Phosphorus fractionation in sediment and agricultural soils surrounding the Lake Toho (southern Benin) in rainy season

ABSTRACT

In recent years, land use related to anthropogenic activities has contributed to high contamination of surface waters. During the last decade, Lake Toho, in the republic of Benin, has suffered enormous anthropogenic pollution caused by the use of fertilizers from farmers around the lake. To assess the impact of these activities, we assessed the mobility and bioavailability of phosphorus in cultivated soils around the lake. The results showed that the cultivated soils around Lake Toho are weakly acidic or even basic with water pHs between 6.25 and 8.3. The humidity of cultivated soils varies from 1% to 38% on the different horizons. The content of organic matter is ranged from 40.30% to 49.70%. In the majority of sites, the surface layer contains a high rate of organic matter. The total phosphorus concentration ranged 1049.74 µg.g-1 to 28436.52 µg.g-1 with a high rate of enrichment at the 30 cm horizon in the majority of the sites. The high content of total phosphorus recorded at the superficial horizon is due to the use of fertilizers to amend the soil. All forms of phosphorus are represented (P-L, P-Fe, P-Ca, P-Al and P-OM). The organic fraction predominates on the upper layer of the soil with the exception of sites located outside crop fields. The strong correlation recorded between the TP, the Pr, the P-L and the P-OM shows that the high content of phosphorus at the upper horizon of the soil is due not only to the anthropogenic contribution but also to the source rock. The remarkable presence of phosphorus in the P-L, P-MO fractions poses a risk of phosphorus transport to the lake. This can lead to the phenomenon of eutrophication which can cause the death of fish as well as the appearance of toxins harmful to aquatic species.

Keywords: Mobility, bioavailability, phosphorus, Lake Toho, cultivated soils

INTRODUCTION

Phosphorus is one of the essential elements for the life of living beings. Indeed, it is a building block of DNA, ATP and phospholipids [1]. Calcium phosphates are major constituents of the skeleton. Thus, phosphorus is mainly found in bones, teeth and nervous tissue in humans.

Phosphorus is involved in plant growth processes [2, 3, 4, and 5]. Before agricultural industrialization, in the terrestrial biogeochemical cycle of phosphorus, plants assimilated phosphate ions present in the soil solution, while the heterotrophic processes of decomposition of organic matter returned the mineral phosphorus to the soil. This complementarity of autotrophic and heterotrophic metabolisms constitutes the essence of the phosphorus cycle in pre-industrial agriculture. Phosphorus is one of the three major elements of fertilization, along with nitrogen and potassium. It plays an important role in root development and early cycle growth. The nitrogen and phosphorus contained in these chemical fertilizers cause environmental problems such as eutrophication and the toxicity of surface waters[6]. Eutrophication can lead to surface water anoxia due to the respiration of plant biomass and its degradation by aerobic bacteria [7, 8 and 9].

This phenomenon can lead to the elimination of the most demanding species and the development of invasive species, the development of algal biomass and an increase in the turbidity of surface waters, inducing the appearance of bad odors as well as a change in the water color [10].

In the soil, phosphorus is found in several soluble and mineral forms. However, the soluble fraction (PO_4^{3-}) is the only fraction that can easily be uptaked by plants and crops [11]. The other forms that cannot be assimilated by plants end their course in surface water, accumulate in the soil or seep into groundwater [6]. The study carried out [12] on the Porto-Novo lagoon revealed a strong presence of organic phosphorus in the sediments. The main cause mentioned is the use of organic fertilizers in agriculture in the lagoon catchment area, and the presence of living or degrading animal and plant organic matter.

Lake Toho, located in southern Benin, has experienced the death of fish on several occasions in 2012, 2018 and 2021. According to information from PNE-Benin, the 2012 drama occurred following a stormy rain that changed the turbidity of the water. This phenomenon led the fish into a state of deoxygenation and cost them their lives. In 2018 and 2021, the same drama happened again on the same lake with a change in color. The main cause mentioned for the past two years is the dumping of harmful substances from an unknown source[13] which certainly led to the pollution of water and/or sediments. In addition, studies have shown that Lake Toho is subject to nitrogen, phosphorus, organic and metallic pollution [14 and 15]. The probable causes mentioned by these authors are related to agricultural activities characterized by the use of chemical NPK fertilizers, herbicides and pesticides. The phosphorus in these fertilizers and pesticides can end up in surface waters. The high phosphorus content in these waters leads to the proliferation of blue-green algae, the degradation of which leads to the formation of toxins; the other consequence is eutrophication which results in water anoxia resulting in the loss of diversity.

The transfer of phosphorus contained in chemical NPK fertilizers applied in cultivated soils to water resources is a simple concept but difficult to assess, given the number of possible physicochemical and biological mechanisms involved and the types of soil. It is therefore preferable to study the mobility and bioavailability of phosphorus in cultivated soils in order to better understand and describe the dynamics of phosphorus transfer from soils to water resources.

MATERIALS AND METHODS

2.1 Study area

Located in the south of Benin between 6°36 35 - 6°40 N and 1°45 - 1°50 E, Lake Toho, covers an area of 9.6 km² at low water and 15 km² during flooding with an average depth of 2.1 m[16]. It has an average length of 7 km; a southern width varying between 0.5 and 2.5 km and about 500 m in northern width. It is part of the Mono basin. The latter covers an area of 374 km² and is located in the western complex of wetlands in southern Benin[14]. Lake Toho straddles the municipalities of Athiémé, Lokossa and Houéyogbé and crosses the villages of Vèha, Logbo (municipality of Lokossa), Tohonou and Tokpa (municipality of Houéyogbé). The valley of the Sazué River serves as an outlet during the flood season through two channels. This valley also serves as a tributary during the Mono floods.

Due to its geographical location, the Lake Toho area is influenced by a subequatorial climate characterized by two dry seasons (mid-July to mid-September and mid-November to mid-March) and two rainy seasons (mid-March mid-July and from mid-September to mid-November) dominated by continental winds and the harmattan[17]. The annual rainfall varies between 544 mm and 1376 mm while the temperature ranges between 20.6 and 33.5°C with an annual average of 28°C. The relative humidity is very high and varies from 65% in January to 80.6% in June[15].

2.2 Sampling

The sampling campaign was carried out in January 2022 at thirteen (13) sites. The sites were chosen according to the position of the cultivated fields in relation to the lake as well as in relation to the water supply. The position of the different sites in relation to the lake is presented in Figure 1 below.

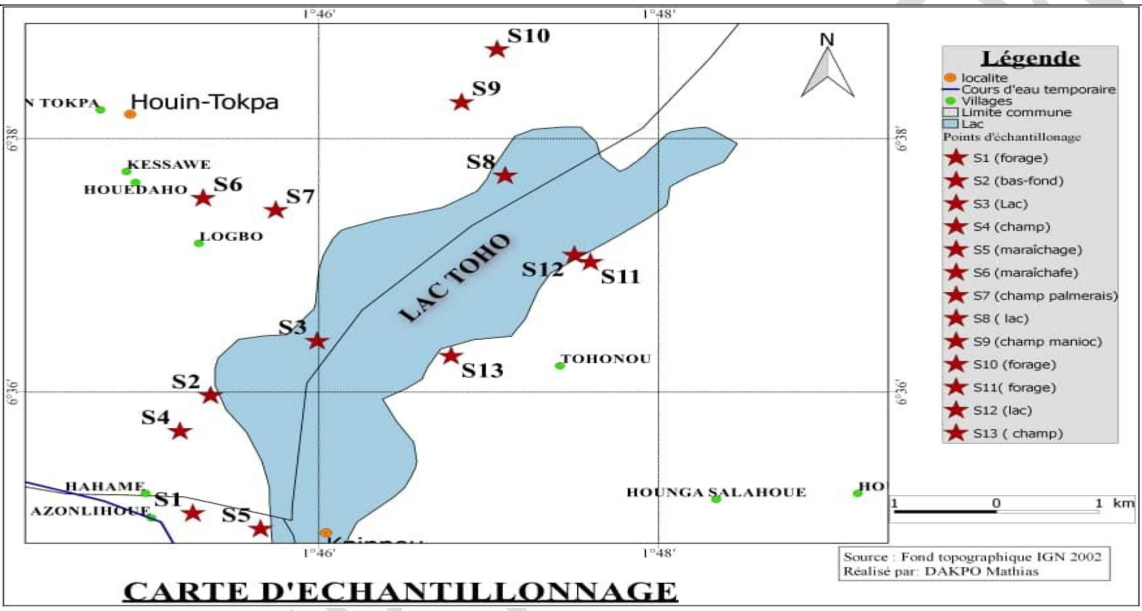

Figure 1: Sampling map

2.3 Analytical methods

Physicochemical parameters were analyzed. The pH of the sediments was measured according to standard NF X 31-103 1992 while the humidity was determined according to standard AFNOR X31-102, AFNOR 1994. As regards organic matter, the Walkley method-Black [18] was used. The phosphorus content is determined by mineralization with potassium persulfate in an acid medium (H_2SO_4) at 120°C for 2 hours. The fractionation of phosphorus was carried out following Rydin and Welch[19] scheme.

RESULTS AND DISCUSSION

3.1 Physicochemical parameters

pH and pH_{KCl} :

The water pH of the soils around Lake Toho ranges from 6.25 to 8.3 (Figure 2). The highest pH value is recorded at the site 12 to 90 cm deep and the lowest value at the site 13 to 90 cm deep. At the same site, the pH varies very slightly passing from one horizon to another with the exception of site 12 and site 13 which are sites located near Lake Tohonou. The pH_{KCl} ranges from 5.66 to 7.91 (Figure 3); the highest and lowest values are recorded at site 13. On 9/13 of the sites, the pH_{KCl} is inversely proportional to the depth. The average value of pH_{KCl} is lower than that of pH_{water} on almost all the sites (Figure 4).

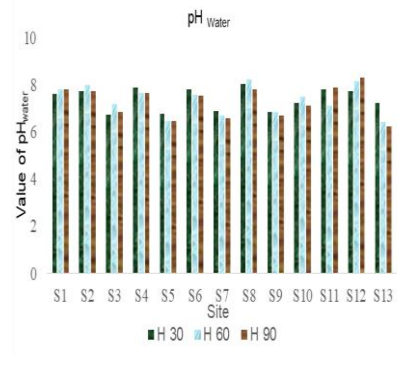

Figure 2: pH_{Water}

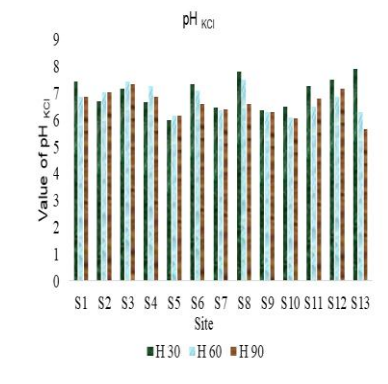

Figure 3: pH_{KCl}

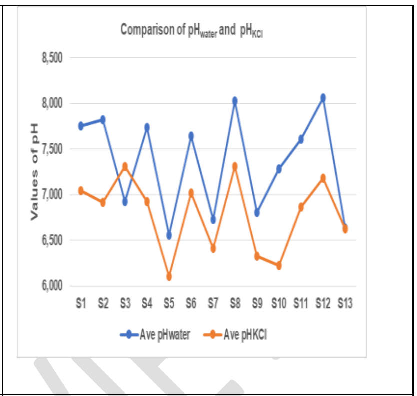

Figure 4: comparison of pH

Humidity and Organic mater

According to Figure 5, water content in the soils around the lake varies from one horizon to another. This water content increases proportionally with depth on 9 of the 13 sites.

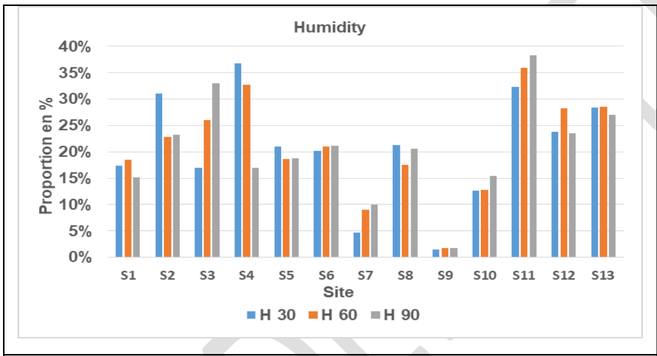

Figure 5: Humidity

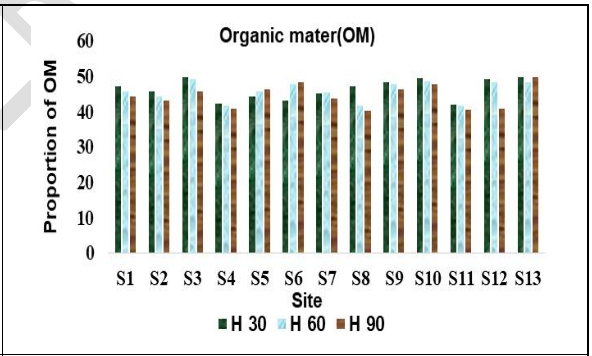

Figure 6: Organic mater

The Figure 6 presents the variation of organic matter in soils. The highest levels of soil organic matter are recorded at sites 3 (lake) and 13 (field not far from the lake). For the majority of sites, the organic matter content is higher in the upper horizon and decreases towards the bottom. This is explained by the fact that it is this part of the ground that receives dead leaves, plant debris and animal carcasses. Sites located outside the fields have low organic matter content.

Total phosphorus (TP) and fractionation

According to Figure 7, the TP varies from 28436.52 µg.g-1 to 1049.74µg.g^{-1}. The highest value is observed at site 2 and the lowest at site 11. For the majority, phosphorus is mainly concentrated in the upper soil layer H30-H60.

The sites outside the fields (S1, S11) and the sites located in the unamended fields (S4, S9) have low phosphorus content.

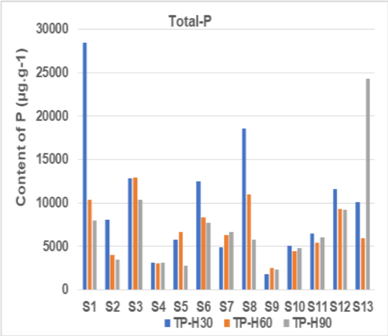

Figure 7: Total phosphorus

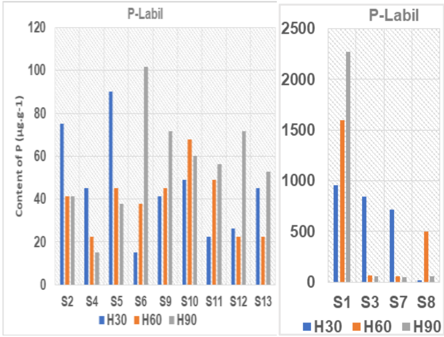

Figure 8: mobile phosphorus

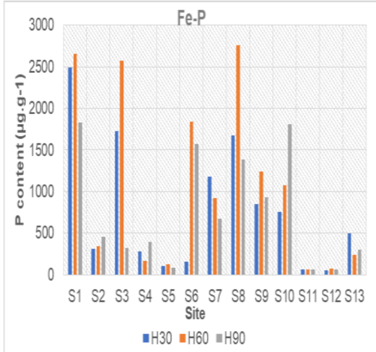

Figure 9: Phosphorus bound to iron

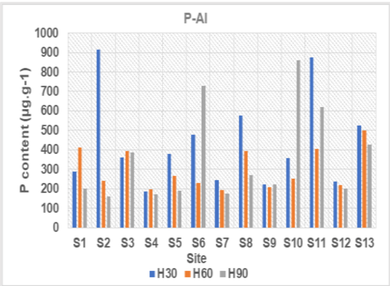

Figure 10: Phosphorus bound to aluminum hydroxides

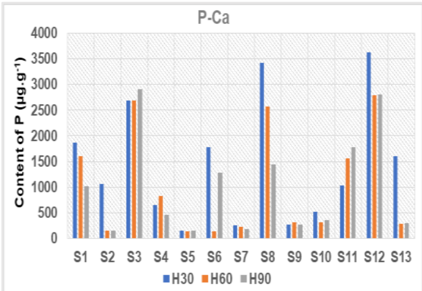

Figure 11: Phosphorus bound to calcium

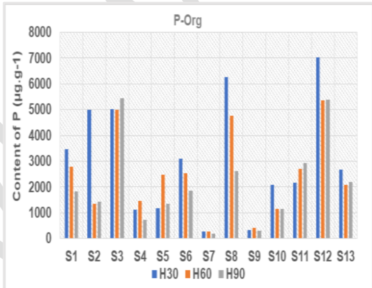

Figure 12: Phosphorus bound to Organic

The different phosphorus fractions obtained are as follows:

As reported in Figure 8, the labile form of phosphorus is found concentrated in the lower horizon H90 in more than 50% of the sites. This can be explained by the fact that this fraction of phosphorus can migrate to the depth. At sites S3, S4, S5 and S7, labile phosphorus exists more in the H30 horizon than in the other horizons, while at sites S8 and S10 labile phosphorus is more present in the H60 horizon than in the other horizons. At the seven (7) other sites, labile phosphorus exists more in the H90 horizon than in the other horizons.

According to Figure 9, phosphorus is strongly bound to iron in the majority of sites (8/13) at the level of the H60 intermediate layer. At site 13 phosphorus is strongly bound to iron in the upper horizon H30 while at sites S2, S4, and 10, phosphorus is strongly bound to iron in the lower horizon, H90.

From Figure 10, phosphorus is bound to aluminum hydroxides and organic matter in the upper soil layer (H30) at most sites (8/13). With the exception of sites 6 and 10, the phase of phosphorus bound to aluminum hydroxides and organic matter decreases as it progresses from the surface to the depth.

According to Figure 11, the fraction of phosphorus bound to calcium is found preferentially in the upper layer of the soil (H30). In the majority of sites, this fraction of phosphorus decreases from the surface to the depth.

According to Figure 12 the organic phosphorus is more concentrated at the top layer of the sols. This fraction is more present than any others.

The residual fraction of phosphorus is found either at the surface (H30) or at depth in the majority of sites (Figure 13). At sites 1, 2, 4, 6, 8 and 10 the residual fraction predominates in horizon 30; at sites

5 and 11, the residual fraction predominates in the 60 horizon, but at the other sites, the residual fraction predominates in the 90 horizon.

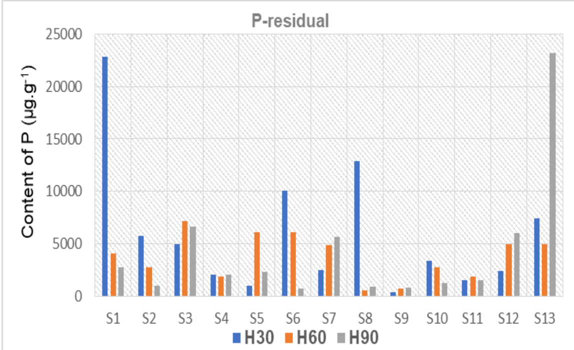

Figure 13: Residual phosphorus

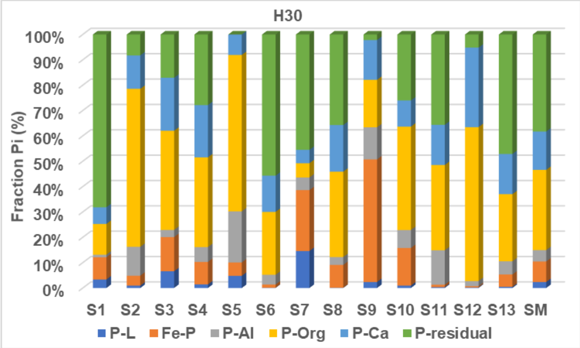

Figure 14: cumulative proportions of the phosphorus fractions at H 30

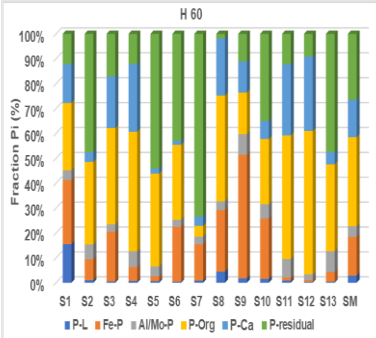

Figure 15: cumulative proportions of the phosphorus fractions at H 60

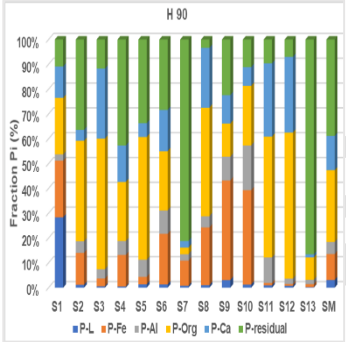

Figure 16: cumulative proportions of the phosphorus fractions at H 90

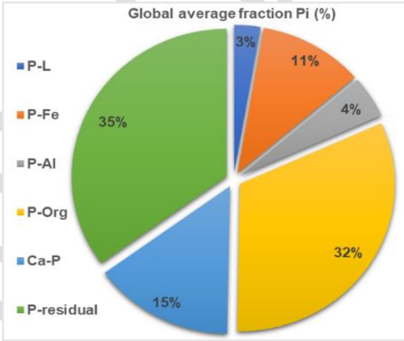

Figure 17: Global average fractions proportion

Spatial distribution of the different forms of phosphorus in the different horizons

According to figure 14 and 16 on the H30 superficial horizon, the residual fraction predominates in the majority of sites except at sites 2, 3, 5, 9 and 12. Apart from the residual fraction which predominates, phosphorus is preferentially bound to organic matter, calcium iron oxide and. At the S1 site, the labile fraction of phosphorus predominates.

On figure 15, at horizon 60, the organic fraction predominates on the majority of sites except at sites 7, 8 and 9. In the other fraction, the residual fraction predominates, phosphorus is preferentially bound to iron oxide and calcium.

On figure 17 show global tendency of the fractionation. The residual and organic fraction predominates and residual (35%) more followed by calcium (15%) and iron (11%). The two last fraction are aluminum (4%) and labil-P (3%)

Statistical analysis

The results of the principal component analyzes (PCA) indicated that the first two axes explain 49.37% of the initial information, which is sufficient to guarantee precision in the interpretations. The circle in figure 18 shows the correlations between the physicochemical parameters of the soil, the total phosphorus per layer and the different forms available in the soil. The component axes indicate on the one hand a strong correlation between the TP, the P-r and the F1 axis. On the other hand, it indicates a strong correlation between the F2 axis and organic matter that opposes humidity. There is a strong correlation between the pH, the fractions linked to calcium according to the horizon.

Figure 19 shows that sites rich in organic matter contrast with sites dominated by moisture. The lower the humidity, the higher the organic matter. The S1 and S3 sites are dominated by Fe-P at the 60 horizon, the S9, S10, S7 sites are dominated by residual P but low in organic matter at the 90 horizon, the S4 and S2 sites have a high rate of humidity at horizon 30 and sites S8 and S12 exhibit high pH and are dominated by Ca-P.

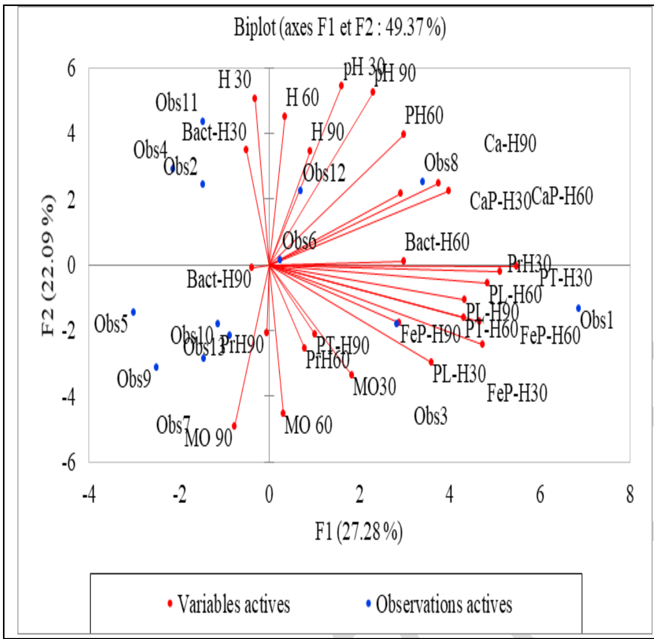

Figure 18: Correlation circle showing the different forms of phosphorus and the different soil parameters

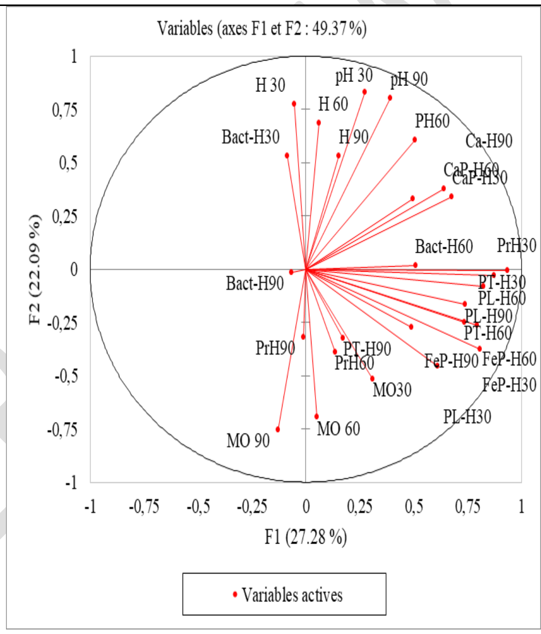

Figure 19: Distribution of sampling sites on the factorial graph

Discussion

The results obtained in the present study showed that the cultivated soils around the Lake Toho have pH_{water} between 6.25 and 8.3 and pH_{KCl} between 5.66 and 7.91. The water pH values recorded are in agreement with the results of Igué et al. [20] which stipulate that the pH values of the soils of Benin are between 6.6 and 7.2 in the cultivation areas and was classified in the category of neutral to weakly acidic. We observe a weak evolution of the pH from neutral to weakly basic. The soils cultivated around the Lake Toho are therefore now weakly acidic to weakly basic.

According to the work of Schvartz et al. [21] soil moisture is one of the parameters that condition the phenomena of mineralization of organic matter and mobility of phosphorus. The humidity of the cultivated soils around Lake Toho varies from 1% to 38% on the different horizons. Sites S1 and S10 are located next to boreholes, therefore the decrease in humidity recorded from the surface to the depth at sites S1 and S10 is due to the spillage, by the populations, of water on the surface and which migrate up to horizon 60. Site S11 is not only next to a borehole but also not far from the lake, which explains the increase in humidity recorded on this site starting from the surface towards the depth. In addition, the same remarks were observed at the majority of the sites located not far from the lake (S3, S12 and S13). On the other hand, in the lowlands, the surface layers are more humid and therefore contain more water; this is due to the clayey nature of this part of the soil. Indeed, pH and humidity influence the dynamics that exist between the organic and inorganic fraction of the soil through the process of immobilization [22, 23].

Organic matter has sorption sites allowing it to fix phosphorus[24]. The content of organic matter recorded in the present study is between 40.30 to 49.70%. In the majority of sites, the surface layer contains a high rate of organic matter. Organic matter includes all the organic constituents, dead or alive, of plant, animal or microbial origin, transformed or not, present on the surface of the soil. This explains the high content of organic matter recorded on the surface layer of the soil compared to the lower layer. Those values remain higher than the founded à the end of dry season (May 2022) [25]. Also those values could be highly estimated by the height humidity which transferred carbon to the lower layer and the possible oxidations of other metals highly presents in the soils. This was reveled in the fractionation according to high values of phosphorus bound to iron, calcium and aluminum. In the Walkley-Black method the excess of non-reactive dichromate solution oxidize a Fe (II) solution to determine the real dichromate solution uses for organic determined.

The analysis carried out showed that the total phosphorus is between 1049.74 $\mu g.g^{-1}$ and 28436.52 $\mu g.g^{-1}$ with a high rate of enrichment at horizon 30 on the majority of the sites. According to Beaudin [5], the surface application of non-submerged fertilizers causes an enrichment of the upper layer of the soil in phosphorus leading to the accumulation of inherited phosphorus stocks, which can represent, in certain regions, up to 80% of the stock of phosphorus present today in the first 30 cm of arable land [1]. The high content of total phosphorus recorded at the level of the superficial horizontal in cultivated fields is due to the use of fertilizers to amend the soil. This fact can lead to the contamination of surface water by runoff or groundwater by filtration. In addition, the enrichment of the upper layer of the soil in phosphorus gives the runoff a high phosphorus content and an enrichment of the subsoil by filtration [5]. By comparison, the total phosphorus content recorded in the cultivated soils around Lake Toho is much higher than the content recorded by Renneson [10] in the agricultural soils of Wallonia (508-717 $mg.kg^{-1}$), in the ferruginous tropical soils in southern and central Benin (118.40 $mg.kg^{-1}$) [20], Le Noe [1] in agricultural soils in France over horizon 30 (750 $mg.kg^{-1}$ - 900 $mg.kg^{-1}$). This difference can be explained by an accumulation of phosphorus in the soils in a non-mobile form. Shoreline materials can contain as much phosphorus as the surface horizon of agricultural land [26], which also explains the high total phosphorus content recorded at the level of the surface horizon of the lake shore (S3, S8 and S12). This therefore constitutes a medium-term risk for the aquatic environment.

Phosphorus is mainly found in the P-L, P-Fe, P-Ca and P-Mo fractions. The organic fraction predominates in the upper soil layer with the exception of sites located outside crop fields (S1; S10). This affinity of phosphorus with organic matter on this layer is due to the high content of organic matter recorded on this layer.

The fraction bound to iron predominates in the lower layer from 60 cm. This observation is due to the ferritic nature of the soil. The first layer is made up of debris, dead leaves and others; below this layer is the iron-rich soil for the majority of sites. This explains the high proportion of the iron-bound fraction at horizon 60.

The labile fraction predominates at the 30 and 60 horizons for the majority of sites. Also, this fraction is part of the mobile forms. This form of phosphorus is the dissolved form that can be taken up by plants in the soil solution but can also end up in runoff.

As for the fraction of phosphorus bound to calcium, it predominates in the upper layer (H30) in most sites. The dominance of these fractions on the upper soil layer explains the high phosphorus content at this soil horizon.

The enrichment of soils with phosphorus is at the origin of the spatial variability of phosphorus concentrations in surface waters [27]. The high phosphorus content found in cultivated soil is the cause of the high phosphorus concentration recorded in the waters of Lake Toho [15]. The strong correlation recorded between the TP, P-r, P-L and P-MO shows that the high content of phosphorus at the upper horizon of the soil is due not only to the anthropogenic contribution but also to the source rock. The opposition of organic matter and observed humidity confirms the analysis made. This shows that humidity is inversely proportional to organic matter content.

Soil phosphorus is adsorbed by soil particles while that of chemical fertilizers and other soil fertilizers is soluble [28]. The predominance of different phosphorus fractions in the upper soil layer, with the exception of the residual fraction, shows that the phosphorus enrichment of cultivated soils around the lake is due to anthropogenic activities.

Conclusion

The poor agricultural activities practice characterized, among others, by the use of chemical fertilizers causes enormous environmental concerns, particularly to water resources. The results show that the soils cultivated around the Lake Toho are weakly acidic or even weakly basic with high organic matter content in the surface layer of the soil. There is a high phosphorus content in cultivated soils with a predominance in the organic fraction on the upper layer of the soil with the exception of sites located outside crop fields. The high content of total phosphorus recorded at the level of the superficial horizontal is due to the use of fertilizers to amend the soil. The domination of mobile phosphorus fractions leads to the phenomenon of eutrophication that can cause the death of fish in Lake Toho. But phosphorus is not the only element of chemical fertilizers used in agriculture, the determination of nitrogen and its different forms in the soils cultivated around the Lake Toho also remains essential to the study of the impact of agricultural activities on water resources mainly on Lake Toho.

References

1. Le Noë Julia, Gilles Billen, Nicolas Roux, Josette Garnier, Vincent Thieu, Marie Silvestre (2018). Phosphorus stocks in agricultural soils: origin and fate. PIREN-Seine phase VII - 2018 report – P stocks in agricultural soils.
2. Morel R., (1996). Cultivated soils. 2nd edition, National Agronomic Institute, Paris-Grignon, France. ISBN: 9782743001490

3. Johnston A.E., (2000). Soil and plant phosphate, Paris: International Fertilizer Industry Association.
4. Frossard E., Julien P., Neyroud J.-A. & Sinaj S., (2004). Phosphorus in soils. State of the situation in Switzerland. Environmental notebook n°368. Federal Office for the Environment, Forests and Landscape, Bern.
5. Beaudin I., (2006). The mobility of phosphorus. Literature review. Quebec Agriculture and Agrifood Reference Center July 2006.
6. Souidi Rania, (2021). Recovery of phosphorus from wastewater in the form of vivianite using the electrocoagulation method. Thesis from the University of AVAL, P120.
7. Pellerin S., Morel C. & Dorioz J-M., (2005). Environmental assessment of phosphorus, in Girard et al., Eds, Paris, DUNOD, chap. 28, 1-18.
8. Garrigues, A., (2007). Limit the impact of phosphorus. Hydroplus, 169, 29-36.
9. Gerdeaux, (2007). Phosphorus and eutrophication of fresh waters. Mechanisms and consequences in the great lakes. Oceanis, No. 33-1/2. 75-86.
10. Renneson Malorie, (2018). Effect of soil characteristics and agricultural practices on the availability of phosphorus in the soils of Wallonia. Thesis of University of Liège – Gembloux agro-bio tech p224.
11. Daneshgar, S., Callegari, A., Capodaglio, A.G. and Vaccari, D. (2018). “The potential phosphorus crisis: resource conservation and possible escape technologies: a review”. Resources 7 (2): 37.
12. Chouti K.W., Atchichoe W., Tometin L., Daouda M. (2017). Bioavailability and mobility of phosphorus in the sediments of the Porto-Novo lagoon. Journal of applied biosciences. https://dx.doi.org/10.4314/jab.v114i1.1. 13p.
13. CWP-BENIN (2021). The massive death of fish in Lake Toho. http://gwppnebenin.org/mort-massive-des-poissons-dans-le-lac-toho-un-cas,1155.html
14. . Kple Evelyne, (2008). Contribution to the study of organic and nitrogen pollution of the waters of Lake Toho in the Mono department. End of training report for obtaining the professional license diploma, University of Abomey-Calavi p 84.
15. Gbaguidi Gouvidé Jean, (2018). Contribution to the protection against chemical pollution of a lentic system in the tropics: Lake Toho in southern Benin, West Africa. End of training dissertation produced and defended for obtaining the Professional Master's degree in Hydrology p95.
16. . Ahouansou R.H., J. Monhouanou, M-C. Savi, F. Akplogan and P. Djossou, (2008). Evaluation of the technical and economic performance of a palm fruit pulper in Benin, Bulletin de la Recherche Agronomique du Bénin Number 60– June 2008.
17. Codjo Victor, Zannou Afio and Biaou Gauthier (2020). Socio-economic determinants of the use of fishing gear and practices destructive of fishery resources on Lake Toho in Benin (West Africa). Int. J. Biol. Chem. Science. 14(8): 2670-2683.
18. Jackson JFC, Nevissi AE, and Dervalle FB (1984). Soil Chemistry Analysis, Prentice Hall Inc., Engle Works Cliffs, New Jersey, 498 pp.

19. Rydin E., Welch E.B., (1998). Aluminum dose require to inactivate phosphate in lake sediments, Water Research. Flight 32; Elsevier Science Ltd, Pergamon, 8p.

20. Igue. A. M, A. Saidou, Adjanohoun A., Ezui G., P. Attiogbe, G. Kpagbin, H. Gotoechan-Hodonou, S. Youl, T. Pare, I. Balogoun, J. Ouedraogo, E. Dossa, A. Mando and J. M. Sogbedji (2013): Assessment of soil fertility in southern and central Benin. Bulletin of Agricultural Research of Benin (BRAB) Special issue Maize Fertility – January 2013 BRAB online (on line) on the website http://www.slire.net ISSN on paper (on hard copy): 1025-2355 and ISSN online: 1840-7099.

21. Schvartz C., Muller J.C. & Decroux J., (2005). Guide to reasoned fertilization: France Agricole 2005 editions. ISBN 2-85557-120-0.

22. . Oberson A., Besson J.M., Maire N. & Sticher H., (1996). Microbiological processes in soil organic phosphorus transformations in conventional and biological cropping systems. Biology and Fertility of Soils, 21(3), 138-148.

23. . Richardson A.E., Barea J.M., McNeill A.M. & Prigent-Combaret C., (2009). Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil, 321(1-2), 305-339.

24. . Schadeck N., (1997). Retention and mobilization of phosphorus in agricultural soils in Belgium. Particular application to wet areas. Doctoral thesis. Catholic University of Louvain, Louvain-la-Neuve, Belgium.

25. Tometin L, Chouti W, Chitou N, Sotondji R, Fatombi J, Mama D, Bawa L. Impacts of pollutants (phosphorus, nitrogen and potassium um) from agricultural activities on the soils and waters of Toho Lake (Benin) International Research Journal of Pure & Applied Chemistry 24: 2023 (in press)

26. Dorioz, J.-M and Blanc, P., (2001). Control of the external phosphorus load of water bodies and functioning of watersheds. In: Water in rural areas-Aquatic life and environment. INRA Editions, France.

27. Michaud A.R., Richard Lauzier and M.R. Laverdière (2005). Phosphorus mobility and agri-environmental intervention in an agricultural watershed: Case study of the Au Castor stream, tributary of the Aux Brochets river, Quebec. Agrosol. 16 (1): 47-60.

28. Michaud, A.R. and M.R. Laverdière (2004). Cropping, soil type and manure application effects on phosphorus export and bioavailability. Can. J. Soil Science 84(3): 295-305.