Scientific Research Publishing

American Journal of Analytical Chemistry, 2026, 17(7), 254-268
https://www.scirp.org/journal/ajac
ISSN Online: 2156-8278
ISSN Print: 2156-8251

Assessment of Trace Metals (TMs) in Fertilizers Formulated from Phosphate Slimes through the Progressive Substitution of Phosphoric Acid

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How to cite this paper: Diao, H., Faye, M., Faye, M. and Gaye, A. (2026) Assessment of Trace Metals (TMs) in Fertilizers Formulated from Phosphate Slimes through the Progressive Substitution of Phosphoric Acid. *American Journal of Analytical Chemistry*, **17**, 254-268.
https://doi.org/10.4236/ajac.2026.177015

Received: May 11, 2026
Accepted: July 14, 2026
Published: July 17, 2026

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Abstract

As part of valorizing ICS slimes, chemical fertilizers were produced according to 6-20-10, 15-10-10, and 15-15-15 formulas. Their quality was evaluated based on parameters related to dissolution, in particular conductivity, solubility, and pH. This dissolution releases chemical elements and induces the deposition of trace metals (TMs). The analysis of the samples provided key parameters essential for understanding the behavior of the fertilizer. The concentrations of TMs were measured by X-ray fluorescence spectrophotometry. Four major elements, cadmium (Cd), chromium (Cr), copper (Cu), and lead (Pb), were identified. Their concentrations varied depending on the fertilizer formulation and the proportion of slimes incorporated. Cadmium remains generally low (0 to 30.59 ppm) and complies with regulatory thresholds. Chromium shows high levels, reaching up to 404.63 ppm. Copper and lead, which are correlated, present moderate concentrations, with maximum values of 64.6 and 15.22 ppm, respectively. The measured pH is acidic and inversely correlated with conductivity. The results demonstrate the quality of fertilizers based on slimes and their compliance with agricultural standards. Environmental safety was observed for formulations containing 15% P_2O_5 at 25% slimes substitution, while compliance depended on both fertilizer formulation and slimes substitution level.

Keywords

Slimes, Phosphoric Acid, Fertilizer, Trace Metals

1. Introduction

The valorization of mining waste, such as gypsum, slimes, and fluosilicic acid, has become a priority in environmental management strategies, particularly for the extractive industry, as recommended by the European Union Directive 2006/21/CE [1]. Slimes, residues generated during phosphate ore processing, represent not only a source of pollution but also an opportunity for developing value-added products [1]-[3]. However, these wastes are known for their content of metallic compounds [4], which often raises concerns regarding their use as fertilizers in agricultural crops [1].

This study focuses on the valorization of slimes from the Senegalese Chemical Industries (ICS), considered as natural phosphate, through the formulation of chemical fertilizers. The primary aim is to quantify the Trace Metals (TMs) present in these fertilizers to assess their quality for agricultural use. The fertilizers were formulated based on the 6-20-10, 15-10-10, and 15-15-15 formulations. In each formulation, the progressive substitution of phosphoric acid by slimes was carried out at increments of 0%, 25%, 50%, 75%, and 100%, in order to investigate its impact not only on fertilizer and nutrient contents, as explored in previous studies, but also on trace metal concentrations, which constitute the focus of the present work.

Naturally occurring and used in industry, TMs can be dispersed into soils and water through atmospheric transport, posing risks to ecosystems and the food chain [4]. Phosphate rock, the raw material for phosphate fertilizers, contains variable concentrations of these metals [5] [6], depending on its geological origin [7] [8]. The objective, therefore, is to evaluate the concentrations of trace metals such as cadmium (Cd), chromium (Cr), copper (Cu), and lead (Pb), and their variation according to the fertilizer formulation and the proportion of slimes used.

The analysis also integrated dissolution parameters (solubility, conductivity, pH) that influence the release of nutrients and metals. This study evaluates the potential of slimes as fertilizers while emphasizing their limitations and environmental impacts.

2. Materials and Methods

To assess the quality of fertilizers derived from slimes, particularly their nutrient and trace metal (TMs) contents, several analytical methods were employed. This section describes the materials, the formulation process, and the techniques used for TMs analysis to evaluate the fertilizers' compliance with agricultural standards. Three fertilizer formulations, namely 6-20-10, 15-10-10, and 15-15-15, were prepared using various raw materials following an optimized formulation procedure. The samples coded 1A to 5A, 1B to 5B, and 1C to 5C correspond to five progressive slime substitution levels (0%, 25%, 50%, 75%, and 100%) for formulations A, B, and C, respectively.

Several formulation trials were conducted during fertilizer preparation to achieve the targeted nutrient compositions. However, only the final optimized formulations were retained for analysis. All analytical measurements (pH, conductivity, nutrient content, solubility, and XRF) were performed in duplicate for each sample, and the reported values represent the average of the duplicate measurements.

2.1. Raw Material

Fertilizers were formulated using slimes derived from phosphate processing at ICS, containing 24% P_2O_5 and trace metals (Cd, Cr, Cu, Pb). Other materials used included phosphoric acid (52% P_2O_5), sulfuric acid (98%), potassium sulfate (51% K2O), and urea (46% N). Three formulations were developed: A (6-20-10), B (15-10-10), and C (15-15-15). In each case, phosphoric acid was progressively replaced by slimes at rates of 0%, 25%, 50%, 75%, and 100% to evaluate the effects on fertilizer quality and TMs content.

2.2. Fertilizer Formulation Process

The formulation process is carried out in two main stages, as illustrated in **Figure 1**.

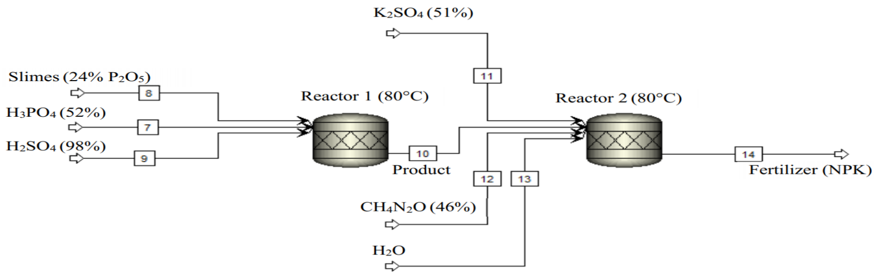

Figure 1. Flowsheet of process for the formulation of complex compound fertilizers based on slimes.

The formulation process begins in a first reactor maintained at 80˚C, where the slimes are mixed with phosphoric and sulfuric acids to release the contained elements, including phosphorus, organic matter, and Trace Metals (TMs). After the reaction leading to the formation of triple superphosphate (TSP), potassium sulfate (K2SO4) is added to adjust the K2O content. The mixture is then transferred to a second reactor, also maintained at 80˚C, where urea and water are added to complete the NPK (nitrogen-phosphorus-potassium) formulation, ensure optimal homogeneity, and dissolution of the components.

2.3. Chemical Analysis of Nutrient Elements

The formulated fertilizer samples were analyzed to determine their contents of:

- Total nitrogen (N): measured using the Kjeldahl method,
- Phosphorus (P_2O_5): determined by UV spectrophotometry after acid digestion,
- Potassium (K2O): quantified by flame photometry,
- Organic matter (OM) and carbon (C): determined using the modified Anne method (a simplified version of the Walkley-Black method),
- Citrate-soluble P_2O_5 (P_2O_5SC) and water-soluble P_2O_5 (P_2O_5SE): measured by dissolution in citrate and water, respectively.

These analyses confirmed the suitability of the 6-20-10, 15-10-10, and 15-15-15 formulations for agricultural applications.

Additional tests were also performed to evaluate dissolution behavior and the potential environmental impact of these fertilizers, particularly concerning the presence of trace metals.

2.4. Dissolution Parameters of Fertilizers

For each fertilizer formulation, dissolution tests were carried out to measure the following parameters:

- Solubility: determined through water dissolution tests to quantify the fraction of fertilizer that dissolves and influences the release of Trace Metals (TMs).

- pH: measured in a 10% (w/w) aqueous solution to assess the acidity of the solution after fertilizer dissolution.

- Electrical conductivity: measured to evaluate ion release in solution, it provides insight into the solubility behavior of both nutrients and trace metals.

2.5. Trace Metals Analysis

The concentrations of trace metals in the fertilizer samples were determined using X-ray fluorescence (XRF) spectrometry with a Niton XL3T XRF Analyzer. This non-destructive technique enables the quantification of the most common trace metals (TMs) found in phosphate fertilizers, including cadmium (Cd), chromium (Cr), copper (Cu), and lead (Pb), with data processing performed using the integrated NDTr 6.5.2 software. The following **Figures 2-4** present the instrument and its operating software.

Figure 2. Vertical layout of the Niton XL3T XRF Analyzer.

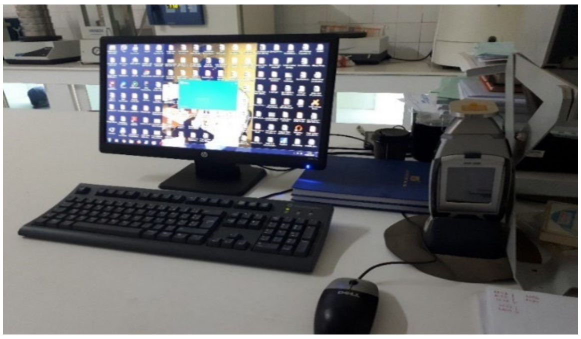

Figure 3. General view of the device connected to the computer.

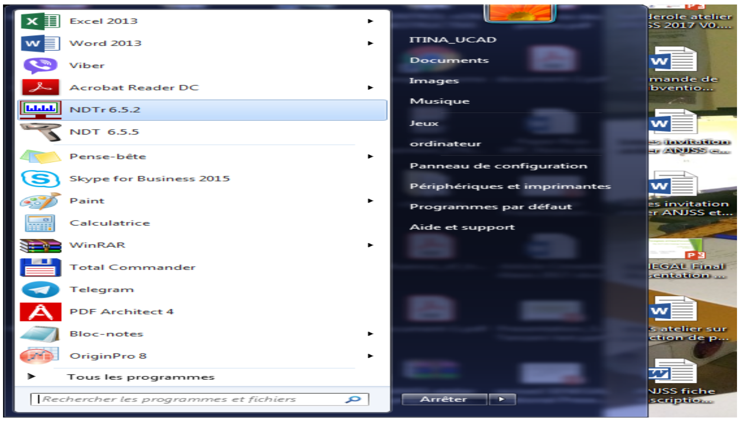

Figure 4. Opening of the NDTr 6.5.2 software.

2.6. Sample Preparation and Analysis

The mineral composition was determined by X-ray fluorescence spectrometry, using the Niton XL3T XRF analyzer connected to a computer equipped with NDTr 6.5.2 software for data acquisition and processing. This is a multi-element, rapid, and non-destructive analysis technique that allows for the identification and quantification of most chemical elements present in a sample.

For each analysis, a quantity of 1.2 g of powder was mixed with 0.12 g of the binder (Hoescht wax), then placed into a compression mold. A pressure of approximately 15 tons was applied using a press for 2 to 3 minutes to obtain a compact pellet suitable for analysis. The pellets were then analyzed using the Niton XL3T XRF analyzer, which was previously calibrated using certified standards. The analysis is based on the excitation of atoms in the sample by an X-ray beam whose energy is sufficient to eject electrons from the inner shells. The subsequent rearrangement, involving the return of electrons from the outer shells to the vacant energy levels, is accompanied by the emission of characteristic X-rays, whose energy is unique to the emitting element. The emitted spectra are recorded and processed by a pulse height analyzer. The identification of elements is based on the energy of the emitted peaks, while their quantification is determined from the intensity of these peaks.

2.7. Impact of Slimes on Trace Metal Concentrations

The effect of progressively substituting phosphoric acid with slimes on Trace Metals (TMs) concentrations (Cd, Cr, Cu, Pb) was investigated for each fertilizer formulation (6-20-10, 15-10-10, 15-15-15) at different substitution rates (0%, 25%, 50%, 75%, and 100%). The objective was to assess environmental risks, identify critical contamination thresholds, and optimize the formulations to balance agronomic efficiency with safety.

2.8. Safety Standards and Concentration Limits

The concentrations of trace metals in the formulated fertilizers were evaluated against relevant international regulatory frameworks. For cadmium (Cd), the results were compared with the limit established by Regulation (EU) 2019/1009 [9] for phosphate fertilizers marketed in the European Union, namely 60 ppm P_2O_5. For the other trace metals, the results were assessed using limits and recommendations reported in the scientific literature and international regulatory guidelines, as no single harmonized standard exists across all jurisdictions. In the United States, trace metal limits in fertilizers are generally regulated at the state level and may depend on fertilizer application rates rather than fixed concentration thresholds. These comparisons were used to evaluate the environmental suitability and regulatory compliance of the formulated fertilizers.

The results of this study refer to Regulation (EU) 2019/1009, which establishes a cadmium limit of 60 ppm P_2O_5 for phosphate fertilizers, as cadmium is considered one of the most critical contaminants at elevated concentrations. However, this regulation does not provide harmonized limits for several other trace metal elements (TMEs), whose permissible concentrations are often defined by national regulations. Therefore, the concentrations of these trace metals were also compared with national fertilizer regulations compiled by Hutton and Meeus (2001) and the Fertilizer Industry Federation of Australia (2003), as cited by [10].

The trace metal concentrations obtained in this study can also be compared with values reported in the literature. Verbeeck *et al.* [11] investigated the trace metal composition of phosphate fertilizers used in Europe, while Gómez *et al.* [12] evaluated trace metal contents in phosphate fertilizers marketed in Peru. Such comparisons provide useful benchmarks for assessing the environmental quality and regulatory compliance of fertilizers produced from phosphate slimes.

2.9. Statistical Data Analysis

To analyze the interactions between different fertilizer components (formulations, trace metals, and progressive substitution of phosphoric acid with slimes), a Principal Component Analysis (PCA) was performed using RStudio 23.3.0. This multivariate statistical method allows data to be summarized and reduced while retaining the most important information. It provides a graphical representation that facilitates the interpretation of relationships between variables and the classification of samples based on their similarities [13] [14]. In this study, PCA was used to identify relationships among trace metal concentrations (Pb, Cu, Cr, Cd) and to classify the fertilizer samples according to their chemical composition and the proportions of slimes in the formulations. Principal Component Analysis (PCA) was performed using the FactoMineR package in R. Prior to the analysis, all variables were mean-centered and scaled to unit variance (standardized). A correlation matrix was used because the analyzed variables were measured in different units and had different scales, ensuring that each variable contributed equally to the analysis.

3. Results and Discussion

3.1. Chemical Composition of the Formulated Fertilizers

The fertilizers formulated from slimes, phosphoric acid, urea, and potassium sulfate were analyzed to determine their chemical composition: %N, $\%P_2O_5$, %K2O, carbon (C), organic matter (OM), and C/N ratio. These parameters help assess the nutritional quality of the fertilizers and their potential impact on soil and crops. The samples, divided into three groups (A, B, and C) according to their formulation, are summarized in **Table 1** below.

Table 1. Results of chemical analyses of fertilizer samples classified by groups (A, B, and C).

Formula	SAMPLE	%N	$\%P_2O_5$	$\%K_2O$	%OM	%Corg	C/N
6-20-10	1A	6.18	19.81	9.92	0.09	0.05	0.01
	2A	6.03	20.28	9.82	1.77	1.03	0.17
	3A	6.26	20.06	9.88	5.98	3.47	0.55
	4A	5.69	20.04	10.05	6.05	3.51	0.62
	5A	5.51	19.56	8.34	8.44	4.90	0.89
15-10-10	1B	14.11	10.59	8.15	0.89	0.52	0.04
	2B	14.47	10.03	10.80	3.55	2.06	0.14
	3B	14.52	10.61	10.54	5.99	3.47	0.24
	4B	13.92	10.34	9.77	6.13	3.55	0.26
	5B	14.28	10.70	10.91	7.88	4.57	0.32
15-15-15	1C	15.66	15.11	11.64	1.06	0.61	0.04
	2C	14.28	14.35	11.92	4.80	2.72	0.19
	3C	15.40	15.03	14.12	5.49	3.18	0.21
	4C	15.37	17.31	11.84	6.42	3.72	0.24
	5C	15.38	15.62	11.90	7.24	4.20	0.27

This table clearly demonstrates the complexity of the chemical variations observed among the three fertilizer formulas studied (6-20-10, 15-10-10, and 15-15-15), particularly with respect to nitrogen, phosphorus, potassium, and organic components such as carbon and organic matter. The increase in organic matter with higher slimes substitution rates is particularly noteworthy, as it reflects the organic contribution of the slimes, which could positively influence soil fertility. Furthermore, complementary analyses, which form the core of this study, were conducted to measure the concentrations of trace metals (TMs).

The results, presented in the following sections, are used to assess their environmental impact and compliance with international standards.

3.2. Solubility, Electrical Conductivity, and pH of the Fertilizers

The analysis of solubility, electrical conductivity, and pH made it possible to evaluate both the agronomic efficiency and the environmental impact of the fertilizers. The results are presented in **Figure 5**.

Due to logistical constraints related to chemical analyses, solubility could only be measured in the samples containing 50% slimes. **Table 2** below presents the solubility values of the fertilizers at this level for the three studied formulations.

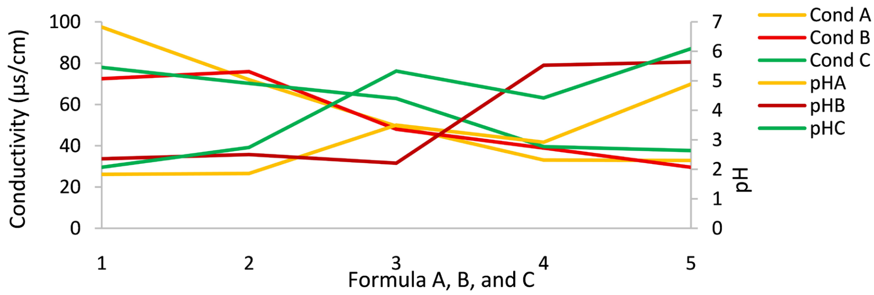

Figure 5. Electrical Conductivity and pH of Formulas A, B, and C.

Table 2. Results of chemical analyses of fertilizer samples classified by groups (A, B, C).

Content (%)	3A	3B	3C
Total Nitrogen	**6.26**	**14.52**	**15.40**
Total P_2O_5	**20.06**	**10.61**	**15.03**
Citrate-soluble P_2O_5	19.73	10.11	12.63
Water-soluble P_2O_5	19.20	10.87	12.71
K_2O	**9.88**	**10.54**	**14.12**

As per **Figure 5**, a general trend was observed for the three formulations, with a gradual increase in pH and a decrease in conductivity. The 6-20-10 formulation (A), being more acidic and highly conductive, reflects its high proportion of phosphoric acid, whereas the 15-10-10 (B) and 15-15-15 (C) formulations exhibit higher pH values and lower conductivity from the outset. The progressive substitution of phosphoric acid with slimes reduces acidity and ionic solubility, which leads to slower nutrient release. This modification affects agronomic efficiency, closely linked to phosphate solubility, which remains satisfactory with over 95% of total soluble P_2O_5 for 50/50 slimes and H3PO4. For comparison, a study by [15] on Djebel El Onk phosphate containing 20% total P_2O_5 reported an assimilable P_2O_5 content exceeding 75%, with agronomic tests confirming the effect of the amount of fertilizer released by these fertilizers. However, although this solubility enhances nutrient availability, it may also lead to the simultaneous release of other compounds, such as trace metals (TMs) present in the fertilizers [4]. Therefore, it is crucial to quantify these elements to assess their potential impact.

3.3. Trace Metal Contents in the Formulated Fertilizers

X-ray fluorescence (XRF) spectrometry was used to detect and quantify 10 trace elements (Pb, Ni, Cu, Zn, V, Cd, Cr, Se, Mo, and Co) in the 15 fertilizer samples and in the phosphate slimes used as raw material. For clarity, only the four most relevant trace metals are discussed in detail. The reported values correspond to the average of duplicate analyses. The results were compared with regulatory limits and guideline values reported in the literature to assess compliance and environmental suitability. **Table 3** presents the trace metal concentrations measured in the slimes and the corresponding fertilizer formulations. This comparison allows the assessment of the influence of slime incorporation on fertilizer trace metal content and the evaluation of their environmental suitability.

Table 3. Trace metal composition of slimes and the three fertilizer formulations.

SAMPLE	*TMs contents (ppm)*			
	Cd	Cr	Cu	Pb
Slimes	40.56	1103.29	135.61	22.86
1A	<LOD = 0.001	90.13	44.15	11.17
2A	9.39	236.19	13.09	3.79
3A	10.42	279.15	13.41	3.56
4A	30.59	413.34	64.6	15.22
5A	14.22	404.63	41.76	5.43
1B	<LOD = 0.001	84.63	40.64	9.77
2B	<LOD = 0.001	89.44	43.63	11.27
3B	13.13	162.62	18.51	5.04
4B	<LOD = 0.001	179.4	50.24	13.79
5B	11.57	233.41	15.53	4.2
1C	<LOD = 0.001	68.1	30.06	7.56
2C	<LOD = 0.001	96.22	51.01	13.27
3C	9.57	145.98	10.7	2.98
4C	<LOD = 0.001	218.4	51.47	14.24
5C	13.53	283.45	28.95	5.75

Compared to the average values of phosphate rock (Cr 188 ppm, Cd 25 ppm, Cu 32 ppm, Pb 10 ppm) reported by [7] [11], the slimes exhibit higher trace metal concentrations, specifically 1103.29 ppm, 40.56 ppm, 135.61 ppm, and 22.86 ppm for Cr, Cd, Cu, and Pb, respectively. These levels influence the composition of the formulated fertilizers according to the formulation and the target P_2O_5 percentage. Table 3 shows that for Cu, Pb, and Cd, the concentrations in the fertilizers remain below international standards (EU [17]), whereas Cr largely exceeds these thresholds, except in samples containing up to 25% slimes [5] [7]. This observation suggests a potential limit to the proportion of slimes that can be used to substitute phosphoric acid. In summary, the following points should be noted for each element due to their presence in the formulated fertilizers:

- Chromium (Cr): Cr is the dominant trace metal. Its high concentration in slimes is reflected in all fertilizer types exceeding 25% substitution, which may raise environmental or agronomic concerns due to its potential toxicity.
- Cadmium (Cd): Although Cd is elevated in slimes, it is often low or even absent in fertilizers, likely due to precipitation or dilution during formulation. A substitution rate of up to 25% could yield a fertilizer compliant with current standards.

- Copper (Cu) and Lead (Pb): Given their low concentrations in slimes, these elements appear at much lower levels than Cr and remain well below regulatory limits. Their presence does not affect the viability of substituting phosphoric acid with slimes, regardless of the percentage used.

While chromium (Cr) content appears high, its impact on crops is limited. Studies have shown that the phytoavailable fraction strongly depends on soil characteristics, such as pH, conductivity, and organic matter, which buffer the release of these trace metals once in the soil [1]. Regarding cadmium (Cd), even when concentrations occasionally exceed standards, the associated risk remains low. Lina KASSIR demonstrated that Cd mobility and solubility depend on soil pH, organic matter, and type: they increase in acidic, sandy soils but decrease at higher pH or in the presence of organic matter [4]. Additionally, Henri Calba, Claire Chevassus, and Denis Montange showed, using NH4NO3 extraction, that the phytoavailable fraction of cadmium in slimes does not exceed 0.20% of the total content [1]. Other researchers, including [16], in agreement with [18], have shown that lead (Pb) and copper (Cu) exhibit limited mobility in soil. Lead is primarily immobilized by clays, phosphates, and carbonates, while copper is strongly adsorbed by organic matter. However, their mobility can increase under specific conditions, particularly in the presence of dissolved organic matter.

These results illustrate the complexity of trace metal interactions depending on the formulation and slime percentage. In this context, using a data analysis tool could contribute to a better understanding of this variability.

3.4. Principal Component Analysis (PCA) of the Samples

To further investigate and identify multivariate relationships among the parameters, a Principal Component Analysis (PCA) was conducted. The PCA, performed using RStudio, included 15 samples from the three formulations, considering the four main trace metals (Cd, Cr, Cu, and Pb) as variables. The results are presented in **Table 4** (eigenvalues of the principal axes) and **Table 5** (correlation matrix of the trace metals).

Table 4. Eigenvalues and explained percentages for the principal axes.

Content (%)	Dim1	Dim2
Eigenvalues	2.15	1.54
% of Total Variance Explained	53.81	38.62
Cumulative % of Variance Explained	53.81	92.43

The results show that the first two principal components explain 92.43% of the total variance, with Dim 1, having an eigenvalue of 2.15, accounting for 53.81%, and Dim 2, with an eigenvalue of 1.54, explaining 38.62% of the information. These two principal axes contain the bulk of the information, which renders the other factors negligible.

It is therefore essential to investigate the interrelationships among trace metals in the fertilizer samples. The following correlation matrix offers a detailed assessment of these interactions and highlights the strength and direction of associations among the key variables (Pb, Cu, Cd, and Cr).

Table 5. Correlation matrix of trace metals in fertilizer formulations.

Variables	**Pb**	**Cu**	**Cd**	**Cr**
Pb	**1**			
Cu	**0.9388588**	**1**		
Cd	−0.2114280	−0.05928875	**1**	
Cr	0.2399170	**0.44936947**	**0.59752185**	**1**

This correlation matrix reveals the relationships among the trace metals present in the fertilizers and provides a clearer understanding of their interactions, which is essential for effective management and for assessing their environmental impact. As previously noted, the PCA indicates strong correlations between the Cu-Pb and moderate between Cd-Cr pairs and underlines their influence on the total data variance. These variables contribute significantly to dimensions D1 and D2, which together account for 93.3% of the total information, as shown in **Figure 6**.

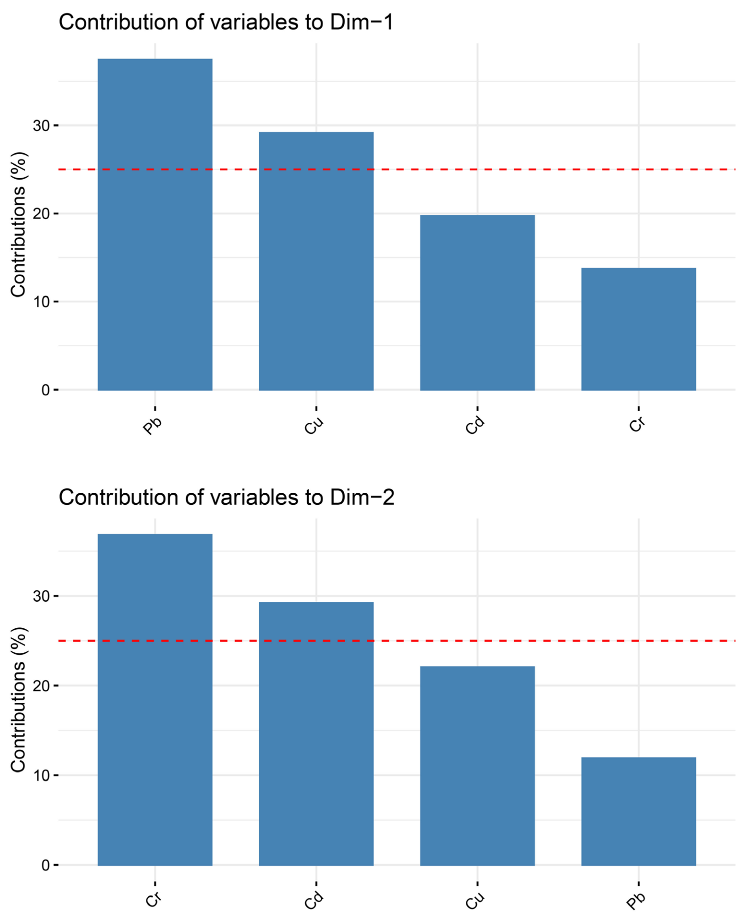

Figure 6. Scree plot of the factors.

Dimension 1 (Dim-1) primarily reflects the combined influence of Lead (Pb) and Copper (Cu), underscoring their strong interdependence within the fertilizer formulations. Similarly, Dimension 2 (Dim-2) captures the association between Chromium (Cr) and Cadmium (Cd), which plays a key role in differentiating the samples. The complementarity between Dim-1 and Dim-2 thus reveals a distinct pattern of interaction between the Cu-Pb and Cd-Cr pairs. These relationships among the various trace metals, dependent on the formulation characteristics, are clearly depicted in the variable correlation circle and the dendrogram shown in **Figure 7** and **Figure 8**, respectively.

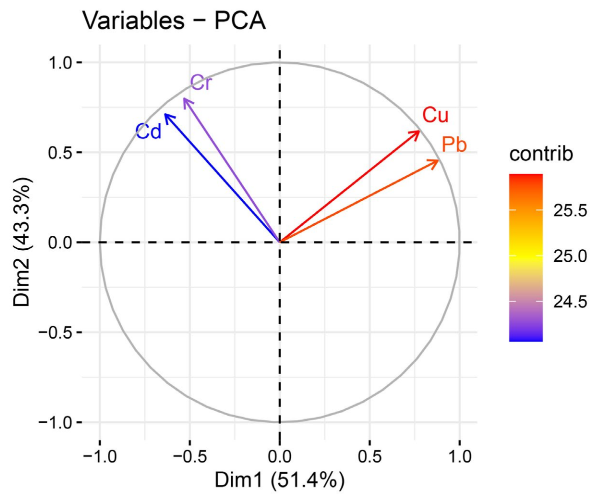

Figure 7. Hierarchical cluster analysis variable.

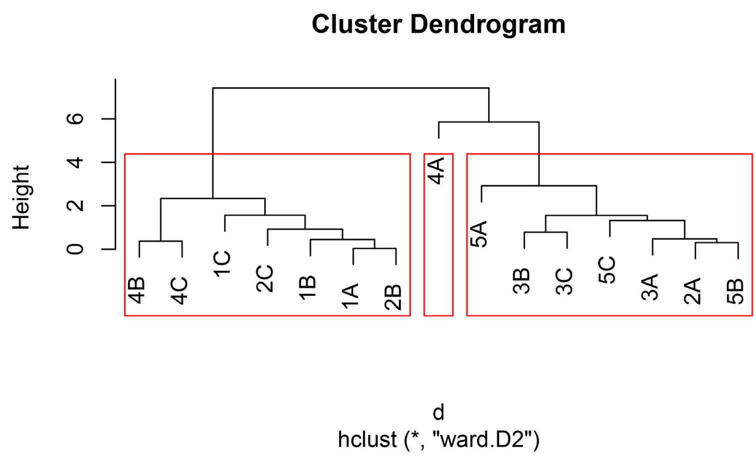

Figure 8. Correlation circle of the fertilizer samples based on Cr, Cd, Cu, and Pb.

This correlation circle highlights the duality observed between the Cu-Pb and Cr-Cd pairs, stemming from the initial trace metal contents of the slimes. The acute angles formed between these compounds indicate similar variability in their composition across the fertilizer samples, with the Cu-Pb pair remaining below regulatory thresholds. Although their concentrations differ, Cr and Cd evolve in parallel across all formulated samples.

This is further confirmed by the dendrogram in **Figure 8**, which supports the hypothesis of a 25% substitution limit for slimes in most cases of phosphoric acid replacement in fertilizers. The dendrogram identifies three groups: the first includes all samples containing up to 25% slimes, except for sample 2A, which shows a high chromium peak due to its P_2O_5 content of 20.28%. The second group consists solely of sample 4A, characterized by elevated levels of all trace metals. Finally, the third group comprises samples with high trace metal concentrations (Cd and Cr exceeding the limits) from the three studied formulations.

This trace metal composition of the slimes reflects the specific characteristics of the phosphate ore from the Taïba mine of the Industries Chimiques du Sénégal, as demonstrated by [19].

4. Conclusions

This study evaluated the trace metals (TMs) composition of fertilizers formulated by substituting phosphoric acid with phosphate slimes, in order to assess their potential environmental impact. In addition to quantifying the essential nutrients in the three formulations (6-20-10, 15-10-10, and 15-15-15), key parameters such as trace metal content, pH, electrical conductivity, and solubility were analyzed. The fertilizers were generally acidic (1.83 - 6.09), with pH increasing and conductivity decreasing as the proportion of slimes increased. Formulations containing a 50/50 ratio of slimes to phosphoric acid released over 90% of the total P_2O_5, suggesting similar release behavior for lower substitution levels.

Among the analyzed trace metals (Cd, Cr, Cu, Pb), results revealed elevated Cr and Cd concentrations, with Cr exceeding regulatory thresholds for substitutions above 25% for the 6-20-10 formula, whereas Cu and Pb remained within acceptable limits. Consequently, a 25% substitution limit appears to be the optimal balance between nutrient efficiency and environmental safety for 15-15-15 & 15-10-10 formulas. Principal Component Analysis (PCA) corroborated this finding and demonstrated significant correlations and variability among the trace metals, which reflect the intrinsic geochemical characteristics of the Taïba phosphate ore, in agreement with previous studies.

For practical implementation and environmental protection, a 25% phosphate slime substitution level appears promising for selected formulations, although compliance remains formulation-dependent. Further field trials on representative crops are recommended to evaluate agronomic performance and environmental impacts under real agricultural conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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