



## Enrichment of soil and its environmental impact Enriquecimiento fosfórico del suelo y su Impacto ambiental

 Adriano Cabrera-Rodríguez<sup>1\*</sup>,  Rosmery Cruz-Camacho<sup>2</sup>

<sup>1</sup>Instituto Nacional de Ciencias Agrícolas (INCA), carretera San José-Tapaste, km 3½, Gaveta Postal 1, San José de las Lajas, Mayabeque, Cuba. CP 32700.

<sup>2</sup>Instituto de Investigaciones del Tabaco, carretera Tumbadero, km 8½, San Antonio de los Baños, Artemisa, Cuba.

**ABSTRACT:** Phosphorus is one of the three primary macronutrients required for the growth of plants and animals. Its excessive application in agrosystems has generated soils enriched with P in many latitudes. The review's aim is to provide an abbreviated consideration of the meaning enriched with P and its environmental effects. When the balance between the applied P minus the exported is positive, the assimilable P increases. Therefore, an accumulation of P occurs over the years, producing the P-enrichment of soils. Phosphorus participates in the eutrophication of water bodies, which is exacerbated by P-enriched soils. In P-enriched soils, the pH increases, the content of organic matter decreases, the kaolinite is decomposed, nutrition is affected by antagonistic effects, and mycorrhizal function is inhibited.

**Key words:** phosphorus, phosphorus in soil, eutrophication, soil fertility.

**RESUMEN:** El P es uno de los tres macronutrientes primarios requerido para el crecimiento de las plantas y los animales. Su aplicación excesiva en los agrosistemas ha generado suelos enriquecidos con P en muchas latitudes. La revisión que se presenta tiene como objetivo realizar una valoración abreviada sobre el significado de suelo enriquecido con P y las afectaciones ambientales que ello provoca. Cuando el balance entre el P aplicado menos el exportado resulta positivo, se incrementa el P asimilable y se produce una acumulación de P en el suelo, que con el transcurso de los años origina el enriquecimiento en P de los suelos. El P participa en la eutrofización de los cuerpos de agua, lo que se agudiza cuando el suelo está enriquecido con P. En un suelo enriquecido con P se incrementa el pH, disminuye el contenido de materia orgánica, se descompone la caolinita, se afecta la nutrición de las plantas por efectos de antagonismo y se inhibe el funcionamiento micorrízico.

**Palabras clave:** fósforo, fósforo en suelo, eutrofización, fertilidad del suelo.

### INTRODUCTION

P is one of the three primary macronutrients required for the growth of plants and animals; its application is necessary to maintain the production and profitability of crops and animal production (1).

Due to the phosphoric applications over years with mineral fertilizers, organic fertilizers, or both, sometimes irrationally (2), high concentrations of P have been reached in many agricultural soils of different latitudes. Soils with very high concentrations of P have been found in Maryland, USA (3), in Holland (4,5), in other countries of the European Union (6), in China (7), which has been attributed to a more significant contribution of the nutrient than the removal made by the harvested product (1,8,9).

Based on the above, the presented review aims to make an abbreviated assessment of the meaning of soil enriched with P and its environmental effects.

### PHOSPHORIC ENRICHMENT OF THE SOIL

When in an agricultural area, the balance between the applied P minus that extracted by the harvested product (exported) is positive, the phosphoric availability of the soil (assimilable P) increases, and in turn, occurs an accumulation of P in the soil (residuality), which causes the phosphoric enrichment of the edaphic environment (10-15), over the years, that is, the soil becomes what is called a "P-enriched soil". In these cases, the assimilable P exceeds the value considered optimal for the crops, and these do not respond to phosphoric fertilization. The availability of P for crops is determined, in general, from the results obtained by i) the soil analysis, ii) the analysis of the plant or an indicator tissue of the plant, iii) the balance between the P applied to and exported by the harvested product.

\*Author for correspondence: [naniadriano1950@gmail.com](mailto:naniadriano1950@gmail.com)

Received: 22/06/2021

Accepted: 18/09/2021



Soil analysis provides information on the availability of P for plants (16-19), while the analysis of an indicator tissue of the plant (generally leaves or part of them) provides information on the crop's nutritional status (3,20,21). Both methods are valid, and the nutrient recommendation precision increases if both analyses are carried out. The balance method constitutes restoring what is exported from the field with the harvested product to the soil. For this, the chemical analysis must use the entire plant or parts (22,23).

The results obtained from the foliar or soil analysis are compared with already established categorizations to determine the plant's nutritional status or the soil's concentration of available P. In TABLE 1, it is exemplified with soil analysis using Bray and Kurtz No.1 (24), Olsen (25, 26), Mehlich 3 (26, 27) and Oniani (28) methods for determining assimilable P.

These categorizations in most cases are referred to as Low, Medium, High and Very High, also as Very Low, Low, Medium, High and Very High, or as Very Poor, Poor, Medium, Supplied, Very Supplied, among other modalities. In short, it is variable and dependent on the analytical technique, the researcher's considerations, the edaphoclimatic conditions, the plant species, and the management.

On many occasions in the case of soil analysis, other properties are considered to specify further the corresponding assimilable P category, such as pH, texture, organic matter

content, and cationic exchange capacity, among others. In the case of plant analysis, the percentage of humidity of the analyzed sample and the age of the plant at the time of sampling are often considered.

The categories defined for the phosphoric fertility of the soil and the nutritional status of the plants are associated with the dose of fertilizers to be applied, from which the one that corresponds to each specific condition is selected. Based on the difference between the applied P and that exported by the harvest (balance method), it is intended to maintain a stable state of phosphoric fertility of the soil over time (balance equal to "zero"), provided that this fertility is considered appropriate (Medium or High Category). The balance method allows increasing phosphoric fertility in soils with insufficient assimilable P (Low or Very Low) by applying more P than is exported from the field ("positive balance") until it reaches an optimal level of assimilable P concentration. A "negative balance" is appropriate to decrease the concentration in P enriched soils (Very High); the nutrient application is eliminated until the soil analysis indicates that the phosphoric category has reached an adequate level. From that moment on, the strategy will be to maintain a balance equal to "zero". Everything seems to indicate that there is a guarantee that in an agrosystem, the amount of P required for cultivation is applied to the soil; however, unfortunately, this has not been the case; various aspects have led to the phosphoric enrichment of the soil.

**Table 1.** Categorization of assimilable P from the soil determined by different methods.

Extractive solution	Category	P (mg kg <sup>-1</sup> )
0,03 M NH <sub>4</sub> F+0,025 M HCl pH 3,5	<b>Bray and Kurtz No. 1</b>	
	Very Low	< 3
	Low	3-7
	Medium	7-20
0,5 M NaHCO <sub>3</sub> pH 8,5	Adequate	> 20
	<b>Olsen</b>	
	Low	< 5
	Medium	5-10
	Adequate	> 10
	Low	< 10
	Optimum	10-30
High	30-60	
0,2 M CH <sub>3</sub> COOH+ 0,25 M NH <sub>4</sub> NO <sub>3</sub> + 0,015 M NH <sub>4</sub> F + 0,013 M HNO <sub>3</sub> + 0,001 M EDTA	Very High	> 60
	<b>Mehlich 3</b>	
	Low	< 15
	Optimum	15-50
	High	50-100
0,05 M H <sub>2</sub> SO <sub>4</sub>	Very High	> 100
	Critical Level	30
	<b>Oniani (mg 100 g<sup>-1</sup>, P<sub>2</sub>O<sub>5</sub>)</b>	
	Low	< 15
	Medium	15-30
High	30-45	
	Very High	> 45

A widespread issue in agricultural practice is that the farmers are satisfied to apply more nutrient than recommended without also assessing the negative economic impact of this practice.

Applying chemical phosphoric fertilizer or some amendment with appreciable P content and organic fertilizer can also be mentioned. This behavior has been practiced for years in livestock areas, especially in developed countries (29), where livestock excreta are taken and incorporated into the fields. Still, it is almost always the same fields that receive this treatment since that the transfer of wastes from its source to areas far from it makes the production process too expensive.

Another issue that deserves to be mentioned is the usage of fertilizer formulas in agriculture. It is complex to guarantee the dose of some nutrients without exceeding the needs of another, and it is almost always P that is overestimated. Some formulas used in agriculture are:

10-10-10	17-17-17
12-12-12	21-7-14
15-15-15	9-13-17

Another way to supply P to the arable horizon of the soil is through the biogenic accumulation or the nutrient recycling, possible through the incorporation of roots, senescent leaves, branches, flowers, fruits, and harvest residues, which provide part of the P on the surface that the plant extracts from deepest horizons.

## ENVIRONMENTAL IMPACT OF THE P ENRICHMENT SOIL

### Effect on water sources: Eutrophication

Eutrophication is defined simply as the over-enrichment with nutrients of aquatic ecosystems that leads to the growth of algae and anoxic events (2,30) or as the process of organic enrichment or biological productivity of a body of water, accelerated by greater contributions of nutrients (31).

In response to over-enrichment with nutrients, phytoplankton is modified towards an annoying proliferation of algae, which, when decomposed, produces a foul odor and causes a decrease in oxygen, causing the death of the fish (11).

Other problems associated with eutrophication are the presence of toxins in the water, loss of water transparency and a decrease in light reaching deep, the bad taste of drinking water, the disappearance of native plants, and loss of biodiversity (32).

Eutrophication is also a problem in many coastal marine areas, causing the death of coral reefs.

Finally, eutrophication in both fresh and saltwater sources leads to the loss of aquatic ecosystems' aesthetic, ecological and economic values.

Many aquatic ecosystems in the world have been subjected to eutrophication (South America (33-35), Cuba (36-38), Europe (39), China (40), Australia (41), South Africa (42), India (43), United States (44-45) (Table 2).

In addition to N, P is considered a critical component that limits the freshwater quality and causes eutrophication in many lakes and other water sources (2,46,47). The increase in the concentration of P in water bodies is produced, among other causes, by incorporating the nutrient through runoff that occurs in agricultural soils (48-50).

From the above, it can be deduced that to the extent that the applications of P are unnecessarily higher, the greater the risk of P enrichment soil and, at the same time, the greater the risk of participating in the eutrophication processes of the water sources. Hence, knowing how much P is required in each condition is vital to supply the nutrient that meets the requirements and no more.

### Effects on the soil

It is recognized that P has low solubility and low mobility in soils, and it can only be replaced by fertilization (51,52). When phosphoric fertilizer is applied and its granules dissolve with soil moisture, reactions develop between phosphate, soil constituents, and non-phosphorous compounds in the fertilizer, which remove the nutrient from the liquid phase

**Table 2.** Examples of aquatic ecosystems affected by eutrophication.

Ecosystem
Santa Lucía River, Uruguay
Titikaka Lake. Bolivia
Dam La Juventud, Pinar del Río. Cuba; dam Marenga, Ceará. Brazil
Los Guaos River, Santiago de Cuba. Cuba
Ariguanabo River, Artemisa. Cuba
Gulf of Batabanó, Mayabeque. Cuba
Baltic Sea, Black Sea, Mediterranean Sea, Northeast Atlantic. Europe
Taihu Lake, Chaohu Lake, Dianchi Lake, Yangtze River. China
Estuary Peel-Harvey, Mokoan Lake, Darling River. Australia
Reservoir Albert Falls, Reservorio Midmar, Reservoir Hartbeespoort, Coastal Lake Sibhayi, Coastal Lake Kuhlange among others. South Africa
Sukhna Lake. India
Everglades, Florida. United States
Chesapeake Bay, Mid-Atlantic region, United States

and make it less soluble (53). This phenomenon has been known for over a century and a half and is known as fixation or retention of P. Calcium carbonate and hydrated oxides and oxides of Fe and Al are among the soil constituents that participate in the fixation or retention of P, suggesting that P precipitates as Ca, Fe, or Al phosphate, or that it binds chemically to these cations on the surface of soil minerals (54). The retention of P with the mentioned cations is called adsorption and is considered an exchange reaction between the phosphate ions and the hydroxyl ions associated with the metal.

As the concentration of phosphate anions rises, the exchange with the anions (OH)<sup>-</sup> increases, which elevates the density of the negative charge of the colloid and thus, the pH of the solution (55).

Concentrated solutions of P have been shown to decompose kaolinite, leading to the precipitation of an Al-P compound (56). It has also been found that the adsorption of P promotes the release of (SO<sub>4</sub>)<sup>2-</sup> and (SiO<sub>4</sub>)<sup>4-</sup> and pH solution elevation, indicative of the replacement of the mentioned anions and (OH)<sup>-</sup> groups. By increasing the concentration of P, there is an abrupt increase in the release of (SiO<sub>4</sub>)<sup>4-</sup> and not (SO<sub>4</sub>)<sup>2-</sup>, which suggests that the silicate clay minerals are disorganized and the [(SiO<sub>4</sub>)<sup>4-</sup>] is displaced (57).

Evidence has been presented on the solubilization of soil organic matter caused by mono and di ammonium phosphate in the microsites of application of phosphoric sources (58).

The mechanism proposed for the explanation of the behavior described above consists in that the ammonium of the fertilizers replaces several di and trivalent metal ions of the stable complexes of organic matter, thus making the formed complexes more soluble, favoring the movement of organic matter through the soil profile (59). Faced with excess P in the soil, plants tend to show sufficient or excess P. When this occurs, the chlorophyll contents are drastically reduced due to the manifestation of antagonism with anions such as NO<sub>3</sub><sup>-</sup>, since the photosynthetic capacity and, therefore, chlorophyll is directly related to the content of P and N in the plant (60).

High concentrations of P in the soil cause a decrease in the absorption of Zn, either by the formation of precipitates in the soil or by metabolic processes in plants, which prevent the translocation of the nutrient from the root to the rest of the plant (61).

It has been shown that high concentrations of P in the soil decrease the levels of mycorrhizal colonization (62-65), lead to rapid suppression of the arbuscular development, and temporarily inhibit the growth of root colonization (66).

## GENERAL CONSIDERATIONS

The need for P in agriculture is undeniable; however, its use must be rational, in correspondence with soil and plant needs.

Excessive applications of P bring about adverse situations for the environment and agricultural production.

This review has attempted to briefly illustrate the origin of soil phosphorization and its environmental impact. Eutrophication, the increase in soil's pH, the decrease in

organic matter content, dispersion and decomposition of kaolinite, antagonism with other nutrients, and inhibition of mycorrhizal function are among the adverse effects.

From the preceding, it follows that it is an obligation to act efficiently in the use of fertilizers in general and phosphoric ones in particular, which, in addition to being expensive, come from exhaustible sources of nature, already very depressed.

Therefore, it is necessary to establish the best assimilable P analysis method for each condition, know the current state of the soils in terms of their phosphoric availability, update the external and internal P requirements of the crops, establish new categorizations of soil's phosphoric availability, use the balance method (input minus export) accompanied by soil analysis to be able to more precisely adjust the doses of P to apply in each condition and finally, investigate in field conditions the effects that P enrichment could have on soil fertility.

## CONCLUSIONS

- Applications of phosphorus fertilizers in agrosystems in time that exceed the exports made by the harvested product cause the enrichment of the soil with the nutrient.
- The enrichment of the soil with phosphorus facilitates the nutrient to participate in eutrophication from erosive phenomena.
- High concentrations of phosphorus in the soil increase the pH, decrease organic matter content, disperse and decompose kaolinite, cause antagonism with other nutrients, and inhibit mycorrhizal function.

## BIBLIOGRAPHY

1. Sharpley AN, Daniel T, Sims T, Lemunyon J, Stevens R, Parry R. Agricultural phosphorus and eutrophication [Internet]. Second Edition. U.S: Department of Agriculture, Agricultural Research Service; 2003. Available from: <https://naldc.nal.usda.gov/download/26693/PDF>
2. Lee GF. Role of phosphorus in eutrophication and diffuse source control. In: Phosphorus in Fresh Water and the Marine Environment [Internet]. Elsevier; 1973. p. 111-28. Available from: <https://www.sciencedirect.com/science/article/pii/B9780080176970500134>
3. Delorme TA, Angle JS, Coale FJ, Chaney RL. Phytoremediation of phosphorus-enriched soils. International Journal of phytoremediation [Internet]. 2000;2(2):173-81. Available from: <https://www.tandfonline.com/doi/abs/10.1080/15226510008500038>
4. Reijneveld JA, Ehlert PAI, Termorshuizen AJ, Oenema O. Changes in the soil phosphorus status of agricultural land in the Netherlands during the 20th century. Soil use and management [Internet]. 2010;26(4):399-411. Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.14752743.2010.00290.x>
5. Van Middelkoop JC, Van der Salm C, Ehlert PAI, De Boer IJM, Oenema O. Does balanced phosphorus fertilisation sustain high herbage yields and phosphorus contents in alternately grazed and mown pastures? Nutrient Cycling in Agroecosystems

- [Internet]. 2016;106(1):93-111. Available from: <https://link.springer.com/article/10.1007/s10705-016-9791-0>
6. Tóth G, Guicharnaud R-A, Tóth B, Hermann T. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *European Journal of Agronomy* [Internet]. 2014;55:42-52. Available from: <https://www.sciencedirect.com/science/article/pii/S1161030113001950>
  7. Li M, Hu Z, Zhu X, Zhou G. Risk of phosphorus leaching from phosphorus-enriched soils in the Dianchi catchment, Southwestern China. *Environmental Science and Pollution Research* [Internet]. 2015;22(11):8460-70. Available from: <https://link.springer.com/article/10.1007%2Fs11356-014-4008z>
  8. Sharpley AN, Chapra SC, Wedepohl R, Sims JT, Daniel TC, Reddy KR. Managing agricultural phosphorus for protection of surface waters: Issues and options. 1994; Available from: <https://pubag.nal.usda.gov/catalog/54>
  9. MacDonald GK, Bennett EM, Potter PA, Ramankutty N. Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences* [Internet]. 2011;108(7):3086-91. Available from: <https://www.pnas.org/content/108/7/3086.short>
  10. Daniel TC, Sharpley AN, Lemunyon JL. Agricultural phosphorus and eutrophication: A symposium overview. 1998; Available from: <https://pubag.nal.usda.gov/catalog/20276>
  11. Bennett EM, Carpenter SR, Caraco NF. Human impact on erodible phosphorus and eutrophication: a global perspective: increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. *BioScience* [Internet]. 2001;51(3):227-34. Available from: <https://academic.oup.com/bioscience/article/51/3/227/256199?login=true>
  12. Bruulsema TW. Soil Fertility in the Northeast Region. *Better Crops* [Internet]. 2006;90(1):8. Available from: [http://www.ipni.net/publication/bettercrops.nsf/0/AA3D55510F6A6E82852579800081DEC5/\\$FILE/Better%20Crops%202006-1%20p08.pdf](http://www.ipni.net/publication/bettercrops.nsf/0/AA3D55510F6A6E82852579800081DEC5/$FILE/Better%20Crops%202006-1%20p08.pdf)
  13. Catma S, Collins A. Phosphorus Imbalances in the Chesapeake Bay Watershed: Can Forestland and Manure Processing Facilities Be the Answers? *Agricultural and Resource Economics Review* [Internet]. 2011;40(1):116-32. doi: <https://doi.org/10.1017/S106828050000455X>
  14. Fischer P, Pöthig R, Venohr M. The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. *Science of The Total Environment* [Internet]. 2017;599:1130-9. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0048969717306629>
  15. Hirte J, Richner W, Orth B, Liebisch F, Flisch R. Yield response to soil test phosphorus in Switzerland: Pedoclimatic drivers of critical concentrations for optimal crop yields using multilevel modelling. *Science of The Total Environment* [Internet]. 2021;755:143453. Available from: <https://www.sciencedirect.com/science/article/pii/S0048969720369849>
  16. Cabrera A, Arzuaga J, Mojena M. Desbalance nutrimental del suelo y efecto sobre el rendimiento de tomate (*Lycopersicon solanum* L.) y pepino (*Cucumis sativus* L.) en condiciones de cultivo protegido. *Cultivos Tropicales* [Internet]. 2007;28(3):91-7. Available from: <https://www.re-dalyc.org/pdf/1932/193215844015.pdf>
  17. Calderón Puig A, Lara Franquis D, Cabrera Rodríguez A. Confección de mapas temáticos para evaluar la fertilidad del suelo en las áreas agrícolas del Instituto Nacional de Ciencias Agrícolas. *Cultivos Tropicales* [Internet]. 2012;33(1):11-8. Available from: [http://scielo.sld.cu/scielo.php?pid=S025859362012000100002&script=sci\\_art-text&tlng=en](http://scielo.sld.cu/scielo.php?pid=S025859362012000100002&script=sci_art-text&tlng=en)
  18. Scheffe CR, Barlow KM, Robinson NJ, Crawford DM, McLaren TI, Smernik RJ, et al. 100 Years of superphosphate addition to pasture in an acid soil-current nutrient status and future management. *Soil Research* [Internet]. 2015;53(6):662-76. Available from: <https://www.publish.csiro.au/SR/SR14241>
  19. Buczko U, van Laak M, Eichler-Löbermann B, Gans W, Merbach I, Panten K, et al. Re-evaluation of the yield response to phosphorus fertilization based on meta-analyses of long-term field experiments. *Ambio* [Internet]. 2018;47(1):50-61. Available from: <https://link.springer.com/content/pdf/10.1007/s13280-017-0971-1.pdf>
  20. Gagnon B, Ziadi N. Papermill biosolids and alkaline residuals affect crop yield and soil properties over nine years of continuous application. *Canadian Journal of Soil Science* [Internet]. 2012;92(6):917-30. Available from: <https://cdnsiencepub.com/doi/full/10.4141/cjss2012-026>
  21. Almeida FM de, Noval WT la, Cabrera-Rodríguez JA, Arzuaga-Sánchez J. Crecimiento de plantas de papa (*Solanum tuberosum* L. cv Romano), en la provincia de Huambo, Angola, bajo dos densidades de plantación. *Cultivos Tropicales* [Internet]. 2018;39(3):31-40. Available from: [http://scielo.sld.cu/scielo.php?pid=S0258-59362018000300005&script=sci\\_art-text&tlng=pt](http://scielo.sld.cu/scielo.php?pid=S0258-59362018000300005&script=sci_art-text&tlng=pt)
  22. Cañizares PJG. Manejo efectivo de la simbiosis micorrízica arbuscular vía inoculación y la fertilización mineral en pastos del género *Brachiaria* [Internet]. Editorial Universitaria; 2014. Available from: <http://dx.doi.org/10.13140/RG.2.2.27770.95685>
  23. Espinosa CA. Factibilidad y beneficios de la inoculación micorrízica arbuscular en la producción de boniato (*Ipomoea batatas* (L.) Lam.) [Doctorado]. Universidad Agraria de la Habana, Mayabeque, Cuba; 2021. 100 p.
  24. Bray RH, Kurtz LT. Determination of total, organic, and available forms of phosphorus in soils. *Soil science* [Internet]. 1945;59(1):39-46. Available from: [https://journals.lww.com/soilsci/Citation/1945/01000/Determination\\_of\\_Total\\_Organic\\_and\\_Available.6.aspx](https://journals.lww.com/soilsci/Citation/1945/01000/Determination_of_Total_Organic_and_Available.6.aspx)
  25. Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate [Internet]. US Department of Agriculture; 1954. Available from: <https://books.google.es/books?hl=es&lr=&id=doaM88x5agC&oi=fnd&pg=PA3&dq=Estimation+of+available+phosphorus+in+soils+by+extraction+with+sodium+bicarbonate&ots=zZY>

- nTFkPTC&sig=Y\_pfYNmPPs86TM41Udnz\_PrC4dg#v=onepage&q=Estimation%20of%20available%20phosphorus%20in%20soils%20by%20extraction%20with%20sodium%20bicarbonate&f=false
26. Reid K, Schneider K, Joosse P. Addressing imbalances in phosphorus accumulation in Canadian agricultural soils. *Journal of environmental quality* [Internet]. 2019;48(5):1156-66. Available from: <https://access.onlinelibrary.wiley.com/doi/full/10.2134/jeq2019.05.0205>
  27. Mehlich A. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis* [Internet]. 1984 [cited 8/12/2021];15(12):1409-16. <https://doi.org/10.1080/00103628409367568>
  28. Oficina Nacional de Normalización. NORMA CUBANA NC 52. Calidad del suelo. Análisis químico. Determinación de las formas móviles de fósforo y potasio. 1999.
  29. Sharpley AN, McDowell RW, Kleinman PJ. Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and soil* [Internet]. 2001;237(2):287-307. Available from: <https://link.springer.com/article/10.1023/A:1013335814593>
  30. Carpenter SR. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. *Proceedings of the National Academy of Sciences* [Internet]. 2005;102(29):10002-5. Available from: <https://www.pnas.org/content/102/29/10002.short>
  31. Sharpley A, Tunney H. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. 2000; Available from: <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2000.00472425002900010022x>
  32. Fernández-Marcos ML. Contaminación por fósforo procedente de la fertilización orgánica de suelos agrícolas. *Gestión de residuos orgánicos de uso agrícola*, no. May [Internet]. 2011;25-31. Available from: [https://www.researchgate.net/profile/Lugo-Ibader/publication/338544738\\_Lopez-Mosquera\\_ME\\_Sainz-Oses\\_MJ\\_Coords\\_2011\\_Guia\\_de\\_residuos\\_organicos\\_de\\_uso\\_agricola\\_Santiago\\_de\\_Compostela\\_Servizo\\_de\\_Publicacions\\_Universidade\\_de\\_Santiago\\_de\\_Compostela/links/5e1b81ae4585159aa4cb51ec/Lopez-Mosquera-ME-Sainz-Oses-MJ-Coords-2011\\_Guia\\_de\\_residuos\\_organicos\\_de\\_uso\\_agricola\\_Santiago\\_de\\_Compostela\\_Servizo\\_de\\_Publicacions\\_Universidade\\_de\\_Santiago\\_de\\_Compostela.pdf#page=27](https://www.researchgate.net/profile/Lugo-Ibader/publication/338544738_Lopez-Mosquera_ME_Sainz-Oses_MJ_Coords_2011_Guia_de_residuos_organicos_de_uso_agricola_Santiago_de_Compostela_Servizo_de_Publicacions_Universidade_de_Santiago_de_Compostela/links/5e1b81ae4585159aa4cb51ec/Lopez-Mosquera-ME-Sainz-Oses-MJ-Coords-2011_Guia_de_residuos_organicos_de_uso_agricola_Santiago_de_Compostela_Servizo_de_Publicacions_Universidade_de_Santiago_de_Compostela.pdf#page=27)
  33. Aubriot L, Delbene L, Haakonsson S, Somma A, Hirsch F, Bonilla S. Evolución de la eutrofización en el Río Santa Lucía: influencia de la intensificación productiva y perspectivas. *Innotec* [Internet]. 2017; (14):7-16. Available from: <https://www.redalyc.org/jatsRepo/6061/606164031001/606164031001.pdf>
  34. Fontúrbel Rada F. Indicadores fisicoquímicos y biológicos del proceso de eutrofización del Lago Titikaka (Bolivia). *Ecología aplicada* [Internet]. 2005;4(1-2):135-41. Available from: [http://www.scielo.org.pe/scielo.php?pid=S1726-22162005000100018&script=sci\\_art-text&tlng=en](http://www.scielo.org.pe/scielo.php?pid=S1726-22162005000100018&script=sci_art-text&tlng=en)
  35. Wiegand MC, Piedra JIG, Araújo JC de. Vulnerabilidade à eutrofização de dois lagos tropicais de climas úmido (Cuba) e semiárido (Brasil). *Engenharia Sanitária e Ambiental* [Internet]. 2016;21:415-24. Available from: <https://www.scielo.br/j/esa/a/8NnDjzZqCmRGfDhqjicGVXD/?format=html>
  36. Marañón-Reyes AM, Pérez-Pompa NE, Dip-Gandarilla AM, González-Marañón A, Pérez-Silva RM, Ruiz-Estrella A. Evaluación temporal de la calidad de las aguas del río Los Guaos de Santiago de Cuba. *Revista Cubana de Química* [Internet]. 2014;26(2):115-25. Available from: [http://scielo.sld.cu/scielo.php?script=sci\\_art-text&pid=S2224-54212014000200004](http://scielo.sld.cu/scielo.php?script=sci_art-text&pid=S2224-54212014000200004)
  37. Miravet Sánchez BL, García Rivero AE, López Del Castillo P, Alayón García G, Salinas Chávez E. Calidad de las aguas del río Ariguanabo según índices físico-químicos y bioindicadores. *Ingeniería Hidráulica y Ambiental* [Internet]. 2016;37(2):108-22. Available from: [http://scielo.sld.cu/scielo.php?pid=S1680-03382016000200009&script=sci\\_art-text&tlng=pt](http://scielo.sld.cu/scielo.php?pid=S1680-03382016000200009&script=sci_art-text&tlng=pt)
  38. Montalvo JF, López García DB, Perigó E, Blanco M. Nitrógeno y fósforo en las aguas del Golfo de Batabanó, Cuba, entre los años 1999 y 2000. 2017; Available from: <https://aquadocs.org/handle/1834/12938>
  39. Agency EE. Nutrient Enrichment and Eutrophication in Europe's Seas. Moving Towards a Healthy Marine Environment [Internet]. Publications Office of the European Union Luxembourg; 2019. Available from: <https://www.eea.europa.eu/publications/nutrient-enrichment-and-eutrophication-in>
  40. Gao C, Zhang T. Eutrophication in a Chinese context: understanding various physical and socio-economic aspects. *Ambio* [Internet]. 2010;39(5):385-93. Available from: <https://link.springer.com/article/10.1007/s13280-010-0040-5>
  41. Davis JR, Koop K. Eutrophication in Australian rivers, reservoirs and estuaries—a southern hemisphere perspective on the science and its implications. *Hydrobiologia* [Internet]. 2006;559(1):23-76. Available from: <https://link.springer.com/article/10.1007/s10750-005-4429-2>
  42. Matthews MW, Bernard S. Eutrophication and cyanobacteria in South Africa's standing water bodies: A view from space. *South African journal of science* [Internet]. 2015;111(5):1-8. Available from: <https://journals.co.za/doi/abs/10.10520/EJC170780>
  43. Arora SK. A Study of Eutrophication Phenomenon of a Lake of a Modern City of India. *International Journal of Engineering Research & Technology (IJERT)* [Internet]. 2016;5(Issue 06):470-3. Available from: <http://dx.doi.org/10.17577/IJERTV5IS060602>
  44. Noe GB, Childers DL, Jones RD. Phosphorus biogeochemistry and the impact of phosphorus enrichment: Why is the Everglades so unique? *Ecosystems* [Internet]. 2001;4(7):603-24. Available from: <https://link.springer.com/article/10.1007/s10021-001-0032-1>
  45. Cramer S. An examination of levels of phosphorus and nitrogen in the Chesapeake Bay before and after

- the implementation of the chesapeake 2000 program. The Public Purpose [Internet]. 2014;12:65-77. Available from: <https://observer.american.edu/spa/publicpurpose/upload/2014-public-purposechesapeake-sam-cramer.pdf>
46. Dougherty WJ, Fleming NK, Cox JW, Chittleborough DJ. Phosphorus transfer in surface runoff from intensive pasture systems at various scales: A review. *Journal of environmental quality* [Internet]. 2004;33(6):1973-88. Available from: <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2004.1973>
  47. Reid K, Schneider K, McConkey B. Components of phosphorus loss from agricultural landscapes, and how to incorporate them into risk assessment tools. *Frontiers in Earth Science* [Internet]. 2018;6:135. Available from: <https://www.frontiersin.org/articles/10.3389/feart.2018.00135/full>
  48. Hart MR, Quin BF, Nguyen ML. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. *Journal of environmental quality* [Internet]. 2004;33(6):1954-72. Available from: <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2004.1954>
  49. Fischer P, Pöthig R, Gucker B, Venohr M. Estimation of the degree of soil P saturation from Brazilian Mehlich-1 P data and field investigations on P losses from agricultural sites in Minas Gerais. *Water Science and Technology* [Internet]. 2016;74(3):691-7. Available from: <https://iwaponline.com/wst/article-abstract/74/3/691/19426/Estimation-of-the-degree-of-soil-Psaturation-from>
  50. Hayes MA, Jesse A, Tabet B, Reef R, Keuskamp JA, Lovelock CE. The contrasting effects of nutrient enrichment on growth, biomass allocation and decomposition of plant tissue in coastal wetlands. *Plant and Soil* [Internet]. 2017;416(1):193-204. Available from: <https://link.springer.com/article/10.1007/s11104-017-3206-0>
  51. McDowell RW, Sharpley AN. Phosphorus solubility and release kinetics as a function of soil test P concentration. *Geoderma* [Internet]. 2003;112(1-2):143-54. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0016706102003014>
  52. Takahashi S, Anwar MR. Wheat grain yield, phosphorus uptake and soil phosphorus fraction after 23 years of annual fertilizer application to an Andosol. *Field Crops Research* [Internet]. 2007;101(2):160-71. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0378429006002097>
  53. Sample EC, Soper RJ, Racz GJ. Reactions of phosphate fertilizers in soils. The role of phosphorus in agriculture [Internet]. 1980;263-310. Available from: <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/1980.roleofphosphorus.c12>
  54. Wild A. The retention of phosphate by soil. A review. *Journal of Soil Science* [Internet]. 1950;1(2):221-38. Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2389.1950.tb00734.x>
  55. Rajan SSS, Perrott KW, Saunders WMH. Identification of phosphate-reactive sites of hydrous alumina from proton consumption during phosphate adsorption at constant pH values. *Journal of Soil Science* [Internet]. 1974;25(4):438-47. Available from: <https://doi.org/10.1111/j.1365-2389.1974.tb01139.x>
  56. Kittrick JA, Jackson ML. Electron-microscope observations of the reaction of phosphate with minerals, leading to a unified theory of phosphate fixation in soils. *Journal of Soil Science* [Internet]. 1956;7(1):81-9. Available from: <https://doi.org/10.1111/j.1365-2389.1956.tb00865.x>
  57. Rājan SSS, Fox RL. Phosphate adsorption by soils: II. Reactions in tropical acid soils. *Soil Science Society of America Journal* [Internet]. 1975;39(5):846-51. Available from: <https://doi.org/10.2136/sssaj1975.03615995003900050019x>
  58. Bell LC, Black CA. Comparison of methods for identifying crystalline phosphates produced by interaction of orthophosphate fertilizers with soils. *Soil Science Society of America Journal* [Internet]. 1970;34(4):579-82. Available from: <https://doi.org/10.2136/sssaj1970.03615995003400040013x>
  59. Giordano PM, Sample EC, Mortvedt JJ. Effect of ammonium ortho- and pyrophosphate on Zn and P in soil solution. *Soil Science* [Internet]. 1971;111(2):101-6. Available from: [https://journals.iw.com/soilsci/citation/1971/02000/effect\\_of\\_ammonium\\_ortho\\_and\\_pyrophosphate\\_on\\_zn.4.aspx](https://journals.iw.com/soilsci/citation/1971/02000/effect_of_ammonium_ortho_and_pyrophosphate_on_zn.4.aspx)
  60. Singh SK, Reddy VR. Response of carbon assimilation and chlorophyll fluorescence to soybean leaf phosphorus across CO<sub>2</sub>: Alternative electron sink, nutrient efficiency and critical concentration. *Journal of Photochemistry and Photobiology B: Biology* [Internet]. 2015;151:276-84. Available from: <https://doi.org/10.1016/j.jphotobiol.2015.08.021>
  61. Malavolta E. Avaliação do estado nutricional das plantas: princípios e aplicações/Eurípedes Malavolta, Godofredo Cesar Vitti, Sebastião Alberto de Oliveira.-2. ed., ver. e atual. Piracicaba: Potafos [Internet]. 1997; Available from: <http://www.sidalc.net/cgi-bin/wxis.exe/?IsisScript=sibur.xis&method=post&formato=2&cantidad=1&expresion=mfn=003461>
  62. Nagy R, Drissner D, Amrhein N, Jakobsen I, Bucher M. Mycorrhizal phosphate uptake pathway in tomato is phosphorus-repressible and transcriptionally regulated. *New Phytologist* [Internet]. 2009;181(4):950-9. Available from: <https://nph.onlinelibrary.wiley.com/doi/full/10.1111/j.14698137.2008.02721.x>
  63. Breuillin F, Schramm J, Hajirezaei M, Ahkami A, Favre P, Druege U, et al. Phosphate systemically inhibits development of arbuscular mycorrhiza in *Petunia hybrida* and represses genes involved in mycorrhizal functioning. *The Plant Journal* [Internet]. 2010;64(6):1002-17. Available from: <https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-313X.2010.04385.x>
  64. Balzergue C, Puech-Pagès V, Bécard G, Rochange SF. The regulation of arbuscular mycorrhizal symbiosis by phosphate in pea involves early and systemic signalling events. *Journal of experimental botany* [Internet]. 2011;62(3):1049-60. Available from: <https://academic.oup.com/jxb/article/62/3/1049/478338?login=true>
  65. Balzergue C, Chabaud M, Barker DG, Bécard G, Rochange SF. High phosphate reduces host ability

to develop arbuscular mycorrhizal symbiosis without affecting root calcium spiking responses to the fungus. *Frontiers in plant science* [Internet]. 2013;4:426. Available from: [https://www.frontiersin.org/articles/10.3389/fpls.2013.00426/full?utm\\_source=newsletter&utm\\_medium=web&utm\\_campaign=Plant\\_Science-w48-2013](https://www.frontiersin.org/articles/10.3389/fpls.2013.00426/full?utm_source=newsletter&utm_medium=web&utm_campaign=Plant_Science-w48-2013)

66. Kobae Y, Ohmori Y, Saito C, Yano K, Ohtomo R, Fujiwara T. Phosphate treatment strongly inhibits new arbuscule development but not the maintenance of arbuscule in mycorrhizal rice roots. *Plant Physiology* [Internet]. 2016;171(1):566-79. Available from: <https://academic.oup.com/plphys/article/171/1/566/6115000?login=true>