EVALUATING THE EFFECTIVENESS OF SOLARIZATION FOR ENHANCING PHOSPHORUS AVAILABILITY IN ACID SULFATE SOIL: A PILOT STUDY IN PLAIN OF REED, VIETNAM

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Abstract - This study evaluated effectiveness of solarization on the available P in acid-sulfate soil (ASS). The pilot study was conducted in a yam-growing area in Long An, an active ASS in the Plain of Reed. The experiment was conducted for 45 days, with two types of cover sheets and two types of irrigation regimes. The available P in the solarization experiments (from 15.87 to 90.46 mg/kg DW) was higher than the control (from 23.94 to 47.18 mg/kg DW). The highest available P was obtained in treatment (Clear plastic, irrigated) (81.96 ± 6.26 mg/kg DW), followed by treatment (Black plastic, no irrigation) (64.78 ± 14.74 mg/kg DW). The soil pH of the treatment plots (mean of 3.91) was similar to the pH of the controls (mean of 3.83). There was an interaction between the two treatments during the incubation period, which affected the concentration of available P in ASS.

Key words - Available-P; acid sulfate soil; solarization; clear cover sheet; black cover sheet; irrigation regime

1. Introduction

Approximately 40% of the land area in the Mekong Delta is active acid sulfate soil (ASS) (1.178.000 ha) and potential ASS (422,000 ha) [1]. Acid sulfate soils are known as "the worst soils on earth" [2]. These soils are found along many coastlines. They do not cover a large area globally but are often located in areas with high population densities, making these soils important for food security, the environment, and human health [2]. These soils are usually clayey and develop on material rich in pyrite (FeS_2) or other sulfide minerals that have accumulated under anaerobic conditions. Most of these soils were initially covered by swamps or mangroves, but humans have used a large part of these soils for farming. Exposing these soils to O_2, for example, through plowing, results in the oxidation of sulfide minerals, releasing high levels of sulfuric acid, which acidifying the soil strongly (down to pH 3), releasing large amounts of toxic elements (Al^{3+}, Mn^{2+}, Zn^{2+}, Fe^{3+} / Fe^{2+}) [3], [4].

Active ASS are soils in which oxidation of mineral sulfides has occurred in the upper horizon, while potential ASS are those in which a significant amount of unoxidized sulfide minerals remains in the upper horizon [3]. Complex oxides such as jarosite ($KFe_3(OH)_6(SO_4)_2$) precipitate in the B horizon of these soils after pyrite oxidation. The high acidity and presence of large amounts of Fe and Al in these soils indicate that they have a high Phosphorus (P) sorption capacity and, therefore, very low P availability for crops, which may explain farmers' high levels of P fertilizer.

Agricultural intensification in the Mekong Delta began in the 1980s after a large-scale hydraulic structure system was constructed, which significantly contributed to the renovation of this problematic soil type. The water flow controlled through the construction of dikes, sluices, and canals [5] was used to regularly wash the soil to remove acidity and toxic elements from the upper layers, followed by the addition of large amounts of lime, organic matter, and nutrients for crop growth, resulting in the enhancement of the productivity of agriculture in this region.

There are two types of upland cropping systems today. One is the cultivation of land inside the dike, which is completely protected from flooding. The other is in flood-prone areas, in which crops are cultivated in the raised beds made by increasing the soil surface with the soil taken from the topsoil or the deeper layers. The deeper layer in the acid sulfate soil contains the jarosite and pyrite layers. Water taken from the canal system is used to both irrigate crops and remove acidity and toxic elements from the topsoil. Significantly, water flows in this lower Mekong River basin have been strongly changing due to the development of dams and other hydraulic structures in the upper Mekong River. Climate change will worsen the water resource issue in this area, altering the flooding regime and the salt intrusion in the delta. Climate change not only causes the reduction of the land surface, as sea levels are predicted to rise by 30 cm by 2050 [6], but it also increases soil salinity. Saline acid sulfate soils now cover approximately 700,000 ha in the delta [1] and are expected to increase, adding another significant stress to crop production.

There is limited understanding about the dynamics of P in ASS, except that soil P availability is very low [7], [8]. Quang et al. [9] showed that these soils have a high P sorption capacity, which they explained as being due to the presence of poorly organized Al and Fe oxides. Laboratory experiments conducted by Mayakaduwage et al. [10] on sandy acid sulfate soils confirmed this high uptake capacity. They suggested that these soils required an uptake of 350 mg P/kg before an increase in soil P could be observed. The very high P levels in soil observed by Thuy et al. [11] for maize and by Thuy et al. [12] for vegetables suggested that farmers added very high P fertilizer to the soil. Nguyen et al. [13] even suggested that the positive effects of high P fertilizer inputs on rice were related to the precipitation of toxic soluble Fe and Al. In a more recent study, Mayakaduwage et al. [10] showed that alternating periods of flooding and wetness did not result in a significant release of P into the soil solution.

In acid sulfate soils, increasing the ability to release P from the soil will make it easier for plants to absorb, thereby reducing the amount of fertilizer needed and reducing the risk of changing the physical and chemical properties of the soil due to the use of high levels of input P fertilizer. Zhang et al. [14] reported that long-term P fertilizer application can affect the soil's flocculation and water permeability, thereby changing the soil-water interaction and the ability to support plant growth. There is a need for solutions to increase P release that are technically efficient, cost-effective, and simple enough to be applied to a large-scale farming model.

Soil solarization is a non-chemical solution used in agriculture. It creates a greenhouse effect by covering the soil with a plastic sheet under sunlight, raising soil temperature, and effectively controlling weeds, insects, and pests. This technique increased the availability of nutrients in the soil [15]. However, this effect depends on the chemical binding of nutrients to the soil's minerals and several environmental factors in the field.

Given the urgency of using P fertilizer effectively through increasing the ability to release available P from acid sulfate soils, evaluating the effectiveness of the solarization technique for this soil type can support agricultural development. Therefore, this study aims to assess solarization's effectiveness in increasing the available P concentration in a field study on acid sulfate soils under different conditions.

2. Materials and Methods

Field Experiment Design:

Four (4) experiments and a control experiment were set up. Each experiment was designed with two (2) replications. The control experiment was conducted with 2 replications. These experiments were arranged on a plot of land cultivated in rows at Dong Hoa Hamlet, Thuy Dong Commune, Thanh Hoa Ward, Long An Province. The field area was plowed and leveled before being divided into small experimental plots; each plot had an area of 1.5 m x 3.5 m (Figure 1). Each experimental plot was marked by placing four stakes at the four corners as landmarks, and another stake at the beginning of each plot to number the treatments.

Two types of plastic cover were used: clear plastic film and black plastic film. The clear plastic film was Profilm greenhouse film with a 2 m x 100 m size. The black plastic film had a thickness of 25 µm and a size of 2 m x 400 m. Both types of cover sheet were made of polyethylene (PE).

Two types of irrigation regimes were employed, with and without irrigation. Irrigation treatment was designed with a drip irrigation system using the 16 mm irrigation pipes, 0.2 mm thickness, 10 cm spacing between irrigation holes, water flow rate of 2 liters/hour, and an operating pressure of 1.5 bar. Each experimental plot (1.5 m x 3.5 m) was arranged with 3 rows of drip irrigation lines to evenly distribute the irrigation water in the plot.

Figure 1. *Set up of solarization experiment (picture taken in May 2024)*

Procedure for setting up solarization treatments:

After the soil has been tilled and leveled, we install a drip irrigation system for the experimental plots with an irrigation system; for the plots without irrigation, the irrigation system is not installed. Next, we cover the surface of the plots with plastic tarps and bury the four edges of the tarps firmly in the ground to ensure that they are sealed and have no gaps. After that, we carefully check for holes that may appear on the surface of the tarps and fix them immediately if found.

The soil drying experiment model operates for the first 45 days of the 2024 rainy season (from May 28, 2024, to July 12, 2024). Soil samples were collected at the end of the experiment. Soil samples were measured for available P content by the TCVN 8661:2011 method, and pH by a pH meter.

Statistical analysis:

All values are reported as mean ± standard deviation. The data were subjected to a two-way ANOVA with irrigation regime and cover as the independent factors. A significant interaction term was followed by post-hoc pairwise comparisons using Tukey's honest significant difference (HSD) test.

3. Results and Discussion

The results of the available P analysis for ten experimental plots are shown in Table 1. Available P contents varied from 15.87 to 90.46 mg/kg DW for the solarization treatments and ranged from 23.94 to 47.18 mg/kg DW for control plots. The soil pH in all treatments varied from 3.70 to 4.06. pH values showed the high acidity of the topsoil. The solarization treatments did not change the pH of the soil compared to the control.

Figure 2 compares the means of solarization treatments with the control plots. The available P concentration for the solarization treatments (mean of 49.11 ± 23.60 mg/kg DW) was higher than that of the control treatment (mean of 35.50 ± 13.28 mg/kg DW). The highest available P concentration was obtained in the treatment (Clear plastic, irrigated) (81.96 ± 6.26 mg/kg), followed by the treatment (Black plastic, not irrigated) (64.78 ± 14.74 mg/kg).

Table 1. *The available P content and pH of the experimental plots after 45 days of solarization*

Plot Number	Code	Sheet cover	Irrigation regime	Available P content (mg/kg) (mean ± SD)	pH
1	NIB	Black	Irrigation	33.99 ± 5.76	3.88
2	NIC	Clear	Irrigation	78.24 ± 4.05	4.04
3	NNB	Black	Non-Irrigation	77.19 ± 5.70	4.06
4	NNC	Clear	Non-Irrigation	46.97 ± 1.81	3.7
5	NIB	Black	Irrigation	20.18 ± 3.95	3.81
6	NIC	Clear	Irrigation	85.67 ± 6.77	3.91
7	NNC	Clear	Non-Irrigation	42.31 ± 0.56	3.93
8	NNB	Black	Non-Irrigation	52.37 ± 1.83	3.82
9	C	Control	Non-Irrigation	47.00 ± 0.25	3.79
10	C	Control	Non-Irrigation	24.00 ± 0.08	3.87

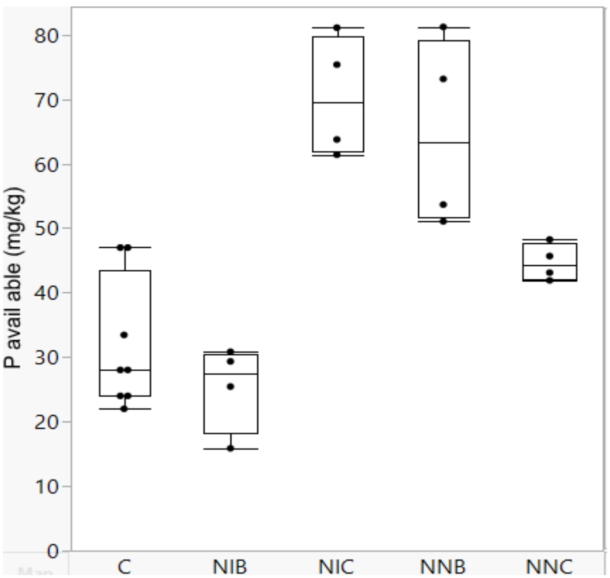

Figure 2. *Concentration of available P for experimental plots after 45 days of soil exposure. Five treatment groups include: C: Control; NIB: Irrigated, Black; NIC: Irrigated, Clear; NNB: Non-irrigated, Black; NNC: Non-irrigated, Clear*

A two-way ANOVA revealed no significant main effect of two factors (irrigation regime and cover type). However, there was a significant two-factor interaction between irrigation regime × cover type ($F = 49.32$, $p < 0.0001$). Post-hoc pairwise comparisons using Tukey's HSD test show that there were differences between the treatments NIC (clear plastic, irrigated) and NNB (black plastic, no watering) compared to the control. There was no difference between the treatments NIB (black plastic, watered) and NNC (clear plastic, no irrigation) compared to the control (Table 2).

Table 2*. Statistical analysis for the comparison of the mean of P available between groups*

Treatment group	**P available (mg/kg) (Mean ± SD)**	**Turkey letter* α = 0.05)**
NIC	81.95 ± 6.26	a
NNB	61.02 ± 12.38	ab
NNC	44.18 ± 2.72	bc
NIB	28.80 ± 11.08	c
C	35.51 ± 13.28	c

** Levels not connected by the same letter are significantly different*

Figures 3 and 4 showed that there was a difference between the treatment (clear plastic, irrigated) and the treatment (black plastic, no watering) compared to the control (p values were 0.0007 and 0.0256, respectively). There was no difference between the treatments (black plastic, watered) and (clear plastic, no irrigation), and the control (p values were 0.2109 and 0.2274, respectively) by each pair of students' t-test.

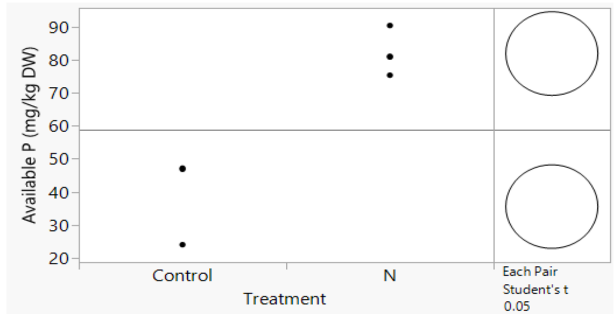

Figure 3. *Available P concentration for the treatment (N: Clear cover, irrigated) compared to the control (C). Mean values were compared with a student's t-test (p = 0.0007)*

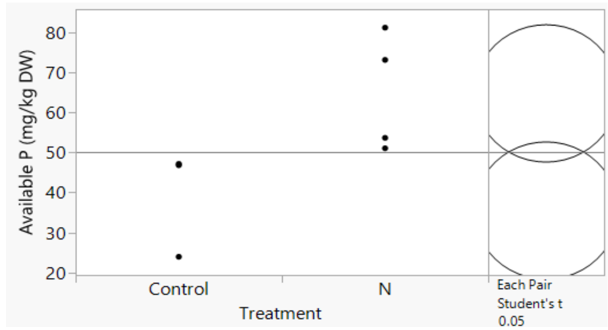

Figure 4. *Available P concentration for the treatment (N: Black cover, no irrigation) compared to the control (C). Compare the mean values with a Student's t-test (p = 0.0256)*

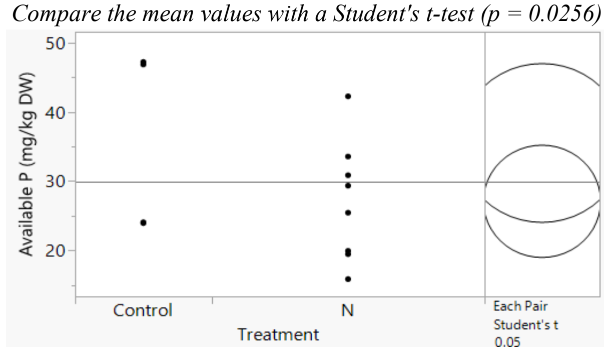

Figure 5. *Available P concentration for the treatment (N: Black cover, irrigated) compared to the control (C). Mean values were compared with a Student's t-test (p = 0.2109)*

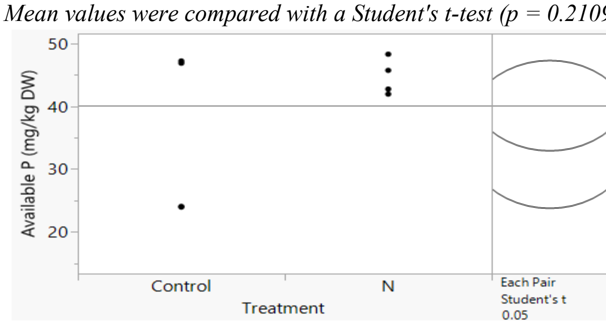

Figure 6. *Available P concentration for the treatment (N: Clear cover, no irrigation) compared to the control (C). Compare the mean values with a Student's t-test (p = 0.2274)*

The results showed that covering with a plastic sheet and watering during the covering process could increase the concentration of available P at different levels. With clear cover, when combined with watering to control humidity, it increased the available P more than without watering, compared to the control. However, with a black cover, not watering resulted in a higher content of available P than the control. There were interactions of the physical heating process during the solarization with soil moisture. Soil moisture increases the heat transfer process in the soil, allowing solar heat to penetrate deeper and more uniformly [16]. The color of the mulch correlated with the temperature and moisture of the covered soil mass. The study of Al-Karaghouli and Al-Kayassi [17] found that, with a transparent mulch, the temperature in the compost mass increased as the moisture decreased. Therefore, the solarization condition influences the P release efficiency.

Solarization enhances phosphorus (P) release efficiency through a combination of thermal and biogeochemical mechanisms. The process elevates soil temperature and sustains a high-humidity, anaerobic environment beneath the covering. These elevated temperatures generally accelerate the kinetics of all chemical reactions, including those governing both P fixation and release. Concurrently, the induced anoxic conditions facilitate the microbial reduction of ferric iron (Fe(III)) to ferrous iron (Fe(II)), thereby releasing phosphate previously bound to iron oxides. This mechanism is supported by the work of Krairapanond et al. [18], whose laboratory experiments demonstrated that more native insoluble P was released from Acid Sulfate Soil (ASS) under reduced conditions compared to oxidized conditions.

4. Conclusion

The study evaluated the ability to release available P in acid sulfate soil through the drying and composting technique. The release level of available P in the drying and composting treatment was higher than in the control treatment (no drying and composting). There was an interaction between the type of cover and irrigation regime on the concentration of available P in the soil after the composting process. The clear plastic and irrigated treatment released the highest available P, followed by the black plastic treatment without irrigation. These results show the possibility of applying this solution on a larger scale, increasing the concentration of available P to support plant growth, and possibly reducing the amount of additional P fertilizer needed for plants.

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