Physico-chemical and biological degradation of the soils of the Lower Sambirano plain, Ambanja District, North-West of Madagascar

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ABSTRACT

The soils of the Lower Sambirano plain are degraded following the pressures of human activities and frequent flooding. This study aims to provide diagnostic elements on the physico-chemical properties of the soils of the study area in order to assess the state of their degradation. Soil samples on 17 profiles distributed in 7 different sites were taken and analyzed at the FOFIFA Madagascar Laboratory. The analysis results obtained were compared with the reference values.

These results show that dark colored soils ranging from dark brown (10YR, 6/3) to black (10YR, 2/1), sandy loam to sandy clay loam soils (balanced textures) and sandy loam soils (balanced textures) and clayey to clayey (clayey texture), acid to slightly basic pH (4.5 to 7.4). These soils are very rich in assimilable phosphorus, manganese, and rich in total calcium, potassium, CEC and V. This indicates that the nutrient retention capacity is sufficient. Then, they are moderately rich in organic carbon, organic matter, magnesium and a sum of exchangeable cations (S). Indeed, the contents of total nitrogen and particularly of sodium proved to be deficient but despite this, the C/N ratio is sufficient.

All of these results lead to the conclusion that the soils of the study area have average but very fragile fertility. However, additional morphoscopic analysis on other samples and that of the Al and Si elements are recommended to check whether these soils are toxic. Accompanying measures to restore these soils are therefore necessary in view of the risks they may incur.

Keywords: *Soil, Lower Sambirano, degradation, physico-chemical properties, profile, flooding.*

1. INTRODUCTION

Soil is one of the most vulnerable natural resources in the world due to the pressures it is under. It is considered a consumable resource that is very slowly renewable but rapidly degraded (Céline C., 2006). Because of its multiple functions, it contributes to human well-being through the ecosystem services it provides (Barrios, 2008). It is a major reservoir of all chemical elements. However, land degradation is increasingly becoming a global phenomenon that continues to grow. Thus, a partial or total destruction of the pedological structure and a reduction in the fertility of the soil, can appear whatever the type of use, this is why, the exploitation of the soil in the long term must s accompanied by measures to conserve this "soil capital". For this, a study of the physico-chemical parameters must be taken into account.

As in Madagascar and for most African countries, agriculture remains one of the keys to economic and social development. It uses natural resources like soil to grow.

Among others, known as the Sambirano River, the District of Ambanja, located in the North-West of Madagascar, is one of the Districts with an agricultural vocation, especially in terms of cash crop and rice cultivation.

This agriculture remains the main source of income for its population; therefore, available land resources are gradually being transformed into agricultural land.

Lately, these lands are increasingly threatened by human activities caused by:

- The increase in pressures due to accelerated population growth,
- Natural disasters which can alter the quality of the soil through severe erosion leading to an environmental imbalance.

Indeed, Lower Sambirano is the area most affected by frequent floods with multiple consequences.

Thus, the overall objective of this article is to diagnose and assess the physico-chemical degradation of soils and its impacts in the study area in order to preserve the quality of these soils by establishing a number of recommendations.

The identification and characterization of soils consists of taking samples in the field in order to carry out detailed physical and physico-chemical analyzes in the laboratory. The following parameters were considered: color, particle size, electrical conductivity, pH, C.org, MO, Ntotal, assimilable P, exchangeable bases (Ca, Mg, K, Na), Mn, CEC, base saturation (V), sum of bases (S).

2. MATERIAL AND METHODS

This study was carried out in the plain of Lower Sambirano, District of Ambanja, North-West of Madagascar.

The study area is limited to the north by the rural commune of Antsakoamanondro, to the east by the rural commune of Benavony, to the south by the rural commune of Antranokarany and to the west by the sea (Figure 1). It is characterized by a relatively flat topography where land use is dominated by agricultural and urban activities.

The study area has a hot tropical climate. But thanks to the existence of the Tsaratanana massif in the East and that of Manongarivo in the South, this region has a specific microclimate of the hot and humid tropical type with an average annual rainfall greater than or equal to 1748mm (PIC, 2015; HELVETAS, 2018) thus protected from the drying SE trade winds (Humbert & Cours Darne, 1965 and Donque, 1972 in Ralisoa, 2000; Rafehimanana, 2012; HELVETAS, 2018). Geologically, the study area is made up of sedimentary formations dating from the Upper Liassic to the Middle Jurassic and postliasic volcanic formations (Miocene to the Quaternary) resting on frankly crystalline substrates (Donnot, 1963; Rakotovao et al. , 2009).

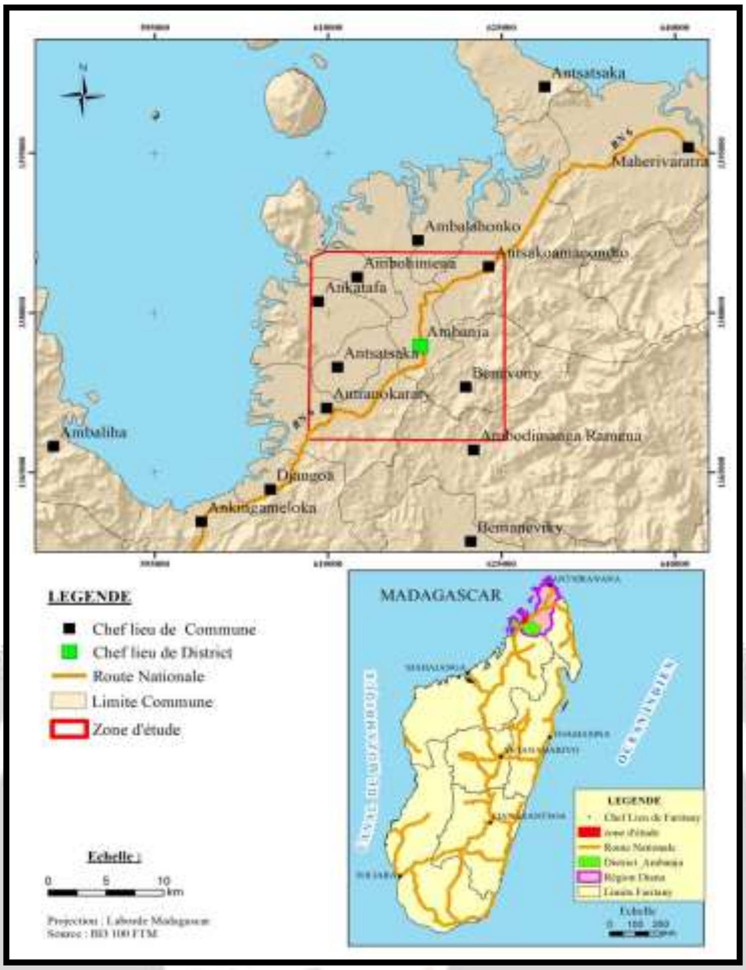


Fig -1 : Location map of the study area

2.1 Method

Soil samples were taken on 17 profiles, distributed over the entire study area (7 sites), in order to obtain more information on the state of soil degradation. The samples taken were then placed in plastic bags that were coded as follows: PABF-I-1, PABF-I-2, PABF-I-3, etc..., with P = Profile, ABF = locality, I = profile number, 1 = horizon number. The listed samples were then sent to the laboratory for routine analysis (physical, chemical and physico-chemical).

2.2 Analysis of samples in the laboratory

All analyzes were made following the protocol in force at the soil laboratory of FOFIFA-Madagascar (table 1). The analyzes focused on granulometry, pH-water, electrical conductivity, organic constituents (organic carbon and total nitrogen), assimilable phosphorus, manganese, CEC, exchangeable bases (Ca2+, Mg2+, K+, Na+).
Then, the soil quality evaluation standards were used for all parameters (Rabe Patrick, 2018), except for the pH scale (Baize, 2000) and for CE, the soil salinity scale (Benabadji et al., 1996).

Table-1 : analysis protocol at the FOFIFA laboratory - Madagascar

Parameters	Method of analysis
Color	Color Chart Munsell
Granulometry	Tamis Φ = 2mm, Gauge from a 1l gauged cylinder with a Bouyoucos densimeter
Electrical conductivity	Extraction diluted to 1/5
pH	pH meter using a glass electrode
Organic carbon	Bouyoucos method

Organic matter	C.org x 1.724
Total nitrogen	Kjehdahl using selenium catalyst
Assimilable phosphorus	Truog method using UV/VIS spectrometer and ammonium molybdate solution
Manganese	Colorimetric method with powdered potassium reagent
Exchangeable bases (Ca, Mg, k and Na)	Atomic absorption spectrophotometry with NH+ acetate
Sum of exchangeable bases (S)	S = Σ Ca + Mg + K + Na
CEC = T	Kjeldahl or (Metson): use of ammonium acetate at pH 7 and distillation
Base saturation (V)	$V = (S X 100)/T$

(Source: Author, 2023)

The statistical treatments of the obtained data were carried out by ACP, ANOVA and Classic Excel.

3. RESULTS AND INTERPRETATIONS

3.1 Color

By the Munsell code method, the results give a dominance of color ranging from dark brown (7.5YR, 2.5/3 to 10YR, 6/3) to black (10YR, 2/1) on the plain, especially under- forestry (cacao, coffee, etc...). Reddish brown colorations were observed on the soil of the periphery (at the bottom of the slope).

3.2 Granulometry

In this study, the identification of the soil texture was based on the grain size analysis characterized by the dimensional distribution of the elementary particles of the constituent material of the soil. The Principal Component Analysis (PCA) shown in figure 2 gives the result of the variances on the principal axes (F1, F2), and the cumulative percentages of inertia of the grain size of the samples. It reveals that, the F1 axis represents the first principal component constituting 88.21% of the percentage of inertia of all the samples. This axis is constructed by the percentage of sands with a positive correlation, and the silt and clay contents correlated negatively. The F2 axis explains the second principal component which is 11.79% of the variance. It is formed by silt with a positive correlation with clay.

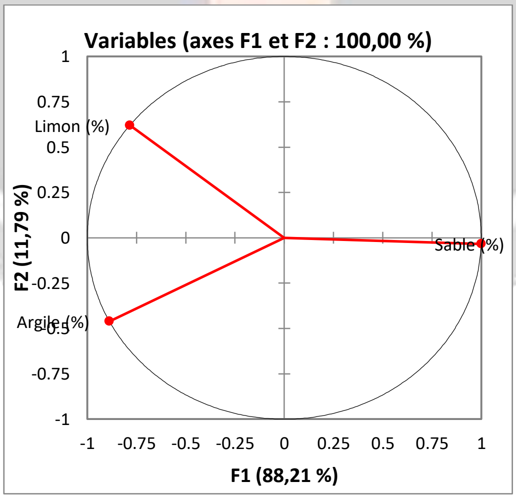


Fig -2 : Correlation circle of grain size variables following F1 and F2 (Source: Author, 2022)

The linear combination of the two main axes gives a cumulative percentage of 100% which contains all of the variables. These values are representative of all the variables.

Thus the representation in PCA of the variables and individuals of the particle size gives the following distribution (fig -3): five (05) profiles (PBNV-I, PBNV-II, PBNV-III, PANT-I, and PANS -I) are made up of more than 60% sand content (more or less coarse), six (06) profiles (PMH-I, PABH-I, PANS-III, PBEM-II, PAMB-I and PANT-II) for clay, three (03) profiles including PABF-I, PBEM-I, PAMB-II for silt and finally two (02) other profiles have contents of more than 50% and silt at 30% and more (PABH-II and PMH-II).

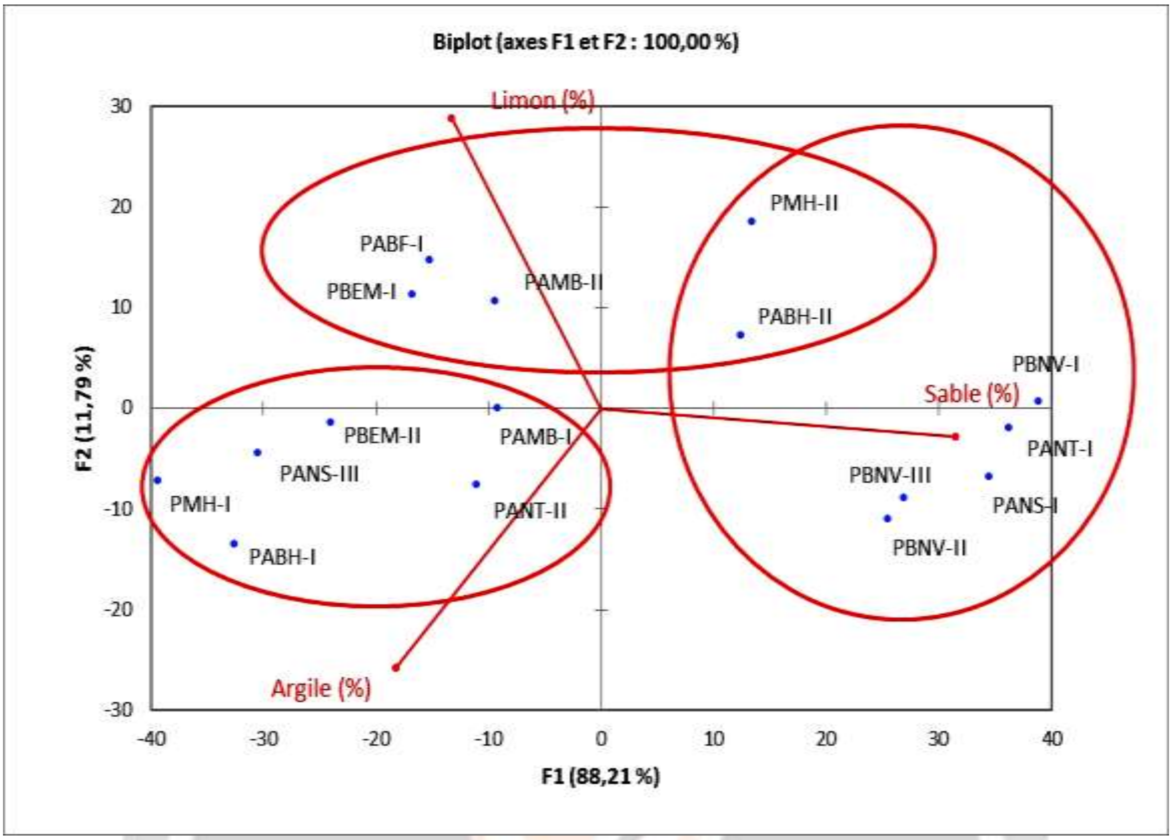


Fig -3: Representation of granulometric variables and individuals (Source: Author, 2022)

The statistical method by Analysis of Variance (ANOVA) shows that the p-values of each particle size element are below the confidence interval ($p < 0.05$) with the following coefficients of determination (R2): 0.81 for clay, 0.709 for silt and 0.761 case for sand. This indicates a very significant difference in the trend of the variables (clay, silt, sand) on the different experimental sites (Figure 4). The synthesis of multiple comparisons per pair (Tukey's test) suggests eight (08) homogeneous groups for clay, then a group of different averages for silt and finally three (03) homogeneous groups for sand. This trend confirms the result obtained by the PCA.

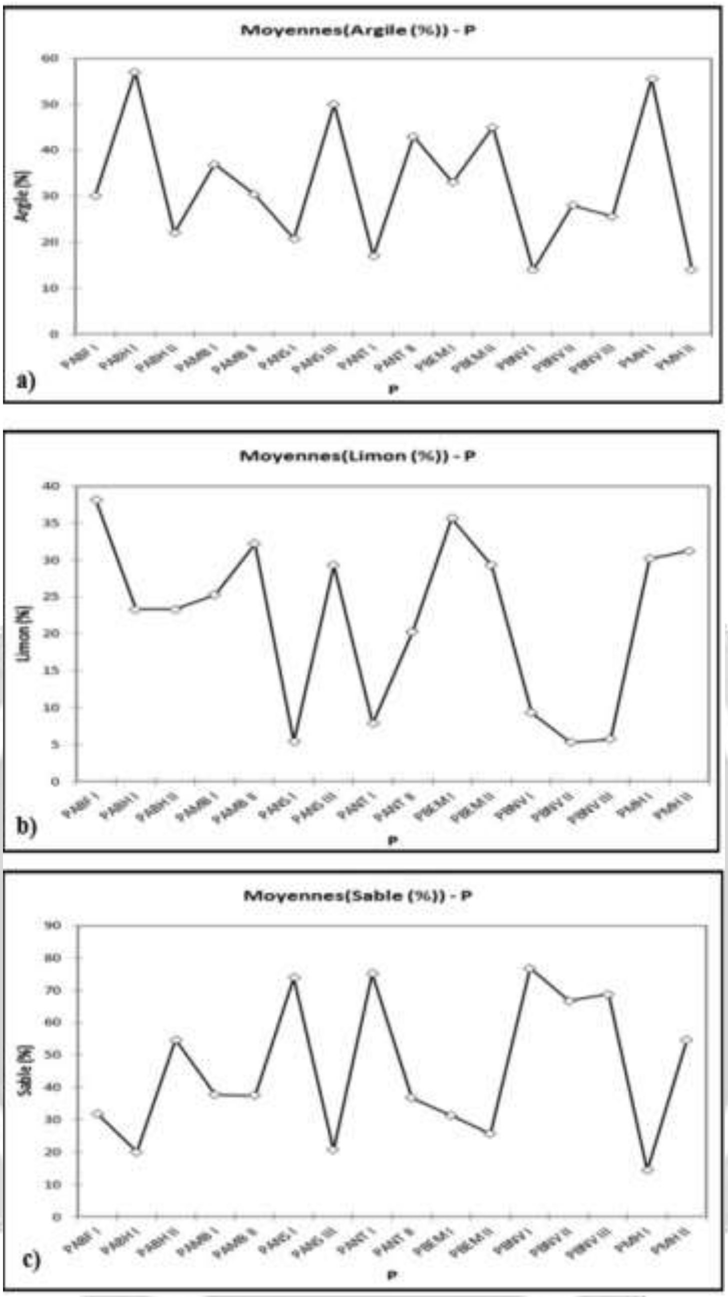


Fig -4: a) Tendency of clay distribution; b) Distribution of silt over the study area; c) Curve of evolution of sand quantities in the study area. (Source: Author, 2022)

In fig -4-a, the two (02) profiles PABH-I (Ambohimena) and PMH-I (Ankatafa) present the largest quantity of clay (>50%). Profiles PANS-III, PBEM-I, PBEM-II, PANT-II, PAMB-I, PAMB-II, PBNV-II and PBNV-III, PABH-II and PANS-I have an average amount of clay (20 at 50%). The others, PANT-I (Antranonkarana), PBNV-I (Benavony) and PMH-II (Ankatafa) are quite low in clay (10 to 20%). On the other hand, in figure 4-b two profiles (PABF-I (Antsatsaka) and PBEM-I (Ambanja)) have high amounts of silt (> 35%).

The PAMB-II, PANS-III, PBEM-II, PMH-I, PMH-II (Ankatafa), PAMB-I, PABH-II and PABH-I and PANT-II profiles also have average amounts of silt (between 20 at 35%) while PANT-I (Antranonkarana), PANS-I (Antsakoamanondro), PBNV-I, PBNV-II and PBNV-III (Benavony)) are characterized by a low amount of silt (<10%). In general, the silt rates in all the profiles analyzed are more or less homogeneous. This may be the consequence of the weathering of the source rocks.

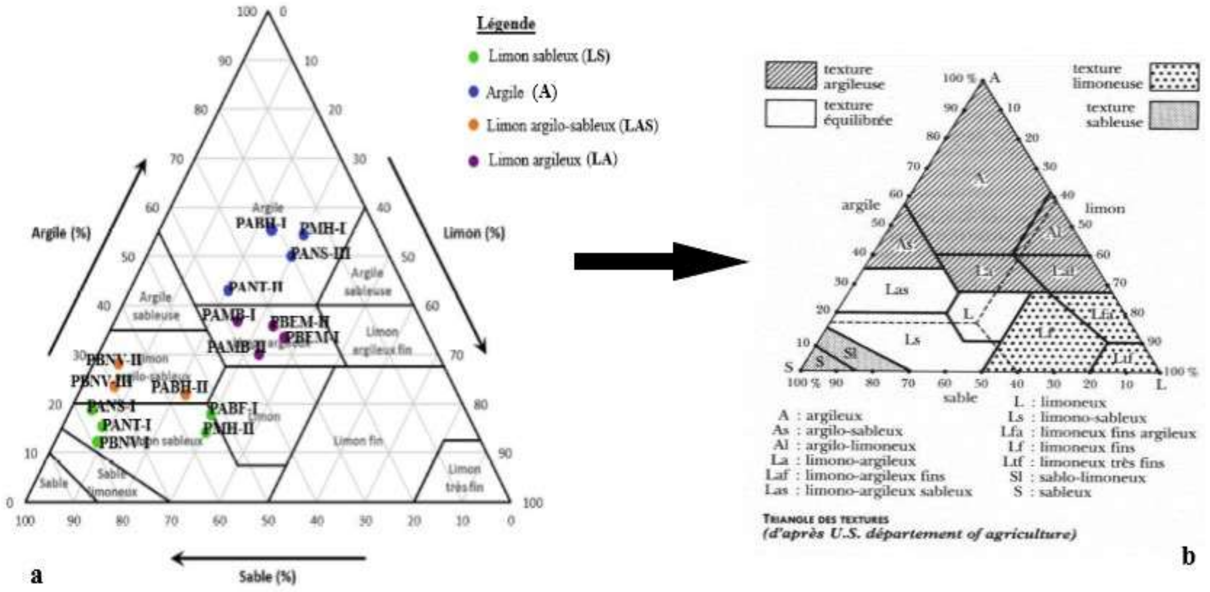


Fig -5: Profile textures projected on the GEPPA ternary diagram (a) and texture class correspondence (b) (Source: Author, 2022)

The projection on the ternary diagram of the GEPPA soil texture, the vast majority of profiles show sandy-loam textures to sandy clay loam because of the importance of the percentage of sands (11 to 81%). This represents 50% of all the constituents (Figure 5). Theoretically this characterizes flood deposits. In addition, some profiles have a clayey and silty-clayey texture.

According to the textural correspondence triangle of the US, these two textures belong to the class of clay-textured sediments, while the sandy-loamy and sandy-clayey-silty textures are classified in the balanced texture. That is to say, the soils located in the plain itself have balanced textures while those around it are clayey in nature.
By referring to the triangle of structural stability as well as that of erodibility, Table 3 gives the results of the correspondence between texture, structural stability and erodibility (or sensitivity to erosion).

Table -3: Correspondence between texture, structural stability and soil erodibility

Profil	**Clay (%)**	**Limon (%)**	**Sand (%)**	**Texture**	**Structural stability**	**Erodibility coefficient**	**Sensitivity to erosion**
PANT-I	17,0	7,9	75,1	Very sandy loam	Instable	5,0	Très forte
PABH-II	22,0	23,3	54,7	Limono-clay-sandy	Instable	3,0	Moyenne
PAMB-II	30,3	32,2	37,5	Limon argileux	Bonne	3,0	Moyenne
PABF-I	30,0	31,9	38,1	Limon sableux	Instable	5,0	Très forte
PMH-II	14,0	31,2	54,8	Limon sableux	Instable	5,0	Très forte
PAMB-I	37,0	25,3	37,7	Limon argileux	Bonne	4,0	Forte
PABH-I	57,0	23,3	20,0	Argile	Très bonne	2,0	Faible
PMH-I	55,5	30,1	14,4	Argile	Très bonne	2,0	Faible
PBEM-II	45,0	29,3	25,7	Argile	Très bonne	2,0	Faible
PBEM-I	33,0	35,6	31,4	Limon argileux	Bonne	3,0	Moyenne
PANS-III	50,0	29,3	20,7	Argile	Très bonne	2,0	Faible
PBNV-II	28,0	5,3	66,7	Limono-clay-sandy	Instable	3,0	Moyenne
PBNV-III	25,6	5,7	68,7	Limono-clay-sandy	Instable	3,0	Moyenne
PANT-II	43,0	20,3	36,7	Argile	Très bonne	2,0	Faible
PANS-I	20,8	5,4	73,9	Very sandy loam	Instable	5,0	Très forte
PBNV-I	14,0	9,3	76,7	Very sandy loam	Instable	5,0	Très forte

(Source: Author, 2022)

Regarding structural stability, the lower part of the study area is in the most unstable pole due to the predominance of fine sand and silt. This explains the low internal cohesion between the particles that make up the soils. They are easily transported by transport agents especially water. Compared to sand, silt is the first and easiest to erode due to its very light weight. Unlike other places with clay content, the soils have good structural stability, which means that they are less sensitive to any form of erosion.

Table 3 indicates the presence of certain risk areas. This is confirmed by the presence of an erodibility coefficient equal to 4 and 5 (highly erodible).
At the scale of the profile, there appears a homogeneous evolution of the texture according to the depth and a progressive variation of the texture at the level of the horizons, a sign of a variation in the energy of deposition.

3 -3 Electrical conductivity

Overall, the electrical conductivity obtained on the samples analyzed shows values between 0.01 and 1.20 mS/cm. It is low for all the profiles, except the PMH-II profile which has an average salinity rate at depth (electrical conductivity ranging from 0.438 to 1.202 mS/cm) (figure 6). This confirms a very low level of salinity in these soils for most of the area. According to the soil salinity scale (Figure 7), they are considered non-saline.

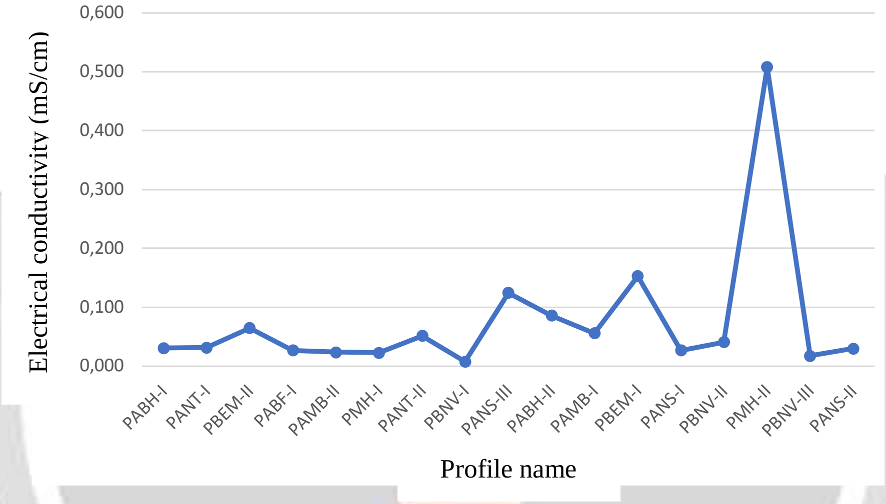


Fig -6: Curve of electrical conductivity by horizon of the experimental sites (Source: Author, 2022)

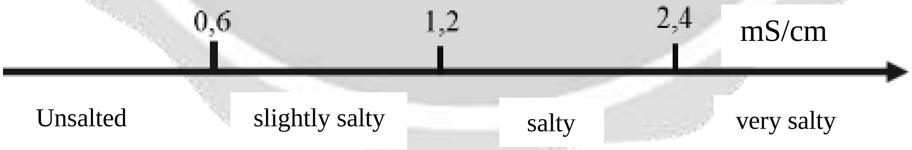


Fig -7: Soil salt scale (Benabadji et al., 1996)

3-4 Chemical Analytical Data Results

- **pH-water**

Figure 8 illustrates the pH-water result of the different samples taken by horizon.
In general, the pH-water range of the study area varies from 4.5 to 7.4 with an average pH-water of 5.9. The results obtained according to the classification of Baize, 2000 (figure 9), show that 54.3% of the samples analyzed present an acid to strongly acid reaction and 21.7% have a slightly acid reaction while 23.9% present a reaction neutral sometimes slightly alkaline in depth (for example the PANS - I profile: in pH = 4.9 in depth 7.4). Tukey's test, with a 95% confidence interval, confirmed that all the samples were acidic: it shows a single homogeneous group (A). However, for the vast majority of crop soils, the ideal pH-water value is between 6.5

and 7.5. However, the analysis of variance (ANOVA) suggests a significant variation in the pH-water values found ($R^2 = 0.734$ and $p>0.05$) with p = p-value and R^2 = coefficient of determination.
These values are low in the superficial horizons (<5.5) and high in depth (>5.7 up to 7.4)) while these values are reversed for the profiles of the peripheral sites.

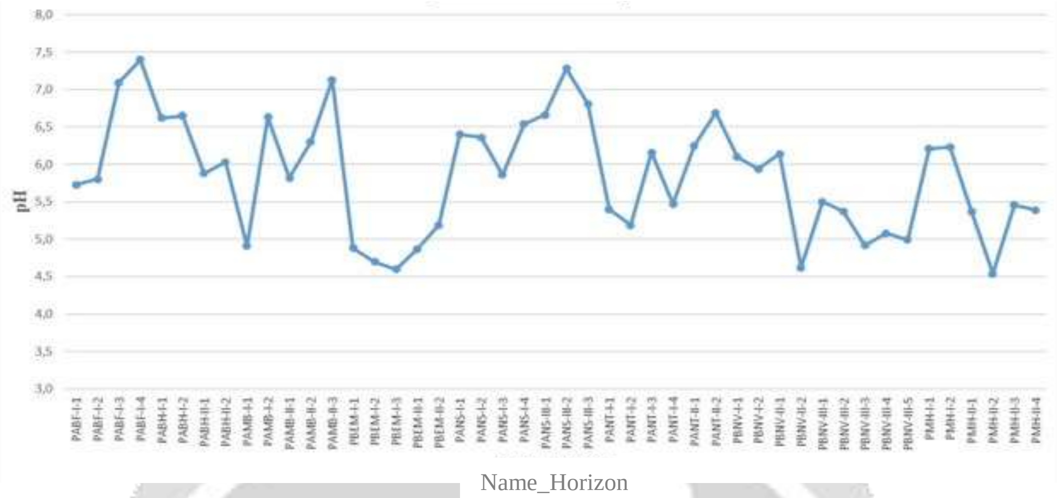
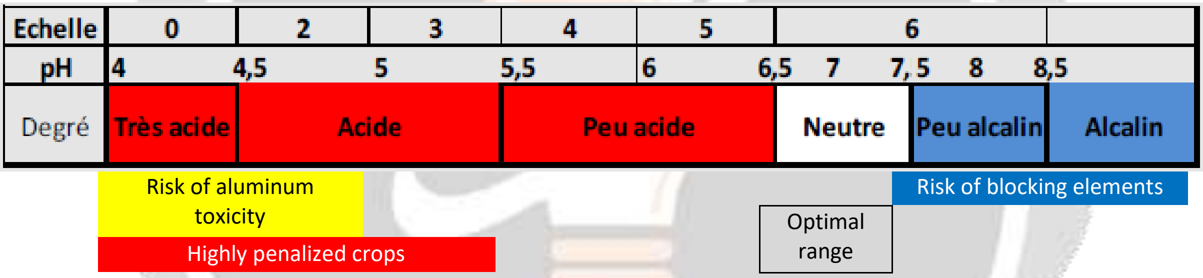


Fig -8: pH-water of the experimental sites *(Source: Author, 2022)*



Echelle	0	2	3	4	5	6	
pH	4	4,5	5	5,5	6	6,5 7 7,5	8 8,5
Degré	Très acide	Acide		Peu acide		Neutre	Peu alcalin / Alcalin

Fig -9: Soil pH-water standard scale (Baize, 2000)

- **Organic constituents (carbon and nitrogen), available phosphorus and manganese**

The results of analysis of the organic constituents of the soil and those of assimilable phosphorus and manganese are given in table 4 and represented graphically (fig. 9, 10, 11, 12).

Table -4: Average content of organic constituents, assimilable phosphorus and manganese per profile

Nom Profil	C (%)	MO (%)	N (%)	C/N	Mn (ppm)	P (ppm)
PABF-I	0,17	0,29	0,09	7,22	2,50	10,86
PABH-I	0,28	0,49	0,03	8,37	0,07	22,66
PABH-II	1,25	2,16	0,13	8,30	14,95	27,79
PAMB-I	1,01	1,74	0,29	3,39	7,44	19,13
PAMB-II	0,42	0,72	0,12	7,74	20,55	9,54
PBEM-I	0,92	1,58	0,10	9,85	33,60	10,79
PBEM-II	1,98	3,41	0,18	9,99	18,75	11,09
PANS-I	0,95	1,63	0,06	14,80	8,23	30,39
PANS-III	0,53	0,91	0,07	8,17	7,64	16,08
PANT-I	0,46	0,79	0,05	8,95	2,07	68,97
PANT-II	0,62	1,07	0,02	26,58	11,30	12,86
PBNV-I	0,12	0,21	0,02	8,00	3,12	11,97
PBNV-II	0,51	0,88	0,09	5,60	5,80	3,21
PBNV-III	0,76	1,31	0,07	12,43	20,72	1,94
PMH-I	0,69	1,19	0,11	6,59	5,80	3,91
PMH-II	0,84	1,44	0,07	16,23	5,16	21,64
⬜	poor	🟦	moderately rich	🟩	very rich	

Table 4 shows that 6.25% of the profiles analyzed (PBEM-II) are rich in total organic carbon (colored in green), 50% are moderately rich (colored in blue) and 43.75% are poor (colored in white), the same is true for the organic matter content.

On the other hand, the total nitrogen contents found vary from 0.01 to 0.34% with an average of 0.09%. Referring to the acceptability standard of 0.1 to 1.5%, 62.5% of the soils studied contain low levels of total nitrogen. 37.5% of the profiles (PABH-II, PAMB-I and II, PBEM-I and II, PMH-I) have acceptable levels (Table. 4). The C/N ratio proves the same distribution as the total nitrogen.

The analysis of variance at a 95% confidence interval shows that the values of total organic carbon, organic matter, total nitrogen and the C/N ratio are not significant (p-value <0.05), their coefficients of determination (R^2) are 0.346, 0.346, 0.441 and 0.573 respectively. Similarly, Tukey's test confirms that the study area is made up of a single homogeneous group (A).

Concerning the assimilable phosphorus contents, 81.25% of the profiles are rich and 18.75 present deficits namely PBNV-II, PBNV-III and PMH-I.
As for the manganese (trace element) content, all the profiles (93.75%) are rich or even very rich, except the PABH-I profile reveals the low content. The ANOVA shows that the values obtained by these two parameters are highly significant ($p>0.05$) with $R^2 = 0.60$ for assimilable phosphorus and $R^2 = 0.831$ for manganese.
But taking into account analysis results by horizon (Fig. 10), we see that the total organic carbon content gradually decreases from the surface to the depth except in the case of the PMH-II profile which has an acceptable content at depth.

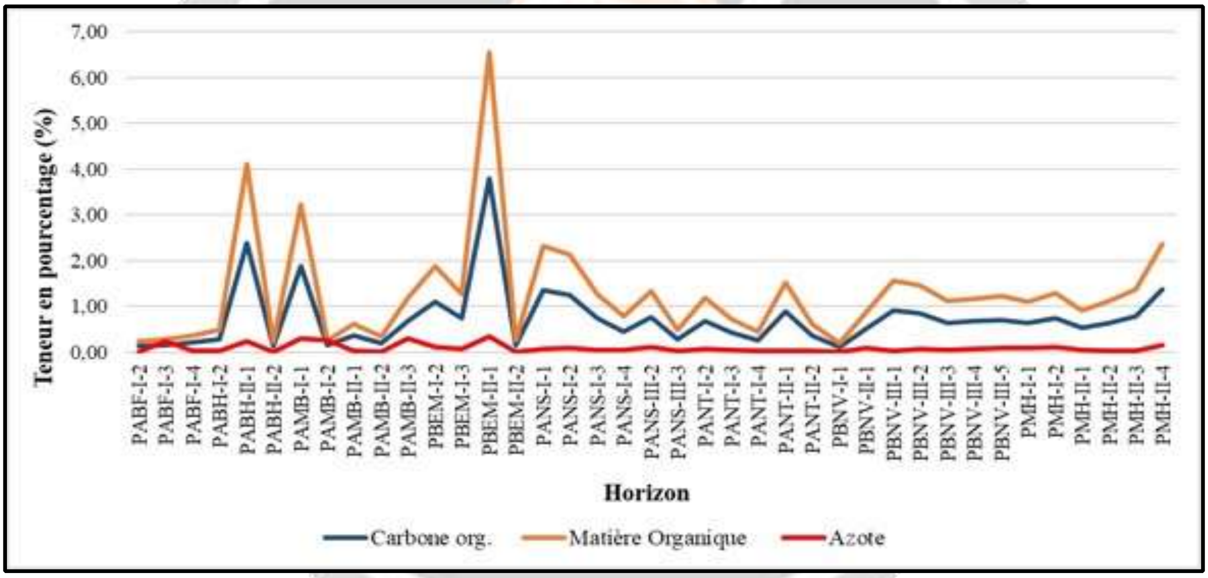


Fig -10: Contents of total organic carbon, organic matter and total nitrogen *(Source: Author, 2022)*

The organic matter contents of the soil samples taken also follow the same type of decrease as the total organic carbon because they depend on the contents of the latter (Fig. 10). These grades vary on average from 0.29 to 3.41% per profile.

At the scale of the profiles, the distribution of the nitrogen content varies with the depth, i.e., in the majority of the samples, it decreases with the depth except for the PAMB-II and PMH-I profiles which are rich in nitrogen in deep horizons (Fig -10). Thus, despite its nitrogen deficiency, the PABF-I profile has an average content in its intermediate deep horizon.
The C/N ratio remains relatively stable (satisfactory) in the majority of deep horizons and sometimes in excess. The values of the C/N ratio are between 3.39 and 26.58; the norm is greater than 10. In general, when the C/N exceeds 11%, it indicates a priori either a poor soil structure, or slowed microbial activity and asphyxiating soil.
The manganese and assimilable phosphorus contents are very rich on the surface then decrease rapidly in the same way as the previous ones down to a few centimeters in depth (intermediate horizons); then remain relatively stable at depth (moderately rich) (Fig.- 11).

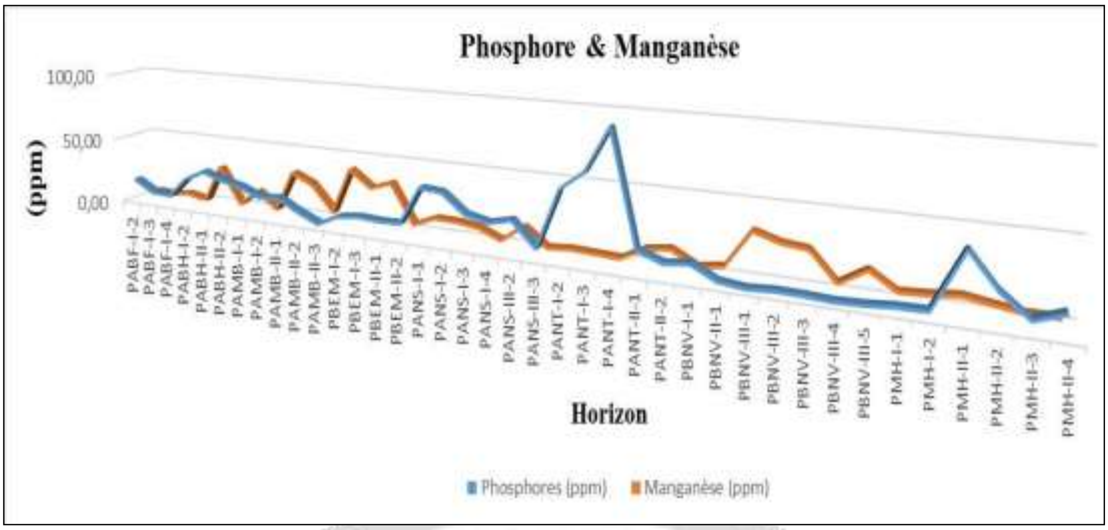


Fig -1 : Assimilable phosphorus and manganese content *(Source: Author, 2022)*

- **Bases exchangeables**

Fig. 12 presents the correlation diagram between the exchangeable base variables projected along the axes F1 and F2 by application of PCA.

It presents a percentage of inertia restored by the factorial axes (F1xF2) of 98.85%. This demonstrates the reliability of the model to describe the data because the linear combination of the two main axes (F1 and F2) is greater than 75%. The F1 axis contains 91.06% of the total information. It is constructed by the respective elements Ca, Mg, and Na. These elements are positively correlated with the F1 axis while the K element is negatively correlated. As in this example the contents of the elements Mg and Na are low, they are negligible.

The F2 axis is formed by potassium (7.79%) with a positive correlation

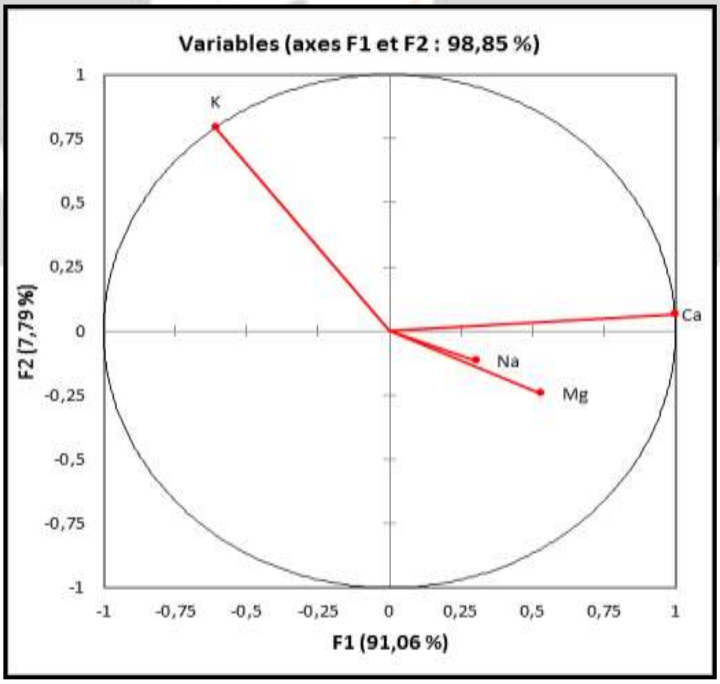


Fig -12: Correlation circle of variables Exchangeable bases *(Source: Author, 2022)*

According to the result obtained by PCA, the distribution of variables and individuals by profile horizon is non-uniform (Fig. 13); therefore, no distinction can be observed between the profile horizons in the different experimental areas.

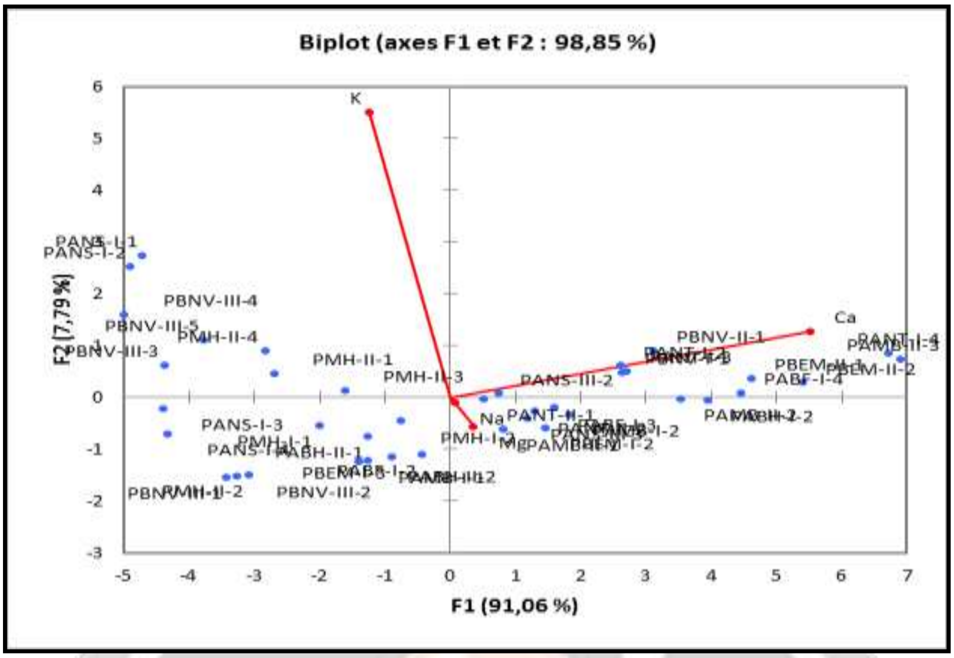


Fig -13: Distribution of variables and individuals *(Source: Author, 2022)*

Due to the fact that it is difficult to distinguish between the contents of exchangeable bases and the horizons of profiles by the PCA method, the classic Excel proved to be the most appropriate method to represent the results using the contents. averages per profile (fig. -14)

This figure shows that the PAMB-I, PAMB-II, PABEM-II, PANT-II, PABH-II and PMH-II profiles are characterized by a high calcium content. The potassium level is relatively moderate in almost all the profiles except for PABF-I, PABH-I, PABH-II, PAMB-I, PAMB-II, PBEM-I and PBEM-II which have a low content.
With regard to the Na and Mg variables, their contents are quite homogeneous, i.e., the magnesium content on all profiles is moderately rich ranging from 1.02 to 1.82 meq/100g except for PBNV-III and PANS-I (acceptable standard: 1 to 3 meq/100g). On the other hand, for the variable sodium (Na), only three (03) profiles out of sixteen (16) have unremarkable contents but they still correspond to the acceptable standard because they are just at the lower limit (acceptable standard: 0.3 at 2 meq/100g).

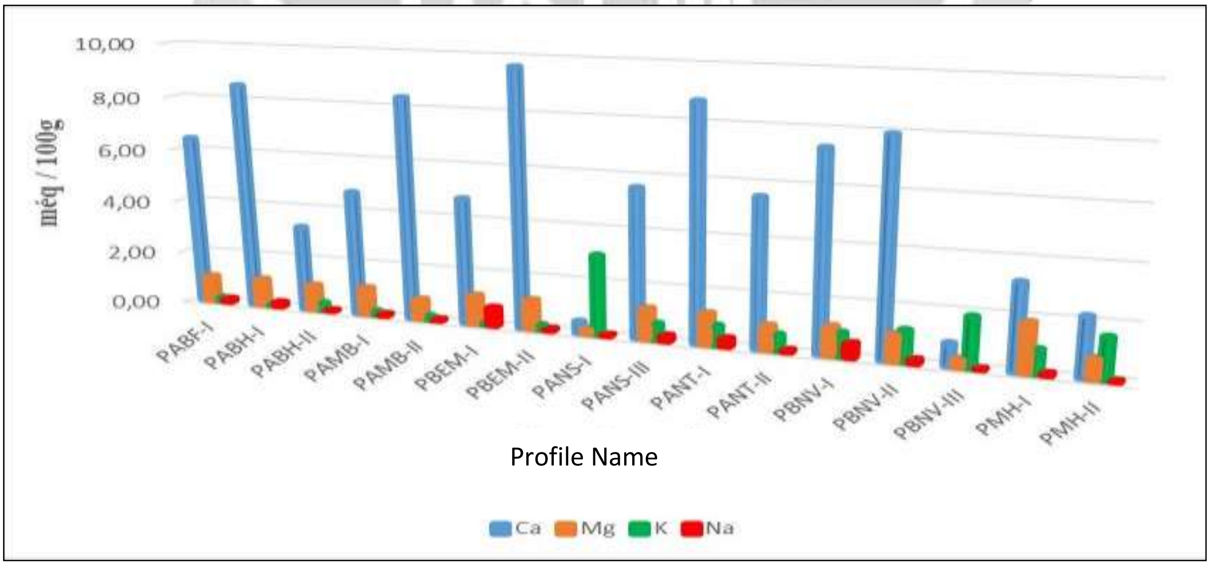


Fig -14: Evolution of exchangeable base rates in the experimental sites

Among other things, the analysis of variance performed on these parameters presents results almost similar to those found on EXCEL. The average Ca contents are very representative ($R^2 = 0.866$ and $p > 0.05$), and for Mg, the difference is significant ($R^2 = 0.695$ with $p > 0.05$). Tukey's test on the synthesis of multiple comparisons per pair thus made it possible to identify seven (07) different groups (A, AB, ABC, ABCD, BCD, CD, D) for the element Ca and three (03) groups for the variable Mg (A, AB, B).
As for the contents of the K and Na variables, the differences in the mean values of K and Na are not significant ($R^2 = 0.561$ with $p < 0.05$ for the K element; $R^2 = 0.226$ with $p < 0.05$ for the Na). For these two variables, Tukey's test reveals a homogeneous group (A) for each variable.

- **Cation Exchange Capacity, Sum of Exchangeable Bases (S) and Base Saturation (V)**

Figure 15 presents the results of the CEC, the sum of the exchangeable bases and that of the base saturation.
Two (02) profiles (PANS-I and PBNV-III) have low CEC values (>10 meq/100g); the standard of acceptability is between 10 – 40 meq/100g; and the others are moderately to highly rich.

Regarding the sum of exchangeable bases, four profiles (PMH-II, PBNV-III, PANS-I and PABH-II) are poor in bases; they show values below the acceptability standards (< 5 meq/100g).
Finally, the base saturation depends on the CEC and S. In this study, the majority of the profiles meet the acceptability standards (40 – 90%) except for the five profiles PMH-II, PBNV-III, PBNV-I, PANT-II and PBEM-I.

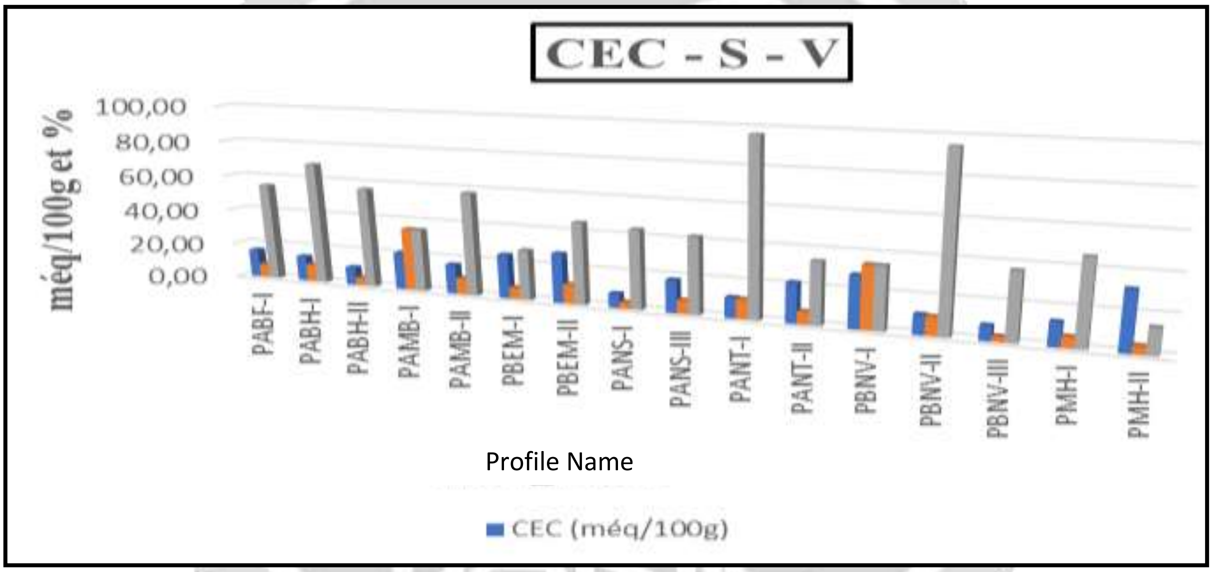


Fig -15: Histogram of Cation Exchange Capacity (CEC), Sum of exchangeable bases (S) and Saturation in bases (V). *(Source: Author, 2022)*

Statistical analysis by ANOVA indicates very significant differences ($p < 0.05$) for these three variables, for which their coefficients of determination (R^2) are: 0.797 for CEC and S and 0.674 for cation saturation (V).
The multiple comparison of the means (Tukey's test) makes it possible to distinguish five (05) different groups A, AB, ABC, BC and C for the CEC, and the sum of exchangeable bases (S), as well as three (03) different groups A, AB and B for saturation in base (V).

4. GENERAL DISCUSSION

The results of the various analyzes carried out on the samples taken in the study area highlight the existence of a correlation between the physico-chemical variables and soil degradation. This allows us to say that soil degradation is partly the consequence of the alteration of the physico-chemical elements constituting these soils. That is to say, from the physical point of view, the results show that the soils of the area are made up of two types of texture:

1. Soils with a clayey texture which include clayey soils proper and those of the silty-clayey type (see fig- 5). This type of soil is found around the perimeter of the study area as well as on the marshy plain generally occupied by rice fields. These are respectively soils of moderately desaturated ferrallitic classes (rejuvenated and typical), soils with little evolved erosion (lithic) and hydromorphic;

2. Soils of balanced texture with a lumpy structure: these are soils of the loam-clay-sandy and loamy-sandy types (see fig- 5). These soils are light and permeable. Indeed, the granulometric results highlight a high proportion of sandy particles sometimes reaching up to more than 70%, and a significant proportion of silt particles. These soil types are concentrated in the flood plain areas. These are little evolved soils of alluvial contributions ("baiboho" in malagasy).

However, in accordance with the results of the EC analytical data (see fig -6) on the soil salinity scale (Benabadji et al., 1996), it can be seen that the soils of the study area belong to the category of non-saline soils because the electrical conductivity values obtained are relatively lower than 0.6 mS/cm. These results are confirmed by the results of the other parameters (water pH, particle size, organic and chemical elements).

Furthermore, the analytical results of the chemical variables reveal that most of the soils sampled are acidic to slightly acidic in nature at the surface, then slightly acidic to neutral at depth and on the intermediate horizons. The latter is the case of samples taken from the floodplain area, especially under the cocoa trees. An acid pH indicates the low rate of salinization and the probable risk of a toxicity phenomenon (alumina?) on the superficial horizons as well as on certain sampling sites.

On the other hand, a slightly acidic to neutral pH is an asset for better nutrient absorption (Amonmide et al., 2020). From this, we can say that the mineral elements are available from the intermediate and deep horizons. The pH close to neutrality is an indicator of the availability of mineral elements contained in the soil (Landon., 1991) while the acidic pH, especially below 5.5, are possible indicators of deficiencies in exchangeable bases and nutrient elements (Ca, K, Mg, N, P) and probable excess in Al, Co, Cu, Fe etc. (Baize, 2000).

With regard to the other chemical variables analyzed, the results show the relative abundance of the organic carbon content in the surface layer, but this content decreases towards the depth. Organic matter also follows the logic of organic carbon fluctuation because it is a function of the latter.

According to Mattieu et al., (2020), a slight decrease in organic carbon or organic matter content can have a negative impact on other parameters such as CEC, nutrient concentration, etc.

In addition, the increase in the accumulation of organic carbon in the soil causes an increase in greenhouse gas emissions (Bradford et al., 2016), but would, on the other hand, be beneficial for soil fertility if the OM stored is an evolved, nutrient-rich OM.

As regards total nitrogen, it is deficient throughout the Lower Sambirano area except in areas covered with plant cover which are generally protected from flooding (PABH-II, PAMB-I and II, PBEM-I and II, PMH- I). According to Saïdou et al., (2012) and Batamoussi et al., (2014), a low total nitrogen content is a limiting factor for crop yield.

Despite the results obtained on organic carbon and total nitrogen, the results in Table 4 also show that, for most of the soils sampled, the C/N ratio corresponds to the acceptability standard except for certain profiles whose horizons of depth have values above or even below the reference thresholds. The C/N ratio ≤ 9 reflects good humus, and a value ≥ 12 indicates that organic matter is difficult to mineralize (Nijimbere et al., 2020).

The assimilable phosphorus and manganese contents are in fact sufficient or even very rich, these can be influenced by the organic matter content.

The assimilable phosphorus and manganese contents are in fact sufficient or even very rich, these can be influenced by the organic matter content.

In addition, analytical results of chemical parameters also show variability in exchangeable cation content (Fig. -15) and cation exchange capacity (Fig. -15). In addition, analytical results of chemical parameters also show variability in exchangeable cation content (Fig. -15) and cation exchange capacity (Fig. -15).

The results on the calcium (Ca2+) and potassium (K+) levels shown in Figure 15 are sufficiently reliable, while the magnesium (Mg2+) and sodium (Na+) contents are estimated to be low to very low throughout the area.

These results demonstrate that the sum values of exchangeable bases (S) found are moderately reliable. This richness in Ca2+ and K+ is closely linked with the soil pH values obtained. That is to say, the acidity of a soil promotes the leaching of basic elements. Since the pH values obtained are acidic to slightly acidic or even neutral; they thus confirm the relative abundance of Ca2+ and K+ ions in all the horizons of the profiles. Na+ ion deficiency indicates that the area is unsalted.

As for the values of the cation exchange capacity (CEC or T) obtained, its analysis proves that the soils of Lower Sambirano, especially in the center of the plain, have a fairly good nutrient retention capacity. This is explained by the presence of organic matter (OM) observed in various places and also by the slightly acidic to neutral pH. We know that CEC levels are linked to soil acidity (pH); which supports the hypothesis of Koull and Halilat (2016) in Seydou et al. (2022) who specifies that CECs are closely linked to soil OM content and clay content.

Similarly, the study area is characterized by the high saturation of the absorbing complex (V or base saturation). Base saturation is a function of pH, CEC and S.

5. CONCLUSION

This study has highlighted the soil results achieved in the Bas Sambirano region. It appears that:

- From a texture point of view, the Lower Sambirano plain is divided into two different zones, one of which is made up of loamy-clayey-sandy soils with sandy loam. These types of soils belong to the class of balanced texture (dominance of fine sands and coarse silts). While the other is characterized by a clayey texture with silty-clayey to clayey soils. The advantage of balanced-texture zones is that they have the ability to retain water and have moderate permeability, while the clay texture favors the mineralization of organic matter.

- In addition, the analytical results on electrical conductivity also reveal that the area is classified as non-saline (no trace of salinity which is a phenomenon not appropriate for plants except in the case of halophilic plants).

- On the other hand, for most of the parameters analyzed, these soils have almost homogeneous physico-chemical and chemical properties. Their pHs are acidic to slightly acidic. As for organic and nutritive elements, these soils respectively show sufficient levels of calcium, potassium, manganese and assimilable phosphorus. The same is true for nutrient retention power (moderately rich CEC) and base saturation. They have moderate organic carbon, organic matter, magnesium and base saturation. These soils also show deficiencies in total nitrogen and especially in sodium. Despite the low total nitrogen content, the C/N ratio is moderately good in the majority of the soils sampled. Sodium deficiency is an asset for soil fertility.

Considering the results obtained, it can be said that the soils of the study area have an average fertility which, in the long term, can threaten the potentiality of productive ecosystems. Among other things, the predominance of silt and fine sand contents can lead to vulnerability to erosion.

Finally, an accompanying measure for the improvement of soil productivity is necessary in view of the high risks due to the frequency of floods, or the problem of structural stability, as well as the drop in production due to the exhaustion of the soil.

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