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Monitoring the Effect of Phosphogypsum Amendment Combined with Cow Manure on the Restoration of Saline Soils: The Case of the Kobongoye Rice Valley, in the Municipality of Fimela, West-Central Senegal

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Abstract

The Kobongoye rice valley, located in the municipality of Fimela (Fatick region, west-central Senegal), faces a major challenge of soil salinization and/or acidification. To restore fertility to the valley's rice paddies, an organo-mineral amendment composed of 0.4 t/ha of phosphogypsum and 0.5 t/ha of cow manure was applied. This before-and-after field study evaluates whether a combined phosphogypsum and cow-manure amendment improves saline rice soils while assessing Pb and Cd accumulation. Soil samples from 29 grid locations were analyzed for physicochemical properties and trace metals, with PCA and spatial interpolation used to examine variability. The soil samples were taken with an auger at a depth of 0 - 30 cm, based on systematic sampling in July 2023 before amendment and in May 2024 after amendment at the same location. The study reports lower EC, modest pH improvement in much of the site, and higher Pb and Cd concentrations that remain below the cited soil thresholds. Organic matter, nitrogen, phosphorus, and potassium contents did not change substantially but did exhibit spatial variation. In light of these results, the use of phosphogypsum appears to be a promising technology, but it requires particular attention to trace metal elements.

Keywords

Saline Soils, Phosphogypsum, Rice Cultivation, Heavy Metals, Kobongoye

1. Introduction

Soil salinization is a major global challenge. According to [1], more than 424 million hectares of topsoil (0 - 30 cm) and 833 million hectares of subsoil (30 - 100 cm) are affected by salts worldwide. In Africa, the area of salt-affected soils is estimated at more than 88 million hectares [2]. In Senegal, salt-affected soils cover approximately 1.7 million hectares, or nearly 45% of arable land [3]. The most affected areas are estuarine and deltaic wetlands. Although often related to the geological context of the Recent Quaternary—characterized, amongst other things, by marine transgressions and regressions—this salinization is significantly exacerbated by climate variability and anthropogenic activity [3] [4]. In the Sine-Saloum river basin, this trend has also been documented by several authors [4]-[7]. Indeed, rainfall deficits combined with high temperatures have favored salt crystallization as well as the capillary rise of salts to the soil surface under the effect of evaporation [3]. This situation has led to a decline in soil fertility and agricultural productivity, resulting in land abandonment and the loss of livelihoods for local populations.

The soils of the Kobongoye valley, located in the municipality of Fimela, Fatick Region, are also affected by salinization and/or acidification, resulting in low rice yields (0.8 $t \cdot ha^{-1}$ on average). To restore the fertility of these salt-affected soils and ensure sustainable rice production, an organo-mineral amendment (phosphogypsum and cow manure), followed by ploughing, was applied in July 2023. Phosphogypsum is a by-product of phosphoric acid synthesis from natural phosphates [8]. It improves the structure of salt-affected soils by replacing sodium with the calcium it contains [9]. However, it contains trace metal elements (TME) such as lead (Pb) and cadmium (Cd), which can be a source of soil contamination. Cow manure, meanwhile, is rich in nutrients such as nitrogen, phosphorus, and potassium. It improves soil structural stability, thereby promoting good water and air circulation [10], and its mineralization contributes to the mineral nutrition of rice.

These technologies need to be evaluated to determine the mechanisms underlying the restoration of salt-affected soils. Accordingly, this study aimed to contribute to the assessment of the effects of phosphogypsum amendment combined with cow manure on the restoration of salt-affected soils and on the potential risks of trace metal element contamination. Specifically, the study assessed the changes induced by the phosphogypsum and organic matter amendment on the physical and chemical properties of the soils (pH, EC, OM, N, P, K, Ca, Mg, ESP, BS, CEC, and texture), before evaluating the risks of lead (Pb) and cadmium (Cd) accumulation.

2. Materiels and Methods

2.1. Study Area

The Kobongoye rice valley lies between latitudes 14˚8' and 14˚10' N and longitudes 16˚46' and 16˚43' W, within the municipality of Fimela, Fatick department and region (west-central Senegal) (**Figure 1**). Its rice-cultivable area covers approximately 200 hectares. The geology of the area has been substantially shaped by marine transgressions and regressions during the recent Quaternary. As a result, the geomorphology is characterized by channels, mudflats, tannes (salt flats), and sand bars. The soil units of the valley consist of tropical ferruginous soils, non-saline hydromorphic mineral soils, and halomorphic soils. The climate, of the coastal North-Sudanian type [11], is characterized by an average annual rainfall of 601 mm over the period 1991-2020. Mean annual temperature is 28.7˚C, ranging from a minimum of 25.4˚C in January to a maximum of 30.4˚C in June. Vegetation in the valley is mainly herbaceous. The valley has a substantial potential for rice cultivation.

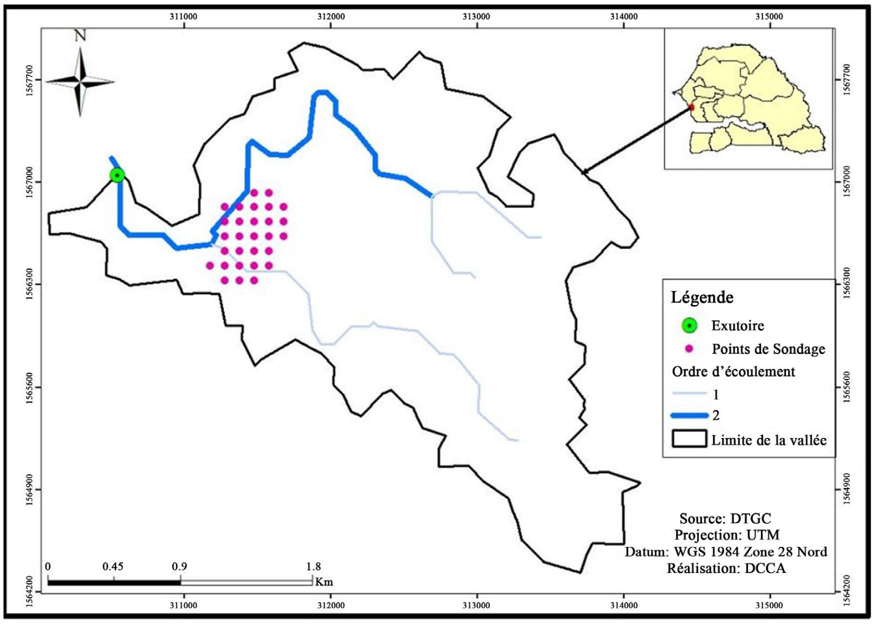

Figure 1. Location of the study area.

2.2. Data Collection, Analysis, and Processing Methods

2.2.1. Data Collection Methods

Although the valley has a cultivable potential exceeding 200 hectares, the organo-mineral amendment—and therefore the monitoring of its effect—concerned an area of 30 hectares, covering the cultivated rice plots that constitute the actual study area. This part of the valley, once delimited (**Figure 1**), was amended with phosphogypsum at a rate of 0.4 $t \cdot ha^{-1}$, combined with cow manure at a rate of 0.5 $t \cdot ha^{-1}$, and ploughed to facilitate incorporation.

A systematic sampling design was applied using a 100 m × 100 m grid. Two soil sampling campaigns were carried out, each comprising 29 sampling points (58 observation points in total), at a depth of 0 - 30 cm. The first campaign took place in July 2023, before amendment and cropping, and the second, at the same location, in May 2024. Both months correspond to peak dry-season conditions (July normally marks the start of the rainy season, but no rainfall had yet occurred at the time of sampling); they were selected to minimize the confounding effect of the seasonal dynamics of capillary salt rise during the dry season and salt leaching during the rainy season. Soil samples were packaged, coded, and sent to the National Pedology Institute (NPI) laboratory for physico-chemical analyses.

It should be noted that the absence of an untreated control plot constitutes a methodological limitation of this study.

2.2.2. Soil Analysis Methods

After air-drying, grinding, and sieving, the soil samples were analyzed for the following parameters: particle-size distribution, pH, Electrical Conductivity (EC), organic carbon, total nitrogen, available phosphorus, Cation Exchange Capacity (CEC), and exchangeable bases. The trace metal elements Pb and Cd were also measured. The analytical methods used are summarized in Table 1 below.

Table 1. Analytical methods for soil parameters.

Parameters	Analytical method
Particle-size distribution	Robinson pipette method (Stokes' law)
pH	pH meter reading (1:5 water extract)
Electrical conductivity	Conductivity meter reading (1:5 water extract)
Organic carbon	Walkley-Black method
Total nitrogen	Kjeldahl method
Available phosphorus	Bray I method
Cation exchange capacity	Metson method (pH 7)
Calcium and magnesium	Titration
Sodium and potassium	Flame spectrophotometry
Lead and cadmium	ICP-OES
Exchangeable sodium percentage	Calculated
Base saturation	Calculated
Organic matter	Calculated

2.2.3. Data Processing and Analysis

Soil analysis data were compiled and processed using Excel and RStudio for descriptive statistics and multivariate analysis (PCA), and ArcGIS for spatial mapping.

The physical and chemical results were interpreted using classification thresholds drawn from the following references: particle-size distribution (Aisne texture triangle); pH (ISRIC, 1993; CRAAQ, 2003); EC (Durand, 1983); P (London, 1984); N (Piéri, 1989); CEC (CRAAQ, 2003; Doucet, 2006); BS (Doucet, 2006); Mg (London, 1984); K (Durand, 1983); OM, C/N, and Ca (Pasquier, 2000).

3. Results

3.1. Descriptive Analysis of the Data

The physico-chemical results of the analyzed samples are presented in Table 2 below.

pH values indicate acidic to slightly acidic soils before amendment with phosphogypsum and cow manure (PGY and CM), and extremely acidic to neutral soils after amendment.

Electrical Conductivity (EC) values indicate soils ranging from non-saline to extremely saline both before and after amendment.

Regarding organic matter (OM), total nitrogen (Nt), and the C/N ratio, no substantial variability in soil characteristics was noted before and after amendment. However, elevated N contents and a rapid-to-optimal OM mineralization rate were observed after amendment.

For available phosphorus (P_2O_5), potassium (K), and magnesium (Mg), no substantial differences were observed before and after amendment. In contrast, calcium (Ca) contents decreased after amendment. Regarding the parameters characterizing the soil adsorbing complex (CEC, BS, and ESP), values before and after amendment were essentially similar.

Particle-size analysis shows a shift from a sandy-loam texture before amendment to a sandy-loam to light sandy-loam texture after amendment.

Table 2. Interpretation of soil physical and chemical parameters.

Parameter	Before amendment		After amendment	
	Values	Interpretation	Values	Interpretation
Texture	-	Sandy-loam	-	Sandy-loam to light sandy-loam
pH	5.2 - 6.5	strongly to moderately or slightly acid	4.3 - 7	Very strongly to moderately or slightly acid and neutral
EC (µS/cm)	41 - 9,280	Non saline to extremely saline	92 - 5,521	Non saline to extremely saline
OM (%)	0.4 - 3.4	low to high	0.6 - 4.3	low to high
Nt (ppm)	0.035 - 0.18	very low to moderate	0.02 - 0.2	Very low to high
C/N	7.22 - 10.73	Fast mineralization	7.22 - 11	Fast to optimal mineralization
P_2O_5 (ppm)	0.6 - 6.8	Low	0.7 - 6.7	Low
CEC (meq/100 g)	6 - 10	Low to moderate	2.8 - 10.4	Low to moderate
Ca^{2+} (meq/100 g)	1.1 - 13.5	Low to high	0.75 - 6.8	Low to moderate
Mg^{2+} (meq/100 g)	0.15 - 3.45	Low to high	0.15 - 1.5	Low to high
K^+ (meq/100 g)	0.08 - 0.2	Low to moderate	0.1 - 0.35	Low to moderate
Na^+ (meq/100 g)	0.85 - 1.03		0.1 - 0.39	
ESP (%)	14.16 - 10.03	Non sodic	3.57 - 3.75	Non sodic
Base Saturation (%)	18.2 - 202.2	low to supersaturated	14.7 - 93.8	low to saturated

3.2. Statistical Analysis of Rice-Growing Soils (n = 29, 15 Parameters) [12]

Water pH showed a modest but real increase (+1.3%), suggesting a limited corrective effect of the amendment on soil acidity, consistent with the weakly acidic character already observed before treatment. More notable is the decrease in electrical conductivity (EC), which dropped by 33.7%. This decline reflects a substantial reduction in the soluble salt load of the soil, a result of particular relevance in the context of these paddy soils, where salinization constitutes a major constraint on production.

Table 3. Comparison before/after amendment (paired Wilcoxon test, n = 29 pairs).

Parameters	Mean before	Mean after	Change	Change (%)
Water pH	5.89	5.96	+0.07	+1.3
EC	1552.2	1028.4	−523.7	−33.7
C (%)	0.52	0.59	+0.07	+13.3
OM (%)	0.89	1.01	+0.12	+13.3
N (%)	0.058	0.062	+0.003	+5.8
C/N	8.49	9.04	+0.56	+6.5
P (ppm)	2.91	1.97	−0.94	−32.3
Ca	3.41	1.67	−1.74	−51.0
Mg	0.60	0.38	−0.21	−35.6
Na	0.23	0.175	−0.056	−24.2
K	0.075	0.179	+0.104	+137.9
S	4.31	2.41	−1.90	−44.2
CEC	8.21	5.61	−2.60	−31.6
V (%)	52.23	44.22	−8.01	−15.3
ESP	2.84	3.27	+0.42	+14.9
Cd	0.096	0.138	+0.041	+43.1
Pb	0.250	0.413	+0.163	+65.0

The amendment therefore appears to have exerted a leaching or complexation effect on soluble ions, limiting their mobility in the soil solution. Organic carbon (C), organic matter (OM), and total nitrogen (N) contents all increased consistently (+13.3%, +13.3%, and +5.8%, respectively), accompanied by a rise in the C/N ratio (+6.5%). This joint increase confirms an effective input of organic matter by the amendment, with a slight rise in the C/N ratio that nonetheless remains within a range favorable to active mineralization, without risk of excessive nitrogen immobilization. This result supports the hypothesis of an organo-mineral amendment rather than simple liming. The behavior of exchangeable cations is more contrasted. Calcium (Ca), magnesium (Mg), sodium (Na), and sulfur (S, comparable to the sum of exchangeable bases) all decreased significantly, with respective declines of 51.0%, 35.6%, 24.2%, and 44.2%. In contrast, potassium (K) showed a dramatic increase of +137.9%, suggesting a targeted potassium input from the amendment, possibly in the form of plant residues, ash, or an associated potassium fertilizer. This redistribution of exchangeable bases—a joint decline in Ca, Mg, Na, and S alongside a sharp rise in K—was logically reflected in the cation exchange capacity (CEC), which decreased by 31.6%, and in base saturation (V), which fell by 15.3 points. This decline in CEC could reflect a loss of exchange sites associated with the leaching of divalent bases (Ca, Mg), a phenomenon that would merit being related to the texture and clay mineralogy of the soils studied. Available phosphorus (P) content dropped by 32.3%, which could indicate either phosphorus immobilization through adsorption/precipitation mechanisms favored by the new physicochemical conditions of the soil, or increased uptake by the crop in response to the improvement of other fertility factors. The exchangeable sodium percentage (ESP), on the other hand, increased slightly (+14.9%), a change that, while remaining below the critical sodicity threshold (generally set at 15%), warrants monitoring insofar as it appears to contradict the decrease in exchangeable Na in absolute terms. The most concerning result concerns the significant increase in cadmium (Cd: +43.1%) and lead (Pb: +65.0%) contents after amendment. This increase is attributable to the phosphogypsum, which contains these metals. Overall, the amendment produced beneficial effects on salinity (decrease in EC), organic status (increase in C, OM, N), and potassium supply, but was accompanied by a decrease in cation exchange capacity, base saturation, and phosphorus availability, as well as an undesirable enrichment in cadmium and lead.

3.3. pH and EC Variability

The boxplots below (**Figure 2**) show the variability of pH and EC values before and after amendment. Most pH values were concentrated between 5.7 and 6.2 before amendment, with extremes of 5.3 and 6.5 and a median of 5.9. After amendment, extreme values ranged from 4.3 to 7, with a clear predominance of values between 5.6 and 6.5, and a median of 6. EC values were more widely spread before amendment (41 to 9,280 µS/cm) than after amendment (92 to 5,521 µS/cm). The interquartile range, which encompasses 50% of EC values, also changed, from 294-2,020 µS/cm before amendment to 150-1,680 µS/cm after amendment. The median EC decreased from 456 to 430 µS/cm before and after amendment, respectively.

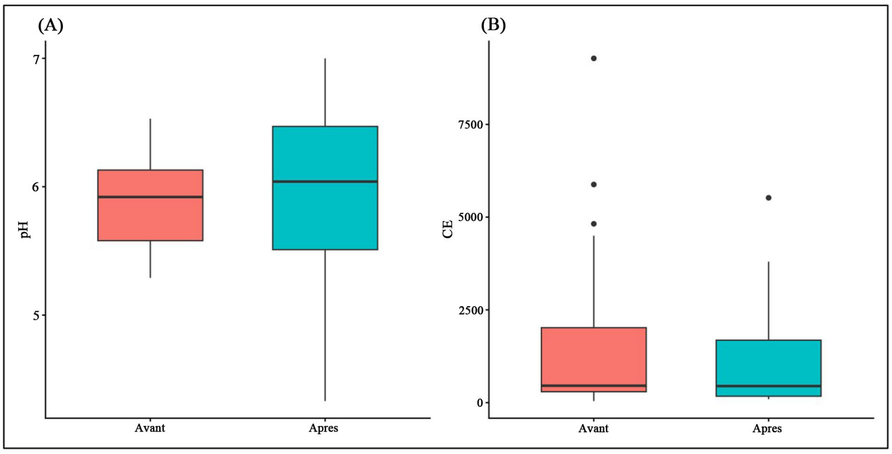

Figure 2. Variability of pH (A) and EC (B) before and after PGY + CM amendment.

3.4. Correlation Analysis Using Multivariate Analysis (PCA)

Multivariate analysis of the soils' physical and chemical parameters identified two principal components for each PCA (**Figures 3(A)-(B)**). The variances explained were 65.16% before amendment and 64.8% after amendment, indicating a satisfactory representation of the data.

Before PGY + CM amendment, Component 1 (36.68% of the variance) was mainly driven by the contribution of Ca, Mg, Na, K, S, BS, ESP, and EC, while Component 2 (28.48% of the variance) was determined by C, C/N, OM, and N.

After amendment, the same two components were still present but with a lower explained variance and weaker correlations between variables. A more significant contribution of particle-size parameters (clay, silt, and sand) and CEC was also observed, in contrast to ESP, which followed an opposite trend.

Both PCAs also revealed a negative correlation between pH and EC. The same pattern was observed between silt and sand, with a stronger correlation after amendment.

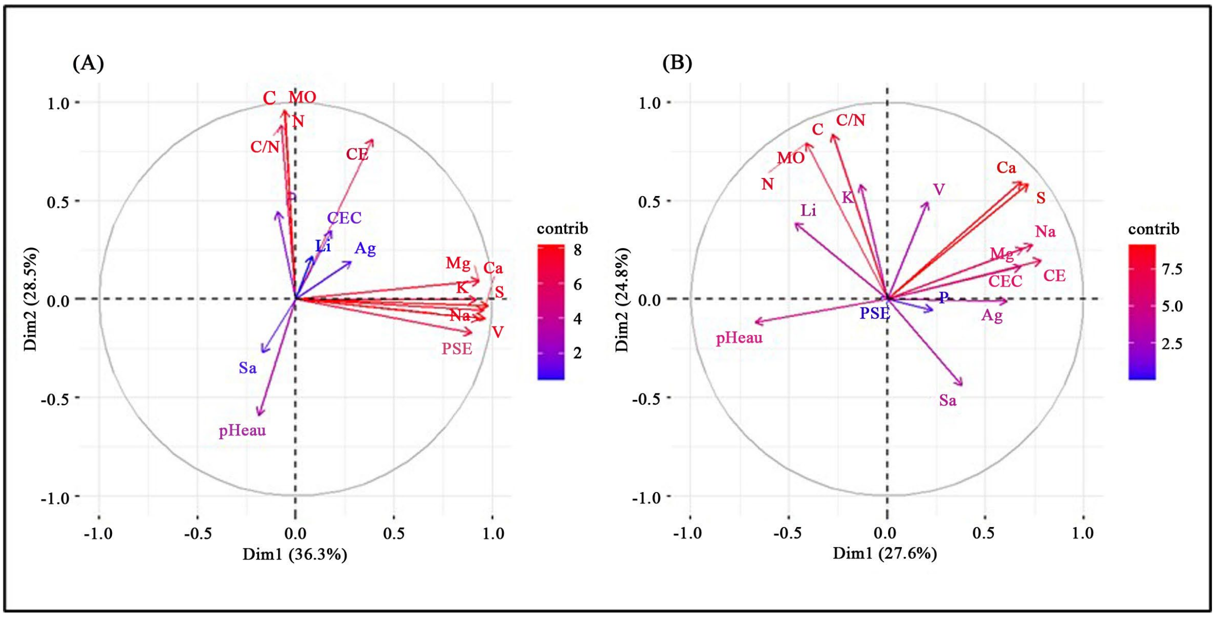

Figure 3. Principal component analysis of soil physicochemical parameters before (A) and after (B) PGY + CM amendment.

3.5. Spatial Distribution of Soil pH, EC, and OM before and after Amendment

3.5.1. Spatial Variability of pH

Spatially, before amendment, soils were dominated by moderately acidic pH, followed by acidic soils located in the North and slightly acidic soils in the Center-East (**Figure 4**). After amendment, the pH distribution became more heterogeneous, with a predominance of slightly acidic soils in the Center and South, followed by moderately acidic soils in the Center-West and acidic soils in the North. However, extremely acidic and very acidic soils were noted in the Northeast, along with patches of neutral-pH soils scattered across the Center and South (**Figure 4**).

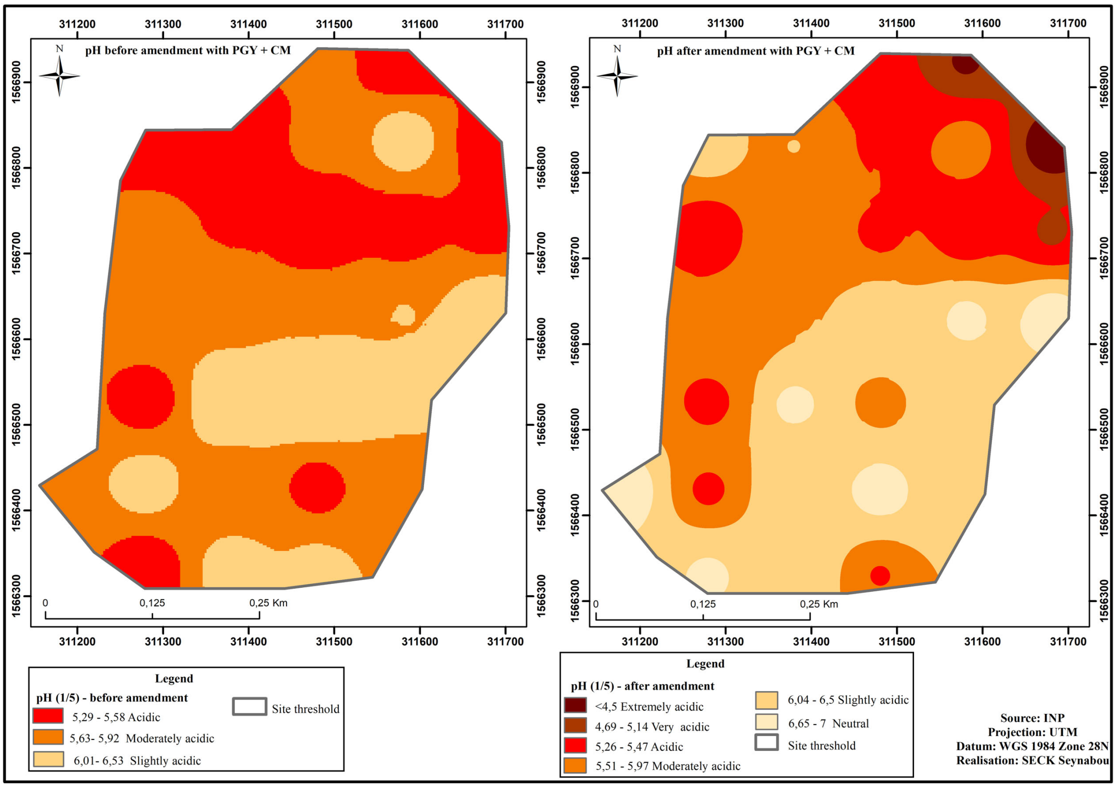

Figure 4. Spatial variability of pH before and after amendment.

3.5.2. Spatial Variability of Electrical Conductivity (EC)

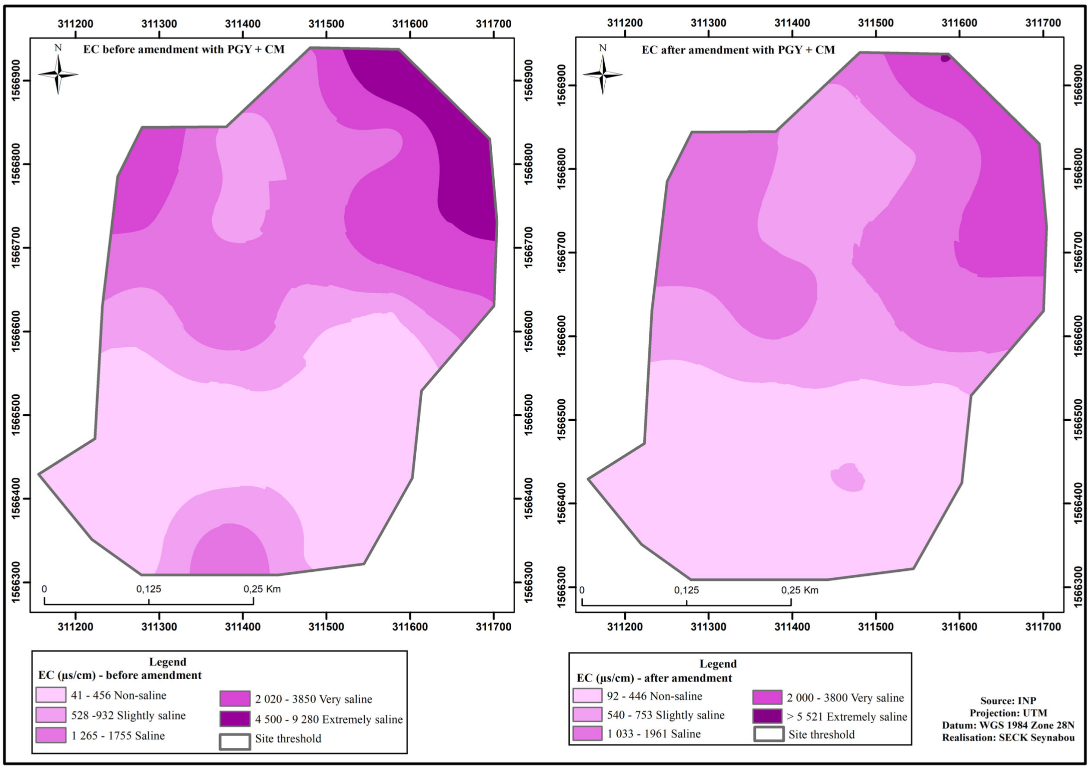

Figure 5. Spatial variability of soil electrical conductivity before and after amendment.

Regarding the spatial distribution of EC, before amendment, non-saline soils were found from the South toward the Center, while saline soils—ranging from slightly saline, saline, and very saline to extremely saline—occupied more than half of the area toward the North-East (Figure 5). After amendment, a significant decrease in the area of extremely saline soils was observed, together with an increase in slightly saline soils at the expense of saline soils (Figure 5).

3.5.3. Spatial Variability of Soil Organic Matter (OM)

Before amendment, soil OM contents were moderate from the North toward the centre of the valley and low from the centre toward the South. Soils well and very well supplied with OM were located in the North-East (Figure 6). After amendment, soil OM contents improved across most of the study area (Figure 6).

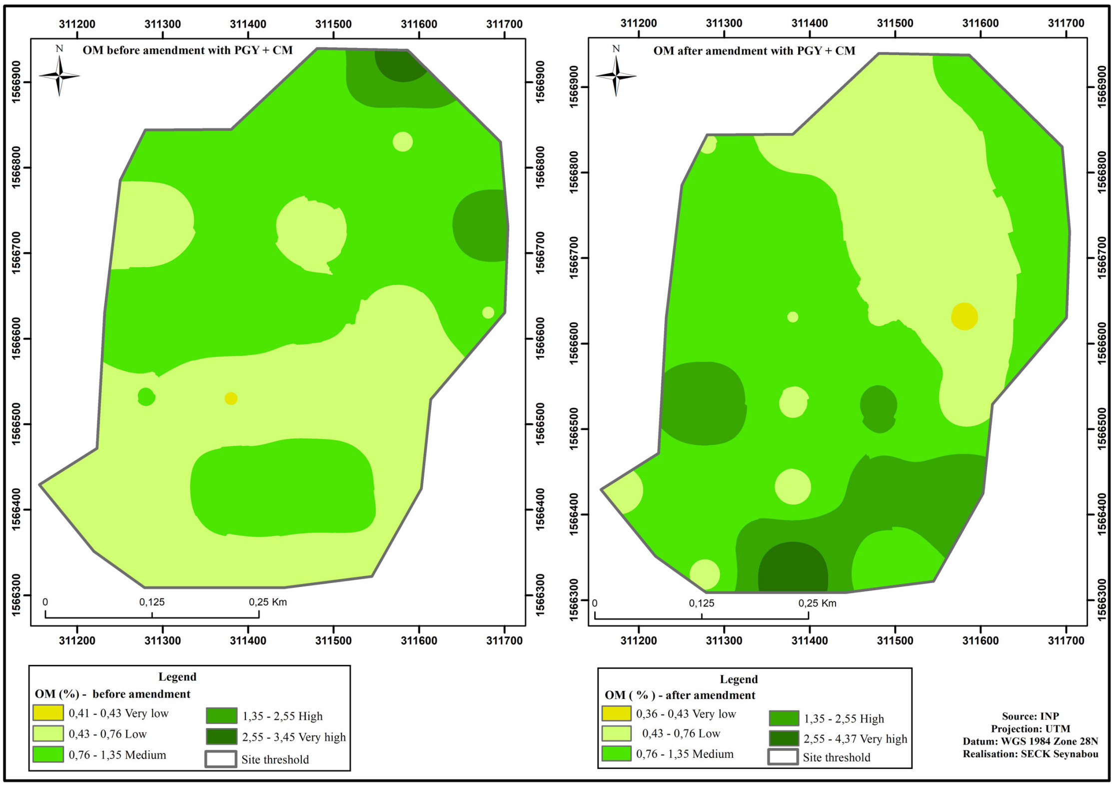

Figure 6. Spatial variability of soil organic matter.

3.6. Spatial Dynamics of Soil pH, EC, and OM after Amendment

Figure 7 summarizes the post-amendment changes in the distribution of soil pH, EC and OM in the studied part of the valley.

Overall, pH increased by 0.2 to 1.24 units across most of the study area, except for a few pockets in the Northeast and West, and small patches in the Center and South, where increases of 0.41 to 1.30 units were noted.

Regarding EC, a decrease of 1,000 to 3,000 µS/cm was observed across most of the study area. Only a small portion of the area recorded an increase in EC, with values ranging from 200 to 1,000 µS/cm.

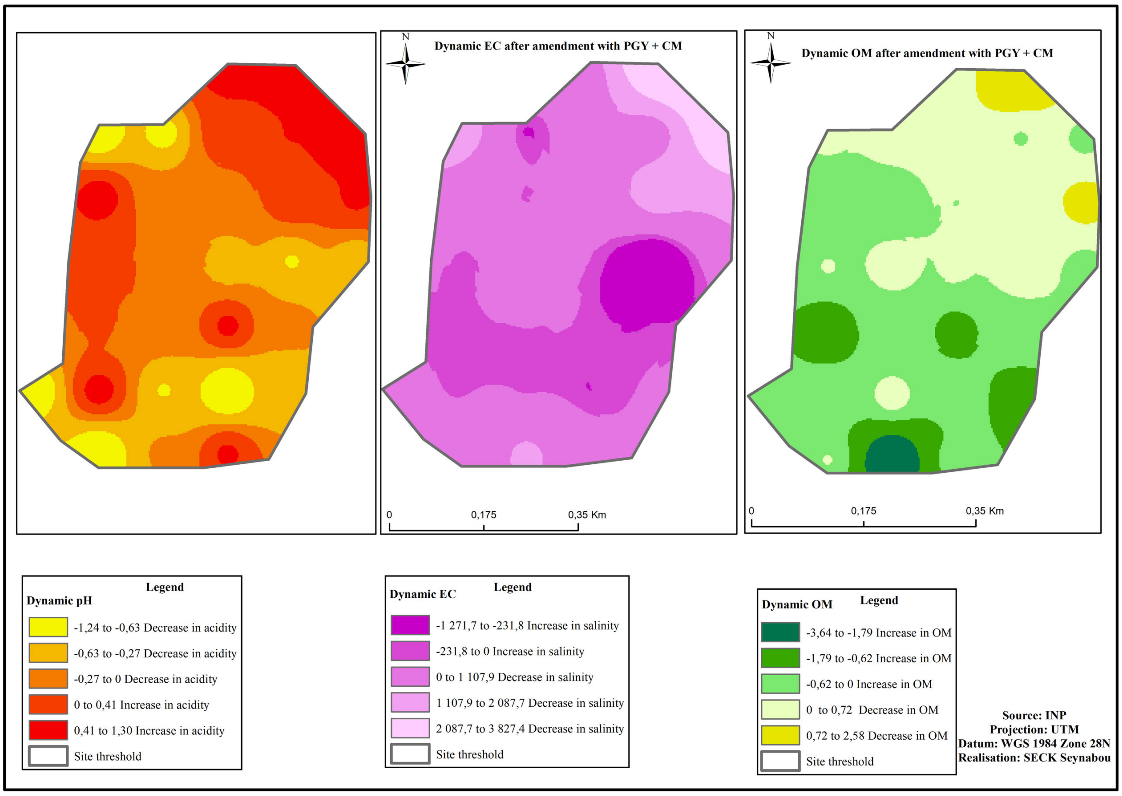

Figure 7. Dynamics of soil pH, EC and OM after amendment.

3.7. Assessment of Soil Pb and Cd Contents before and after Amendment

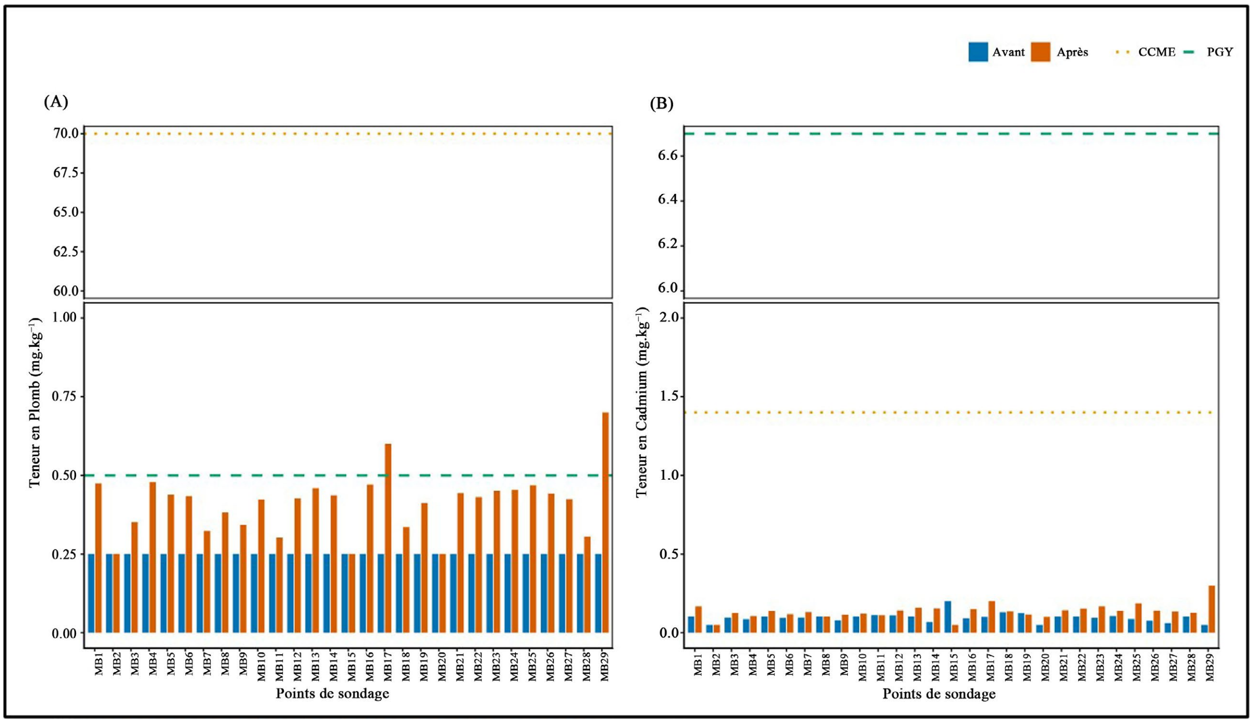

Figure 8. (A) Pb and (B) Cd contents in soils before and after PGY + CM amendment.

Pb and Cd contents are shown in **Figure 8**. The Pb and Cd contents of the applied phosphogypsum were 0.5 and 6.7 mg/kg, respectively.

For Pb, contents increased from 0.05 mg/kg (before amendment) to 0.45 mg/kg (after amendment).

For Cd, an increase from 0.02 mg/kg (before amendment) to 0.29 mg/kg (after amendment) was observed.

The highest values for both lead and cadmium were recorded at sampling point M29, located in the Northeast of the study area.

4. Discussion

This study combined field surveys and GIS tools to investigate the effect of phosphogypsum on soil physico-chemical properties as well as the potential risks of Pb and Cd contamination.

Soil texture was predominantly sandy-loam. Overall, the descriptive analysis showed acidic, saline, and mineralized soils with low OM, N, P, K, Ca, Mg, and CEC contents. Variations were noted in some soil characteristics following phosphogypsum application. pH values became more heterogeneous and slightly higher, reflecting a decrease in acidity. Regarding salinity, EC values were less dispersed, indicating a relative decrease in salinity. Nitrogen contents increased, and the rate of organic matter mineralization slowed, shifting from rapid to optimal. Phosphogypsum amendment therefore appears to have had a positive effect on soil salinity and acidity.

The decrease in EC can be explained by the fact that phosphogypsum, being rich in calcium, enriches soils with Ca^{2+} ions, which replace Na^{+} ions on the colloidal complex [13]. These results are consistent with the findings of Manga [14], who reported a 42.37‰ decrease in soil salinity following phosphogypsum application on acid sulfate soils in Djibélor (Casamance, Senegal). According to Huang *et al.* [15], phosphogypsum combined with manure considerably decreased soil salinity and sodicity while increasing fertility.

The increase in pH toward neutrality is likely related to the effect of phosphogypsum. Indeed, Smaoui-Jardak *et al.* [16] showed that phosphogypsum amendment induces a decrease in soil acidity, which, according to Mesić *et al.* [17], would result from a reduction in aluminum (Al) concentration. Conversely, the occurrence of extremely acidic pH values could be related to several factors, including pyrite (FeS_2) oxidation. Viellefon [18] (1972) considers that pyrite oxidation often leads to pH stabilization around 4, owing to the formation of sulfate minerals such as jarosite ($KFe_3(SO_4)_2(OH)_6$). Vicensi *et al.* [19] (2016) demonstrated that phosphogypsum did not induce any change in soil pH.

Antonio *et al.* [20] report that phosphogypsum application combined with lime increases nitrogen (N) content by up to 50%. In contrast, Vicensi *et al.* [19] found that phosphogypsum amendment had no effect on the evolution of soil phosphorus (P) and potassium (K) contents. These findings are consistent with our results.

The principal component analysis revealed a decrease in correlation strength between variables after amendment, which could be related to the effect of phosphogypsum. This analysis also showed a negative correlation between pH and EC, as well as between silt and sand. In other words, in this specific case, as pH increases, EC decreases, and as silt content increases, sand content decreases, and vice versa. This appears plausible, since the Ca^{2+} supplied by phosphogypsum increases the cation exchange capacity (CEC) through the release of H^+ and Na^+ ions, which simultaneously raises pH and lowers EC. The negative correlation between silt and sand could be explained by soil erosion, mainly water erosion: runoff transports the finest soil particles toward the valley outlet, while coarser particles settle upstream [21].

Spatially, the changes observed in EC indicate a concentration of saline soils in the North and non-saline soils in the Centre and South of the study area. pH, meanwhile, showed greater variability, with the appearance of extremely acidic soils in the Northeast and scattered patches of neutral pH. These changes appear to result from the effect of phosphogypsum on these soil parameters, translating overall into a decrease of 10 to 1,000 μS/cm in EC and an increase of 0.1 to 1 pH unit, confirming the results of Manga *et al.* [14] and Smaoui-Jardak *et al.* [16].

However, the opposite trend observed in the spatial distribution of OM cannot be attributed to phosphogypsum amendment. It could instead be explained by runoff transporting organic matter from upstream to downstream areas.

The increase in soil Pb and Cd contents suggests that phosphogypsum application leads to their accumulation in soils. Similar results were reported by Kassir *et al.* [22], who found higher heavy metal contents in phosphogypsum-treated soils than in untreated soils. It should also be noted that the highest Pb and Cd concentrations were found in the North-East of the study area, which is characterized by extremely acidic soils with pH values below 4.5. According to Kassir *et al.* [22], when pH is below 6, Cd solubility increases and the ionic form Cd^{2+} becomes predominant, whereas above pH 6, Cd is adsorbed onto the soil solid matrix or precipitates. Similarly, Pb predominates when pH is below 6.5 and becomes associated with carbonates when pH becomes alkaline (Lebourg *et al.*, 1987, cited by Kassir *et al.* [22]).

However, the Pb and Cd concentrations recorded in the soils remain below the thresholds allowed for agricultural soils, *i.e.*, 1.4 mg/kg for Cd and 70 mg/kg for Pb (CCME, 1999 and 2025), indicating no contamination risk. This finding is consistent with Outbakat *et al.* [23] and Perez-Lopez *et al.* cited by Wang [24] (2020), who both concluded that phosphogypsum application does not pose a risk of soil heavy metal contamination.

The absence of untreated control plots does not allow the observed decrease in salinity and acidity to be attributed with certainty solely to the organo-mineral amendment, despite efforts to account for seasonal variability. This study should be extended and strengthened over several seasonal cycles and should further investigate the potential transfer of trace metal elements to rice plants and grains.

5. Conclusions

This study assessed the effect of phosphogypsum amendment combined with cow manure on soil physicochemical properties and on soil lead and cadmium contents. The results showed that, following amendment, salinity and acidity decreased across a large part of the study area. Lead and cadmium contents remained below critical thresholds and did not present a contamination risk. However, for a rational use of phosphogypsum and to avoid any risk of contamination, it is essential, prior to amendment, to characterize both the soil (salinity and pH levels) and the phosphogypsum, and to determine the appropriate application rates.

This study should be extended to the entire valley, with monitoring conducted over several years.

Authors Contributions

Jean Henri Bienvenue SENE carried out the data processing, data analysis and drafting of the article.

Seynabou SECK contributed to the data processing and analysis.

Alfred Kouly TINE proofread the article.

Daniel GOMIS took part in the soil analyses.

Tidiane DIOP contributed to the analysis of data on Pb and Cd and provided scientific advice following proofreading of the manuscript.

Conflicts of Interest

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

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