization of the BUNASOLS (Bureau National des Sols) [32], the soils studied are divided into two categories: soils with very low CEC (CEC < 5 meq/100 g) representing 61.54% and soils with low CEC (5 < CEC < 10 meq/100 g) corresponding to 38.46%. The results show that the soils studied have a low capacity for retaining nutrients, linked to their poverty in OM and also to their silty-sandy texture, favoring a high porosity of the soil [3, 37, 45-48]. Taken individually, the contents of exchangeable bases are very low in the soil (Table 1). Ca^{2+} values range from 1.04 to 2.92 meq/100 g, with an average of 1.80 meq/100 g. Those of Mg^{2+} vary from 0.66 to 1.74 meq/100 g with an average of 1.07 meq/100 g. Na^+ contents range from 0.02 to 0.54 meq/100 g with an average of 0.11 meq/100 g. Finally, the K^+ contents vary between 0.11 and 1.16 meq/100 g, with an average of 0.42 meq/100 g. These low concentrations express a depletion of cations and nutrients in the soil.

3.2.8 Base SR (Saturation Rate)

The base SR expresses the occupation of the exchange complex of negative charges by cations: calcium, magnesium, potassium and sodium. This parameter corresponds to the ratio between the sum of exchangeable bases and the cation exchange capacity, expressed as a percentage. It is observed that there is a relationship between soil pH and the SR [31, 49-52]. The more neutral to alkaline the pH, the greater the SR (pH = 7.01; SR = 85%), while for acidic pH, the SR is low (pH = 6.53; SR = 56%). The SR is influenced by permeability, excess water and position on the slope. It represents a leaching index [32]. Depending on the SR, all soils are divided into three classes: moderately saturated soils (40% < SR < 60%), highly saturated soils (60% < SR < 80%) and very highly saturated soils (SR > 80%). These 3 types of soils represent respectively 19.23%, 73.08% and 7.69%.

3.3 Characterization of Soil Fertility

Soil fertility is defined as the capacity of a soil to provide the nutrients necessary for plant development [53]. The classification of soil fertility is treated according to the rating of physicochemical parameters in the land evaluation manual taking into account three parameters: OM, the sum of exchangeable bases and pH (Table 2). The results led to the determination of two soil types based on fertility (Table 3): low fertility soils, unfavorable to the good development of plants (3.85%) and soils of average fertility, favoring an acceptable environment for the development of plants (96.15%). The spatial distribution of fertility in the study area is synthesized in a map produced by the IDW (Inverse Distance Weighting) interpolation method with ArcMap 10.8.1 software (Fig. 7). The results show a depletion of the soil, despite the fact that the sampling period coincides with that of agricultural activities, implying a contribution of agricultural inputs. This recorded fertility could be explained either by the silty-sandy texture or by the low contents of OM, exchangeable bases and nutrients, due to leaching by percolation [5] and the intensification of land exploitation [54-56].

Table 1 Physicochemical parameters of soils.

Sample			Granulometry (%)									Exchangeable bases (meq/100 g)					
	pH	EC	Clay	Silt	Sand	OM (%)	N (%)	P (mg/L)	C/N	∑bases (meq/100 g)	CEC (meq/100 g)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SR	Al^{3+} (meq/100 g)
SLF04	8.03	252	19.61	27.45	52.94	0.75	0.03	16.9	12.74	5.46	6.9	2.75	1.33	0.54	0.84	79	73
SLF09	7.14	65.1	11.76	23.53	64.71	0.65	0.03	0.21	11.09	4.03	5.9	2.08	1.25	0.09	0.61	68	282
SLF13	7.65	90.1	12.75	26.47	60.78	0.81	0.04	0.73	11.44	3.85	6.9	1.77	1.34	0.16	0.58	56	241
SLF06	6.85	69.3	17.65	27.45	54.9	0.69	0.04	3	10.53	3.95	4.9	2.13	1.01	0.14	0.67	81	483
SLF07	6.68	124.4	15.69	25.49	58.82	0.76	0.04	0.33	11.53	4.72	6.1	2.17	1.33	0.14	1.08	77	397
SLP03	7.05	32.7	21.57	25.49	52.94	0.63	0.05	0.58	6.87	2.6	3.9	1.25	0.79	0.05	0.51	67	194
POSL07	6.81	32.4	13.73	25.49	60.78	0.49	0.05	3.5	6.33	2.57	4.2	1.33	1.02	0.09	0.13	61	234
SLF05	6.91	28.4	17.65	21.57	60.78	0.87	0.05	0.78	10.31	3.42	4.68	1.88	1.04	0.09	0.41	73	771
SLP04	6.53	32.4	13.73	19.6	66.67	0.63	0.05	0.26	7.47	2.75	4.9	1.46	0.87	0.05	0.37	56	293
POSL01	6.17	45.6	7.84	17.65	74.51	0.73	0.06	0.23	7.4	3.64	5.42	2.29	1.09	0.02	0.24	67	427
POSL04	6.93	63.4	5.88	13.73	80.39	0.92	0.08	5.9	6.41	3.14	4.98	1.88	1.07	0.02	0.17	63	323
SLF01	7.1	91.4	11.76	17.65	70.59	0.96	0.05	0.3	10.49	3.59	4.9	2.08	1.03	0.14	0.34	73	329
SLF02	7.13	34.1	13.73	7.84	78.43	0.86	0.05	0.27	11.11	2.93	5	1.78	0.76	0.09	0.3	59	249
SLF08	7.04	50.4	39.22	15.68	45.1	0.66	0.04	0.32	10.11	2.58	3.7	1.04	0.97	0.14	0.43	70	95
SLF10	6.61	26.8	19.61	25.49	54.9	0.68	0.05	0.24	8	3.16	4.9	1.67	0.84	0.14	0.51	64	231
SLF11	7.03	31.9	7.84	7.85	84.31	0.77	0.04	0.64	10.93	3.61	5.9	1.67	1.33	0.07	0.54	61	229
POSL08	6.62	61.9	11.76	25.49	62.75	0.43	0.03	11.7	7.35	2.67	4.3	1.45	1.02	0.07	0.13	62	361
SLF03	6.86	17.5	11.76	27.46	60.78	0.71	0.04	0.17	10.89	2.16	2.9	1.04	0.89	0.12	0.11	74	182
SLF12	7.75	218	9.8	23.53	66.67	0.89	0.05	0.23	10.55	5.54	6.9	2.92	1.34	0.12	1.16	80	329
SLP01	6.77	88.9	13.73	21.56	64.71	0.8	0.07	3.12	6.82	3.86	6.9	2.5	1.07	0.12	0.17	56	523
SLP02	7.24	45.7	11.76	26.48	61.76	0.7	0.06	1.28	6.92	4.13	5.9	2.08	1.74	0.07	0.24	70	330
SLP05	6.7	42.3	23.53	19.61	56.86	0.42	0.03	0.37	7.15	2.05	3.02	1.04	0.66	0.05	0.3	68	257
POSL02	6.86	113.2	25.49	19.61	54.9	0.8	0.06	0.02	7.28	2.28	3.9	1.39	0.66	0.03	0.2	58	137
POSL03	7.2	51.8	16.67	22.55	60.78	0.93	0.07	3.8	7.47	2.04	3.3	1.16	0.72	0.03	0.13	62	173
POSL05	7.01	152.1	17.65	21.57	60.78	0.78	0.06	7.6	7.58	4.18	4.9	2.29	1.57	0.12	0.2	85	453
POSL06	7.48	81.8	21.57	15.68	62.75	0.74	0.06	2.5	6.92	3.55	4.82	1.58	1.18	0.28	0.51	74	258
Min	6.17	17.5	5.88	7.84	45.1	0.42	0.03	0.02	6.33	2.04	2.9	1.04	0.66	0.02	0.11	85	771
Max	8.03	252	39.22	27.46	84.31	0.96	0.08	16.9	12.74	5.54	6.9	2.92	1.74	0.54	1.16	56	73
Average	7.01	74.75	15.91	21.23	62.86	0.73	0.05	2.50	8.91	3.40	5	1.80	1.07	0.11	0.42	68	311
BF2001	5.5-8	2	-	-	-	-	-	-	-	-	-	-	--	-	-	-	-

Table 2 Interpretation of soil rating and fertility [32].

Interpretation		Very low	Low	Medium	High	Very high
OM	%	OM < 0.5	0.5 < MO < 1	1 < MO < 2	2 < MO < 3	MO > 3
	Rating	1	2	3	4	5
∑Bases	meq/100 g	< 1	1 < ∑B < 6	6 < ∑B < 11	11 < ∑B < 16	∑B > 6
	Rating	1	2	3	4	5
pH_{water}	Value	> 9 < 4.5	8.5-9 4.6-5	7.9-8.4 5.1-5.5	7.4-7.8 5.6-6	6.1-7.3
	Rating	1	2	3	4	5
Soil fertility	Value	< 4.4	4.5-7.5	7.6-10.5	10.6-13.5	> 13.6

Table 3 Rating of physicochemical parameters and soil fertility of Poura.

Sample	Rating (pH)	Rating (Σ bases)	Rating (OM%)	∑Rating	Fertility
POSL 01	5	2	2	9	Medium
POSL 02	5	2	2	9	Medium
POSL 03	5	2	2	9	Medium
POSL 04	5	2	2	9	Medium
POSL 05	5	2	2	9	Medium
POSL 06	4	2	2	8	Medium
POSL 07	5	2	1	8	Medium
POSL 08	5	2	1	8	Medium
SLP 01	5	2	2	9	Medium
SLP 02	5	2	2	9	Medium
SLP 03	5	2	2	9	Medium
SLP 04	5	2	2	9	Medium
SLP 05	5	2	1	8	Medium
SLF 01	5	2	2	9	Medium
SLF 02	5	2	2	9	Medium
SLF 03	5	2	2	9	Medium
SLF 04	3	2	2	7	Medium
SLF 05	5	2	2	9	Medium
SLF 06	5	2	2	9	Medium
SLF 07	5	2	2	9	Medium
SLF 08	5	2	2	9	Medium
SLF 09	5	2	2	9	Medium
SLF 10	5	2	2	9	Medium
SLF 11	5	2	2	9	Medium
SLF 12	4	2	2	8	Medium
SLF 13	4	2	2	8	Medium

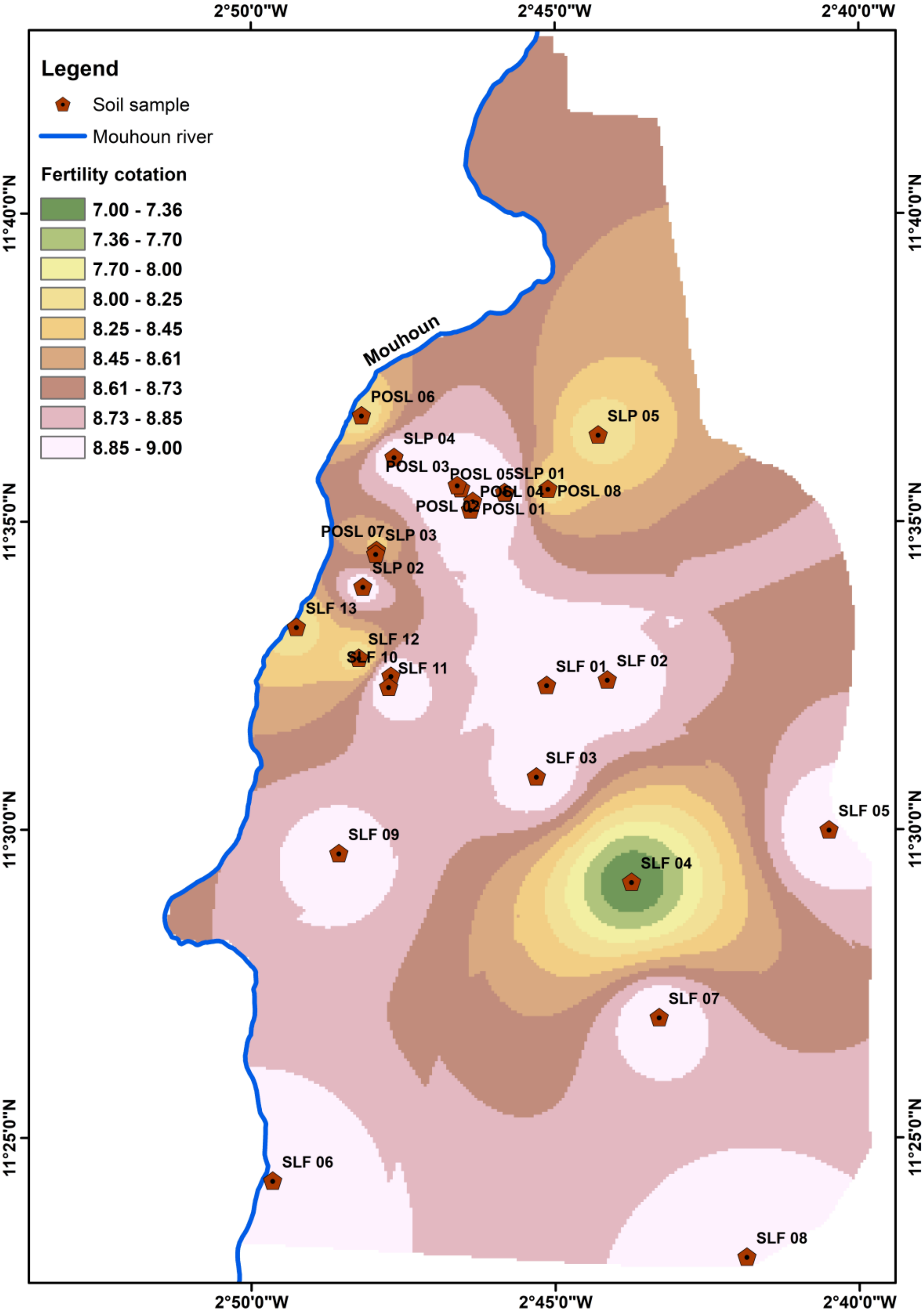


Fig. 7 Spatial distribution of soil fertility.

3.4 Characterization of Soil Pollution

The assessment of soil pollution in this study is carried out according to the 2001 standards of Burkina Faso, establishing standards for the release of pollutants into the air, water and soil. pH and EC are the two physicochemical parameters used to determine soil pollution. pH, EC and CEC influence nutrient bioavailability, plant growth, pollutant behaviour and biological activity [57]. Soil pollution is multiple and varied, but this study will focus on aluminum toxicity and salinization. The assessment of soil Al^{3+} toxicity generally depends on the pH value, and that of salinization on the EC values [58]. Soil salinization is one of the most devastating phenomena worldwide, especially in arid to semi-arid areas with serious land degradation, reduction in cultivable areas and reduction in crop production, and therefore agricultural insecurity [59-63].

3.4.1 Aluminum Toxicity

It is generally expressed at very acidic pH (pH < 5) [32, 60, 64]. However, it seems that aluminum toxicity is not only related to acidic pH, but can also be expressed by the ratio of Al^{3+} to the sum of exchangeable bases plus the Al^{3+} content [65-67]. When this ratio is greater than 30% on average, it expresses aluminum toxicity [67]. According to the same authors, this toxicity can also be expressed by phosphorus deficiency. Analysis of the soil pH results indicates that the values are within the standardized pH range (5.5 < pH < 8), thus indicating conformity between the measured pH and the reference pH (Fig. 8). Therefore, the pH does not indicate any aluminum toxicity, as it is greater than 6.

The determination of the ratio *m* is given by the Kamprath formula [68]:

$$m = \frac{Al}{\sum bases + Al} * 100$$

It is observed that the ratio *m*, in this present study, varies between 93% and 99.6%, which is far above the required threshold limit. This would therefore indicate high aluminum toxicity. As for the phosphorus content, it is between 0.02 and 16.90 ppm with an average of 2.50 ppm. The phosphorus levels are very low in the majority and indicate a phosphorus deficiency in the soil, thus expressing severe aluminum toxicity [65, 66].

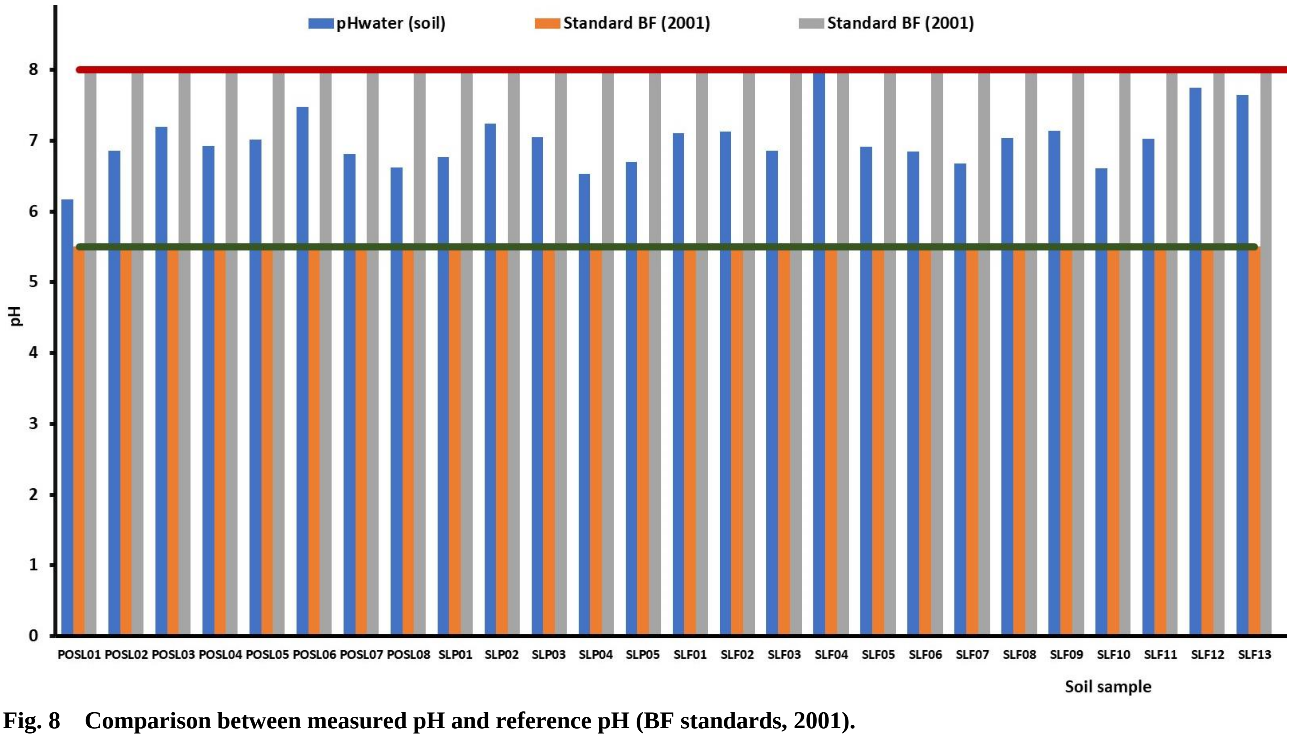


Fig. 8 Comparison between measured pH and reference pH (BF standards, 2001).

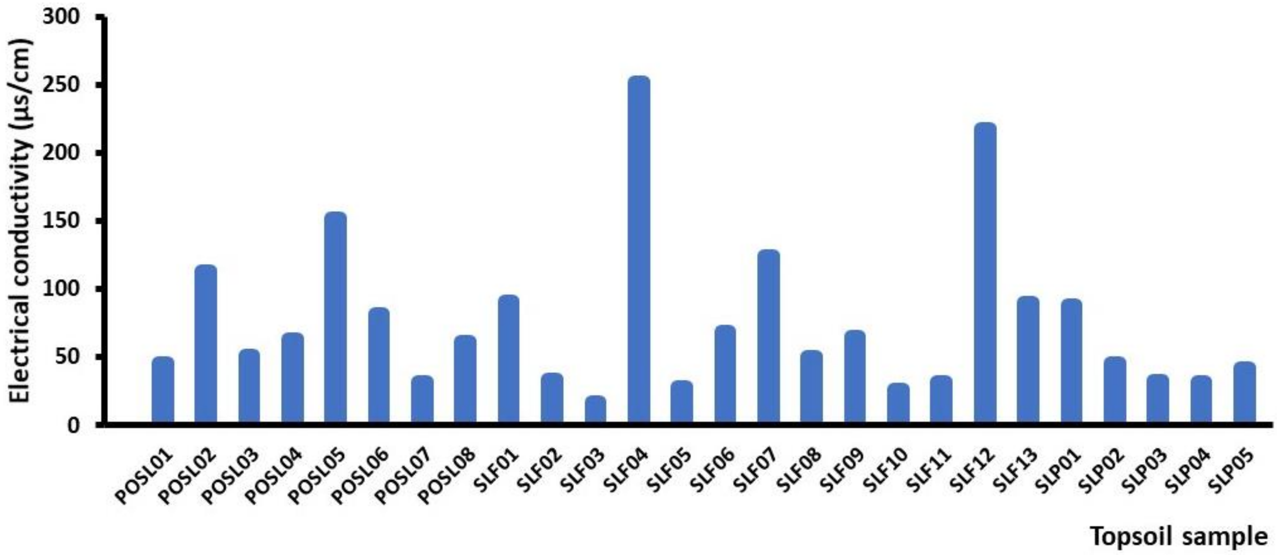


Fig. 9 Electrical conductivity of topsoil (BF standards, 2001 of EC = 2 µS/cm).

3.4.2 Salinization

EC results show high measured values compared to standards (EC > 2 µS/cm) (Fig. 9). Electrical conductivity ranges from 17.5 to 252 µS/cm, with an average of 74.75 µS/cm. It expresses the quantity of soluble salts in a soil and consequently, the salinity and alkalinity of the soil [58]. EC values > 5 µS/cm would indicate high soil salinization [32]. The EC contents, which are sufficiently very high, therefore show a strong salinization of the soils studied.

3.4.3 Sources and Origins of Pollution

Table 4 indicates a strong positive correlation between pH and the following parameters: EC (α = 0.62); C/N (α = 0.45), ∑bases (α = 0.50), CEC (α = 0.41), Mg^{2+} (α = 0.40), Na^+ (α = 0.64) and K^+ (α = 0.46), which means that exchangeable bases play an important role in increasing pH, thus in neutralizing acidic pH to neutral to alkaline pH. The correlation of pH with Al^{3+} is significantly negative (α = -0.34). This indicates that if Al^{3+} increases, the pH decreases and if Al^{3+} decreases, the pH increases. It is noted that all samples with a content greater than 330 meq/100 g in Al^{3+}, have a pH between 6.17 and 7.01 (Table 3), therefore relatively acidic to neutral. These observations express both salinization and aluminum toxicity. While Al^{3+} influences the acidification of the soil solution, the other cations play a neutralizing role [61]. Also, we note a very significant negative correlation of Al^{3+} with sand (α = -0.78) and yet positive with clay (α = 0.47) (Table 4). This would mean that the clay facilitates its retention in the surface soil, while the sand, which constitutes a porous medium, causes it to be leached towards depth. Al^{3+} mineralization is probably linked to the dissolution of aluminous minerals in an acidic medium, facilitating their release, but also to the fine fraction, which has a very high specific surface area for their retention [61, 69, 70]. Therefore, any possible toxicity can only be based on Al^{3+}. This observation corroborates that of certain authors who generally attribute soil toxicity to Al^{3+} [32, 71, 72].

Analysis of EC indicates a significantly positive correlation with P (α = 0.52), ∑bases (α = 0.75), CEC (α = 0.56), Ca^{2+} (α = 0.70), Mg^{2+} (α = 0.44), Na^+ (α = 0.64), K^+ (α = 0.57) and SR (α = 0.50). This correlation could justify the strong mobilization of exchangeable bases to neutralize the acidic soil environment, involving a mineralization of cations, therefore salinization. Silt correlates negatively with sand (α = -0.65) indicating the grain size difference. Sand shows a positive correlation with C/N (α = 0.46). OM is positively correlated with N (α = 0.55) and Ca^{2+} (α = 0.43). These observations could be due to their low mineralization in the soil, noted from their characterization. Nitrogen shows a highly significant negative correlation with

Table 4 Pearson's correlation matrix.

	pH	EC	Clay	Silt	Sand	OM	N	P	C/N	∑bases	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SR	Al^{3+}
pH	1																
EC	0.621	1															
Clay	-0.221	0.003	1														
Silt	-0.061	0.101	0.032	1													
Sand	0.206	-0.065	-0.783	-0.647	1												
OM	0.370	0.296	-0.194	0.080	0.098	1											
N	-0.120	-0.087	0.140	0.351	-0.325	0.546	1										
P	0.316	0.521	0.066	0.046	-0.079	-0.125	-0.115	1									
C/N	0.450	0.350	-0.314	-0.345	0.455	0.303	-0.600	0.013	1								
∑bases	0.500	0.748	0.207	0.119	-0.232	0.331	-0.110	0.277	0.481	1							
CEC	0.415	0.557	0.135	0.260	-0.265	0.333	-0.009	0.173	0.381	0.870	1						
Ca^{2+}	0.330	0.700	0.264	0.153	-0.296	0.426	0.100	0.282	0.325	0.923	0.846	1					
Mg^{2+}	0.401	0.441	0.162	0.174	-0.232	0.160	-0.023	0.244	0.236	0.771	0.687	0.633	1				
Na^{+}	0.642	0.638	-0.055	-0.156	0.139	0.066	-0.339	0.584	0.483	0.551	0.400	0.395	0.319	1			
K^{+}	0.455	0.574	0.075	0.010	-0.064	0.153	-0.410	-0.036	0.620	0.728	0.568	0.515	0.352	0.458	1		
SR	0.287	0.501	0.234	-0.258	-0.018	0.109	-0.210	0.223	0.345	0.535	0.063	0.416	0.431	0.434	0.463	1	
Al^{3+}	-0.337	-0.092	0.470	-0.170	-0.253	0.168	0.204	-0.089	-0.066	0.259	0.227	0.407	0.235	-0.242	-0.015	0.213	1

Values in bold are different from 0 at a significance level of Alpha=0.05.

C/N (α = -0.60) and K^+ (α = -0.41), indicating that N mineralization negatively affects OM decomposition and potassium mineralization [15]. Phosphorus shows a positive correlation with Na^+, illustrating their common role in plant growth [73, 74]. The C/N ratio shows a significant positive correlation with ∑bases (α = 0.48), Na^+ (α = 0.48) and a strong correlation with SR (α = 0.62). The sum of bases (∑bases) indicates a very strong positive correlation with CEC (α = 0.870), Ca^{2+} (α = 0.92), Mg^{2+} (α = 0.77), Na^+ (α = 0.55), K^+ (α = 0.73) and SR (α = 0.54). This observation confirms the dependence of the sum of the bases on the set of exchangeable bases. Ca^{2+} shows positive and significant correlations with Mg^{2+} (α = 0.63), Na^+ (α = 0.39), K^+ (α = 0.52), SR (α = 0.42), but also with Al^{3+} (α = 0.41). The link between Ca^{2+} and Al^{3+} could correspond to a relationship on their mineralogical or substitution origin [61, 75, 76]. Mg^{2+} shows a positive correlation with SR (α = 0.43), hinting at the link between the other bases. As for Na^+, it expresses a positive correlation with K^+ and SR, which could correspond to their nutritional role and their monovalence [61, 76]. Finally, the K^+ parameter shows a significant positive correlation with SR, thus a behavior similar to that of Mg^{2+} and Na^+, all playing a nutritional role in plant growth and therefore, soil fertility [77].

PCA (Principal Component Analysis) of soil physicochemical parameters indicates three (3) distinct groups: G1, G2 and G3 (Fig. 10). We note that all the parameters of G1 are grouped around the F1 axis and those of G2 and G3 are grouped around F2. The contribution of F1 in PCA corresponds to 35.35% of variability, while that of F2 is 18.70% of variability, including a total of 54.05% which is a largely significant proportion. The F2 axis could express the mineralization of Al^{3+} and nitrogen linked to the granulometry, of which the sand fraction would facilitate their mobility by leaching and their retention in the fine fractions. The origin of Al^{3+} is generally natural, but their concentration could be favored by anthropogenic activities such as agricultural and mining activities, which influence the structure of the soil [62, 78-80]. The parameters of G1 around F1, essentially the exchangeable bases, are of pedogenic and therefore natural origin [57, 77]. Since the increase in EC is attributable to Al^{3+} levels and exchangeable bases, it could be assumed that the pollution risk is both natural and anthropogenic. The ions involved

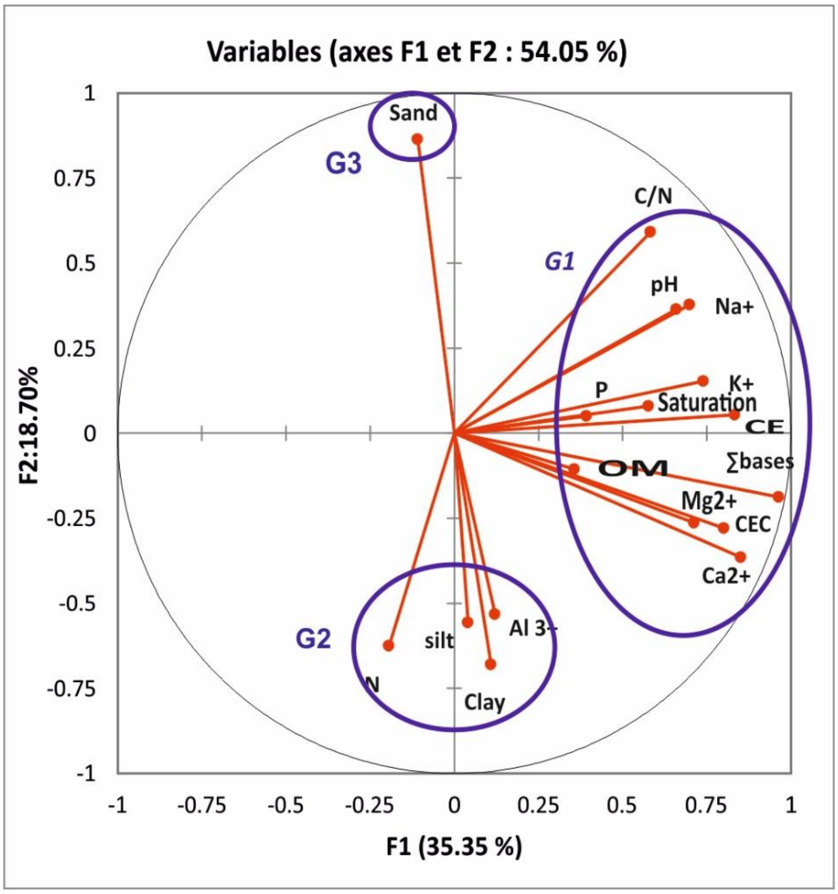


Fig. 10 Principal component analysis of soil physicochemical parameters.

could come from the destabilization of plagioclases, certain ferromagnesians, carbonates of acidic, basic and even sedimentary rocks, linked to supergene alteration.

4. Conclusion

The physicochemical parameters of the soils studied indicate generally low contents. The texture of the soils is mainly silty-sandy with a predominance of the sand fraction. OM, which is an important component of the soil, has a content of less than 1% like most soils in Burkina Faso. The soil fertility assessment of the study area generally indicates average fertility. Investigation into soil pollution through physicochemical parameters has highlighted a high risk of aluminum toxicity and salinization. The pollution would probably be linked to the mobilization of high concentrations of aluminum and exchangeable bases, due to the intensity of agricultural and mining activities in this sub-basin of Mouhoun. The Pearson correlation matrix and the PCA analysis contributed to the conclusion that the chemical elements involved would come mainly from plagioclases, certain ferromagnesian minerals and carbonates, favored by a birimian-type geological context with strong supergene alteration.

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