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# Effectiveness of Silica Humate in Improving Soil Quality in Paddy Field Contaminated by Industrial Waste

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**ABSTRACT**

*Soil degradation caused by industrial waste in Sidoarjo Regency has led to a decline in agricultural productivity, necessitating soil rehabilitation efforts. This study aimed to evaluate the effectiveness of silica humate as a soil amendment on paddy fields contaminated by industrial waste. The experiments were arranged according to the Factorial Complete Randomized Design, where the first factor: 3 kinds of industrial waste namely the pharmaceutical, livestock feed, and paper industry. Second factor; 5 doses of silica humat (0, 10, 20, 30, and 40 kg/ha). The parameters included soil pH, cation exchange capacity (CEC), total nitrogen (total-N), and available phosphorus (available-P), measured at 14 and 56 days after application (DAA). Results showed that the effectiveness of silica humate varied depending on the type of industrial waste and increased over time. On land contaminated with pharmaceutical waste, silica humate increased CEC from 44.34 to 52.52 cmol(+)/kg and available-P from 27.21 to 36.69 ppm at low doses. Land contaminated with animal feed waste showed the best results at a dose of 20 kg/ha, while land contaminated with paper industry waste required higher doses. These findings suggest that silica humate is promising as a viable soil amendment strategy, though optimal dosage rates must be tailored to specific industrial contamination types for maximum rehabilitation effectiveness.*

## 1. INTRODUCTION

The development of the industrial sector in Indonesia has made a significant contribution to national economic growth. However, rapid industrial expansion, especially in the pharmaceutical, animal feed, and paper sectors, has caused negative impacts on the surrounding environment, particularly on paddy fields adjacent to industrial areas. Industries produce waste that affects agricultural areas through river flows and soil seepage (Wang *et al*., 2019). This contamination causes a decrease in organic matter, C/N ratio, and the availability of essential nutrients in paddy soils including nitrogen (N) and phosphorus (P) (Oshunsanya, 2019). Additionally, agricultural land around industrial areas experiences a decrease in pH and accumulation of heavy metals that are potentially toxic to plants (Sruthi *et al*., 2017).

In Sidoarjo Regency, heavy metal content such as manganese (Mn) in paddy soils reaches 844.25 ppm, indicating a high level of contamination (Khasanah *et al*., 2021). This accumulation of heavy metals negatively impacts the physical, chemical, and biological properties of soil, decreases the Soil Fertility Index (SFI), and inhibits plant growth (Mindari *et al*., 2023). As a result, there is a decrease in harvested area for several strategic commodities, such as shallots which shrank from 61 hectares in 2021 to 37 hectares in 2022, as well as a decrease in harvested area of large chilies and sugarcane production (BPS, 2023). This shows that industrial pollution not only causes land degradation but also harms the agricultural sector through decreased production yields.

Efforts to remediate degraded land have become a research focus in recent decades. One promising approach is the use of soil amendments based on organic materials and minerals such as humates and silica. Humate, a stable organic fraction, has proven effective in increasing soil cation exchange capacity (CEC), improving soil structure, and increasing nutrient availability (Tan, 2014). Humic acid acts as a ligand that forms complexes with nutrients, temporarily storing them, and releasing them according to plant needs. Active functional groups such as carboxyl (-COOH) and hydroxyl (-OH) contribute to increased cation exchange capacity and ion adsorption in soil (Mindari *et al*., 2023; Sruthi *et al*., 2017). Rahayu *et al.* (2022) showed that applying humic acid at 40 kg/ha and silica at 1 ton/ha increases nitrogen levels, CEC, pH, and organic carbon in sandy soils, thus potentially optimizing agricultural land fertility in industrial areas.

Silica is a chemical compound found abundantly in various natural materials such as minerals, plants, and others (Hardyanti *et al*., 2017). Silica plays a role in soil nutrient improvement by increasing phosphate availability and stabilizing soil structure through monosilicic acid (Si-OH), which binds with phosphate to form silica-phosphate complexes that are more easily absorbed by plants (Belton *et al*., 2012). Additionally, silica promotes clay particle aggregation, increases water and nutrient retention, and supports plant resistance to biotic and abiotic stresses (Hassan *et al*., 2024; Sahebi *et al*., 2015).

Several previous studies have shown the effectiveness of humate and silica separately in remediating soils contaminated with heavy metals and increasing rice production (Chakim *et al*., 2022; Rahayu *et al*., 2022). However, research on the effect of combining humate and silica to improve the fertility of soil contaminated by industrial waste is still limited. Therefore, this research aims to: (1) Examine changes in pH, CEC, total-N, and available-P after applying combinations of silica humate doses to paddy soils affected by pharmaceutical, animal feed, and paper industry waste; and (2) Determine the optimum silica humate dose capable of improving several chemical properties of paddy soil in areas affected by industrial waste. The hypothesis of this research is that the application of silica humate will increase nutrients and improve the chemical properties of paddy soils affected by industrial waste. This improvement is expected to be reflected in increased total-N, and available-P, as well as improved soil pH and CEC. This research is expected to make a significant contribution to the development of remediation strategies for degraded paddy fields in industrial areas, supporting efforts to increase agricultural productivity, and maintaining the sustainability of national food production.

## 2. MATERIALS AND RESEARCH METHODS

### 2.1. Research Location and Time

This research was conducted at the Land Resources Laboratory, Faculty of Agriculture, Universitas Pembangunan Nasional 'Veteran' East Java from October 2023 to May 2024. Soil samples were collected from paddy fields adjacent to three different types of industrial areas (pharmaceutical, animal feed, and paper) in Sidoarjo Regency, Jawa Timur. Province, Indonesia. The research used an incubation method, covering the stages of sampling, incubation, laboratory analysis, and data processing over eight months.

### 2.2. Research Tools and Materials

This research was conducted using an incubation method with various tools and materials required for field sampling and laboratory analysis. The tools used during the research were hoes, shovels, sacks, mesh sieves, knives, scissors, mobile phone cameras, GPS, stationery, scales, trays, and laboratory equipment. The materials included soil samples, silica humate soil amendment, leonardite, rice husks, 500 ml plastic cups, zip-lock plastic bags, and chemical reagents for laboratory analysis.

### 2.3. Experimental Design

The experiments were arranged in Factorial Complete Randomized Design (CRD). The first factor, location, consisted of three levels representing different industrial exposures: L1 (pharmaceutical industry), L2 (animal feed industry), and L3 (paper industry). The second factor, humic acid-silica dosage, consisted of five levels: P0 (0 kg/ha), P1 (10 kg/ha), P2 (20 kg/ha), P3 (30 kg/ha), and P4 (40 kg/ha). The combined doses of humic acid-silica were determined based on preliminary tests, adjusting the doses of humic acid and silica from previous research conducted by Chakim *et al*. (2022) and Rahayu *et al*. (2022). The experimental design resulted in 15 treatment combinations (3 locations × 5 dose levels). Each treatment was replicated three times, resulting in a total of 45 experimental units or samples. Figure 1 shows the experimental plot layout after randomization using Excel 2019 software.


Figure 1. Experimental plot layout

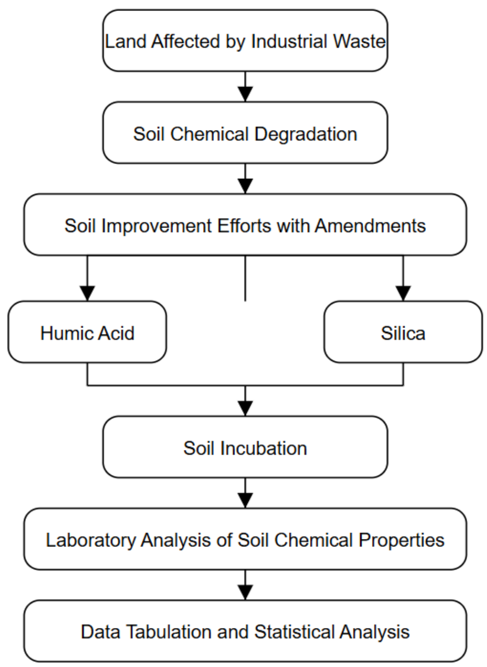


Figure 1. Research flow

### 2.4. Research Implementation

The implementation of the research was summarized in Figure 2 with details steps as the following.

#### 2.4.1. Soil Sampling

Soil samples were collected from three paddy field locations in Sidoarjo Regency that were potentially affected by industrial waste. Soil sampling was conducted at three locations within 0.5 – 1 km from the centers of pharmaceutical, animal feed, and paper industrial activities. The first sampling point was 550 m from the pharmaceutical industry in Ponokawan Village, Krian; the second sampling point was 950 m from the animal feed industry in Balong Village, Sukodono; and the third sampling point was 990 m from the paper industry in Kanigoro Village, Tarik. The selection of these industries was based on differences in soil fertility levels and the potential waste affecting surrounding soil conditions, while also considering road access and irrigation sources. According to Joimel *et al*. (2016) variations in land use and human activities impact soil properties. Sampling was performed compositely at a depth of 0 – 20 cm using a hoe. The soil samples were then brought to the laboratory for basic analysis including measurement of pH, CEC, N-total, P-available, and texture using methods according to the BSIP (2023).

Based on initial soil analysis, the pharmaceutical and animal feed industry locations had silty clay texture, while the pharmaceutical industry location had loam texture. The results of this analysis were used as baseline data to describe soil conditions before silica humate application.

Table 1. Initial Soil Analysis

| Location | pH | CEC (cmol(+)/kg) | Total-N (%) | Available-P (ppm) | Texture | | | Texture Class |
|---|---|---|---|---|---|---|---|---|
| | | | | | Sand (%) | Silt (%) | Clay (%) | |
| L1 | 7.04 | 44.34 | 0.18 | 27.21 | 7 | 67 | 26 | Silty clay |
| L2 | 6.97 | 33.88 | 0.21 | 34.73 | 3 | 74 | 23 | Silty clay |
| L3 | 6.97 | 33.80 | 0.11 | 18.02 | 29 | 49 | 22 | Clay |
| Criteria* | Neutral | High | Low | High | - | - | - | |

Note: L1 = pharmaceutical industry, L2 = animal feed industry, L3 = paper industry, (*) = criteria sourced from the BSIP (2023).

### 2.4.2. Preparation of Incubation Media

Soil samples were air-dried, crushed, and sieved (2.00 mm). 250 grams of soil were placed in each of 90 cups (500 ml) for 2 observation intervals over 56 days. Before treatment, samples were saturated with water to field capacity.

### 2.4.3. Preparation of Soil Amendments

Humic acid was extracted from 10 g of leonardite using the modified method of Stevenson (1994), until the pH reached 2. Silica was then extracted from rice husks using 10% KOH (Agung-M *et al*., 2013). The humic acid extract was mixed with silica. Exactly 200 g of extracted silica was weighed and adjusted to pH 8-9 with 1% KOH solution using a magnetic stirrer at 85°C. After dissolution, the silica was poured into approximately 50 g of humic acid adjusted to pH 4-5 using a magnetic stirrer for 60 min. As much as 1000 ml of humic silica with pH 4-5 was prepared (McMahon, 2010). After the mixing process, chemical characteristics of the resulting humic silica were analyzed. The analysis results showed the potential of humic silica as a soil amendment that can increase fertility and improve soil structure based on the Peraturan Menteri Pertanian (Permentan) No. 261/KPTS/SR.310/M/4/2019 (Table 2).

Table 2. Analysis of humic silica characteristics

| Parameter | Unit | Humic Silica | Requirements (*) |
|---|---|---|---|
| pH | - | 5.3 | 4-9 |
| N-total | % | 0.01 | <2 |
| P-total | % | 0.01 | <2 |
| K-total | % | 0.13 | <2 |

### 2.4.4. Application of Humic Silica

250 grams of air-dried soil from each location were placed in plastic cups and saturated to field capacity, then mixed with humic silica according to treatments. Humic silica was added in liquid form to the soil according to predetermined doses, namely: 0, 10 kg/ha (0.00125 g), 20 kg/ha (0.0025 g), 30 kg/ha (0.00375 g), and 40 kg/ha (0.005 g). The determination of these doses was based on preliminary tests. Soil moisture was maintained at 50% field capacity during the incubation period. Incubation was carried out at room temperature (25±30°C) for 56 days.

### 2.4.5. Laboratory Analysis

Incubated soil samples were collected on day 14 and day 56. Soil from cups was transferred to trays for drying. After drying, the soil was crushed and sieved with 2.00 mm and 0.50 mm sieves. Parameters measured included soil pH, total-N, available-P, and CEC (BSIP, 2023).

### 2.4.6. Statistical Analysis

Data were analyzed using two-way Analysis of Variance (ANOVA) to evaluate the effects of location, humic silica dose, and their interaction. Tukey's Honest Significant Difference (HSD) test at the 5% level was performed if significant differences were found.

## 2.5. Waste Characteristics at Research Locations

Based on the research by Khasanah *et al.* (2021) and preliminary tests, it was found that paddy fields adjacent to industrial areas in Sidoarjo Regency were contaminated with several types of heavy metals such as Pb, Hg, and Cd. However, this research only focused on efforts to improve soil contaminated with Mn-type heavy metal waste at the three paddy field locations near paper, animal feed, and pharmaceutical industries (Figures 3).

The solubility of manganese (Mn) is influenced by soil pH and redox conditions (Rinklebe *et al*., 2016). The oxidation state of Mn is related to soil pH, where oxidative conditions are supported by high pH, while acidic conditions tend to be reductive (Tandzi *et al*., 2018). This relates to the main redox reaction equation of Mn. Excessive Mn levels are toxic to plants, while low pH can cause Mn deficiency due to low Mn availability. In plants, Mn toxicity is characterized by cell wall swelling, leaf tissue necrosis, and the appearance of brown spots on plant leaves (Seran, 2017).

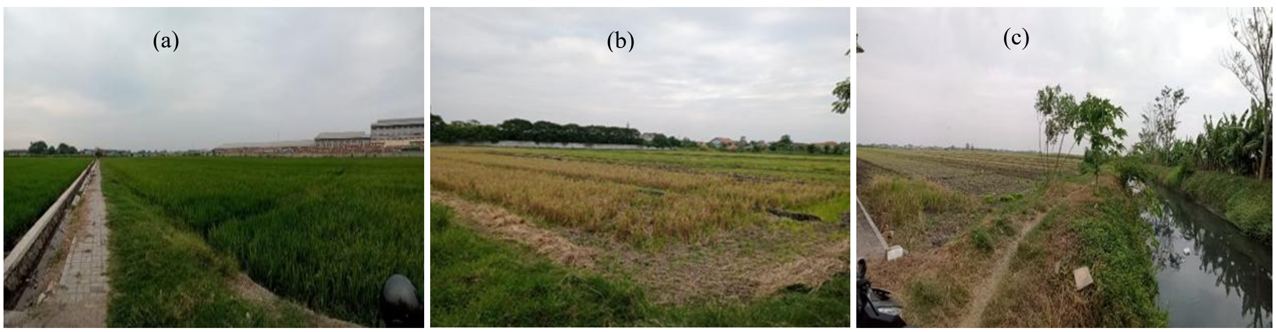


Figure 3. Paddy fields near industrial activity: (a) Paper industry, (b) Pharmaceutical industry, and (c) Animal feed industry

# 3. RESULTS AND DISCUSSION

## 3.1. Effect of Humic Silica on Soil Chemical Properties

The application of humic silica showed a significant influence on soil pH changes in all three research locations. Initial soil pH at all three locations was in the neutral range (Table 3), which according to Hartemink & Barrow (2023), is generally beneficial for the availability of most plant nutrients. This soil pH uniformity indicates that the different types of industries around the land did not significantly affect soil acidity. After humic silica application at location L1 (pharmaceutical industry), pH decreased from 7.04 to 6.70-6.83, while at L2 (animal feed industry), soil pH decreased more significantly from 6.97 to 6.46-6.64. In contrast, L3 showed a slight soil pH increase from 6.97 to 6.76-7.06. These results demonstrate specific interactions between humic silica and soil characteristics at each location.

Table 3. Soil pH values after humic silica application at 14 DAA and 56 DAA

| Humic Silica Dose | 14 DAA | | | 56 DAA | | |
|---|---|---|---|---|---|---|
| (kg/ha) | L1 Pharmacy | L2 Feed | L3 Paper | L1 Paper | L2 Pharmacy | L3 Feed |
| 0 | 6.76$^{cd}$ | 6.47$^{a}$ | 6.85$^{def}$ | 6.70$^{cde}$ | 6.46$^{a}$ | 6.76$^{cdef}$ |
| 10 | 6.81$^{cde}$ | 6.59$^{b}$ | 6.84$^{cdef}$ | 6.82$^{efg}$ | 6.63$^{bc}$ | 6.91$^{fgh}$ |
| 20 | 6.83$^{cdef}$ | 6.54$^{ab}$ | 6.89$^{ef}$ | 6.76$^{cdef}$ | 6.64$^{bcd}$ | 6.95$^{gh}$ |
| 30 | 6.76$^{cd}$ | 6.52$^{ab}$ | 6.94$^{f}$ | 6.79$^{defg}$ | 6.50$^{ab}$ | 6.95$^{gh}$ |
| 40 | 6.73$^{c}$ | 6.57$^{ab}$ | 7.06$^{g}$ | 6.78$^{cdef}$ | 6.46$^{a}$ | 7.00$^{h}$ |
| HSD 5% | | 0.11 | | | 0.16 | |

Note: Mean values with the same letter are not significantly different (Tukey's 5% test), DAA = days after application

Statistical analysis using the 5% HSD test showed no significant difference in pH values, as indicated by the same letters in the table. However, some treatments showed significant differences at different locations. At L1 (pharmaceutical industry), the control treatment (0 kg/ha) showed a decrease from 14 DAA to 56 DAA (6.76 to 6.70), indicating that without treatment, pH can decrease. Meanwhile, a dose of 10 kg/ha was able to maintain the pH value until the end of the incubation period (6.82). At the animal feed industry location (L2), the application of humic silica at doses of 10-20 kg/ha caused a slight increase in soil pH.

The paper industry location (L3) showed a more consistent trend of pH increase, from the initial value (Table 1) to the final incubation period. A dose of 40 kg/ha provided the best results in increasing pH from the initial value. The variation in required doses to create neutral pH is caused by differences in soil buffer capacity at each location. According to Liu *et al*. (2017), soil pH response to amendments is strongly affected by initial soil chemical properties.

The pH difference between 14 DAA and 56 DAA was not significant ($p$ = 0.48), indicating that the effect of humic silica on soil pH tends to be stable during this period. However, small variations (5% HSD 0.11 and 0.16) observed between these two periods may reflect the ongoing process of humic silica interaction with soil components or the influence of waste factors. This pH increase aligns with findings by Mindari *et al*. (2023), who reported that the application of humic materials can increase soil pH through enhanced soil buffer capacity. However, the fluctuating pH responses at the pharmaceutical and animal feed locations indicate the complexity of interactions between ameliorants and soil characteristics in industrial contamination.

Table 4. Soil CEC (cmol(+)/kg) values after humic silica application at 14 DAA and 56 DAA

| Humic Silica Dose (kg/ha) | 14 DAA L1 Pharmacy | 14 DAA L2 Feed | 14 DAA L3 Paper | 56 DAA L1 Pharmacy | 56 DAA L2 Feed | 56 DAA L3 Paper |
|---|---|---|---|---|---|---|
| 0 | 44.96$^{abc}$ | 59.55$^{e}$ | 41.85$^{ab}$ | 46.81$^{gh}$ | 38.20$^{ef}$ | 29.81$^{a}$ |
| 10 | 52.52$^{cde}$ | 56.82$^{de}$ | 46.15$^{abc}$ | 41.27$^{ef}$ | 36.09$^{bcde}$ | 32.67$^{abcd}$ |
| 20 | 47.00$^{abc}$ | 49.20$^{bcd}$ | 39.70$^{a}$ | 42.19$^{fg}$ | 48.30$^{h}$ | 30.54$^{a}$ |
| 30 | 44.53$^{abc}$ | 48.64$^{bcd}$ | 43.66$^{ab}$ | 38.27$^{ef}$ | 36.58$^{cde}$ | 31.97$^{abc}$ |
| 40 | 53.20$^{cde}$ | 50.47$^{bcd}$ | 39.18$^{a}$ | 37.95$^{def}$ | 41.16$^{ef}$ | 30.83$^{ab}$ |
| HSD 5% | | 8.78 | | | 5.37 | |

Note: Mean values with the same letter are not significantly different (Tukey's 5% test), DAA = days after application

Cation exchange capacity (CEC) showed complex fluctuations across all locations without clear dose trends. The soil CEC before humic silica application at all locations was classified as high. According to Antonangelo *et al*. (2024), this indicates good nutrient retention capacity. This is due to similarities in soil texture between locations, where all industrial locations have higher silt and clay content; clay particle surfaces attract and retain cations, thereby increasing overall soil CEC (Rabot *et al*., 2018). Vitali *et al*. (2024) explain that texture variations impact water and nutrient holding capacity, which in turn affects irrigation and fertilization management. After humic silica application, CEC values (Table 4) changed variably depending on the dose during the incubation period. The 5% HSD results show that the animal feed industry location (L2) consistently had the highest values compared to other locations, especially at 14 DAA where the highest value reached 59.55 cmol(+)/kg in the control. At 56 DAA, there was a general decrease in CEC values at all locations, but the response patterns to humic silica doses varied. At the pharmaceutical industry locations (L1) and (L2), a dose of 20 kg/ha provided the highest CEC value at 56 DAA. Meanwhile, at the paper industry location (L3), a dose of 10 kg/ha showed the highest effectiveness. The similarity in dose levels to achieve high CEC values at L1 and L2 is based on the similarity in soil fractions (Table 1). Interactions between humic matter and other soil components can produce diverse effects on CEC, depending on specific soil characteristics (Tan, 2014). The decrease in 5% HSD values from 14 DAA (8.78) to 56 DAA (5.37) indicates smaller variability between treatments over time, possibly due to stabilization of humic silica effects in industrially contaminated soil. These results show that the effectiveness of humic silica in improving soil CEC is influenced by initial soil characteristics, type of industrial contamination, application dose, and time after application.

### 3.2. Effect of Humic Silica on Soil Nutrient

Initial soil analysis revealed similar nutrient patterns across all locations, characterized by low nitrogen content and high phosphorus availability (Table 1), indicating potential nitrogen deficiency commonly found in intensive agricultural soils (Gelderman & Lee, 2019). However, the animal feed industry location showed relatively better conditions (0.21%) compared to the pharmaceutical and paper locations. This condition is due to the organic waste characteristics from the animal feed industry, which can act as a soil nutrient source (Vodyanitskii, 2016). Conversely, the paper industry location showed the lowest values for most parameters, caused by paper industry waste characteristics that tend to be nutrient-poor and high in inorganic materials (Singh *et al*., 2022).

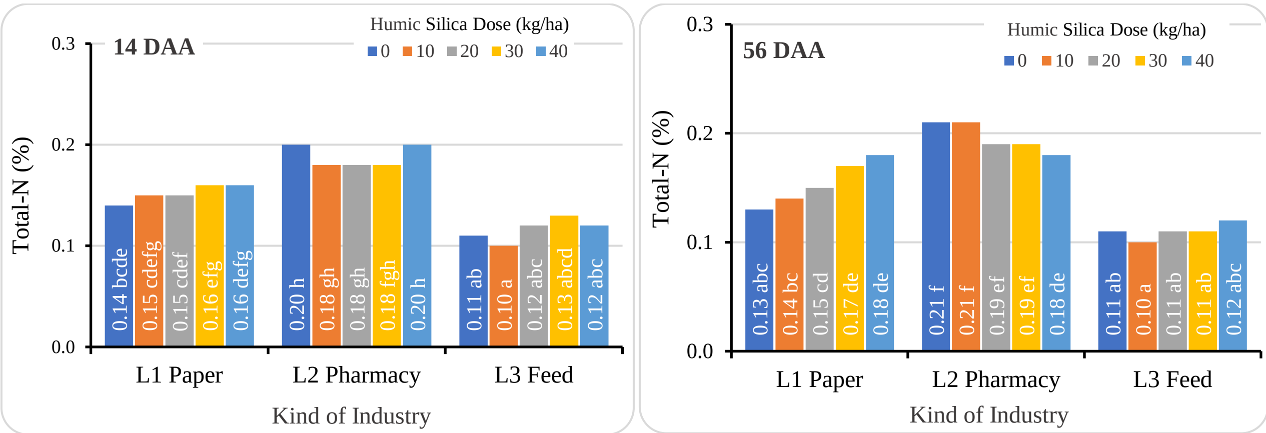


Figure 4. Soil total-N (%) after humic silica application. (a) 14 DAA, (b) 56 DAA. (Different letters indicate significant differences based on HSD 5% = 0.03).

After humic silica application, different effects were observed on total-N content in soil at three locations contaminated with different industrial wastes. The results at 14 and 56 DAA revealed distinct response patterns among the three industrial locations (Figure 4a and 4b). At 14 DAA, the animal feed industry location (L2) demonstrated the highest total-N values, ranging from 0.18 to 0.20%, with the feed location consistently showing superior nitrogen content compared to pharmaceutical (L1: 0.14-0.16%) and paper industry locations (L3: 0.10-0.13%). Statistical analysis using Tukey's HSD test (HSD 5% = 0.03) confirmed significant differences between locations, with L2 treatments receiving the highest significance groupings (fgh-h notations), while L3 consistently showed the lowest values (a-abcd notations).

At 56 DAA, all locations showed overall improvement in total-N content. The feed industry location (L2) maintained its superiority with values reaching 0.21% at optimal doses, while pharmaceutical (L1) and paper locations (L3) showed notable increases to 0.17-0.19% and 0.11-0.12% respectively. This temporal improvement suggests that humic silica effects become more pronounced over time, aligning with research by Ampong *et al.* (2022) which states that humic materials can increase nitrogen retention and stimulate soil microbial activity, indirectly increasing organic nitrogen mineralization.

The optimal dosing strategies varied significantly among locations due to different industrial waste characteristics and their nitrogen content. The feed industry location (L2) showed optimal response at lower doses (10 kg/ha), achieving 0.20% total-N at 14 DAA and 0.21% at 56 DAA, which may be related to the organic-rich nature of animal feed industry waste. In contrast, pharmaceutical (L1) and paper industry locations (L3) demonstrated progressive improvement with increasing doses, requiring 40 kg/ha for optimal performance (L1: 0.16% to 0.18%; L3: 0.12% to 0.12%). This suggests that pharmaceutical and paper waste-contaminated soils require higher humic silica inputs for optimal nitrogen enhancement compared to feed industry contaminated soil.

The superior performance of L2 can be attributed to the organic-rich nature of animal feed industry waste, which likely provides a more favorable environment for humic silica-soil interactions (Fang *et al*, 2020). The higher initial nitrogen content and organic matter at this location created synergistic effects with humic silica, enabling effective nitrogen retention even at lower application rates. Conversely, L1 and L3 locations, with lower initial total-N content, showed positive responses to high-dose humic silica applications, consistent with remediation studies on industrial contaminated soils (Pranckietien & Jodaugien, 2020) .The consistent HSD 5% value of 0.03 across both observation periods provided a reliable threshold for determining statistical significance and confirmed stable experimental variability throughout the study period, indicating that the effect of humic silica on soil total-N tends to be consistent throughout the observation period.

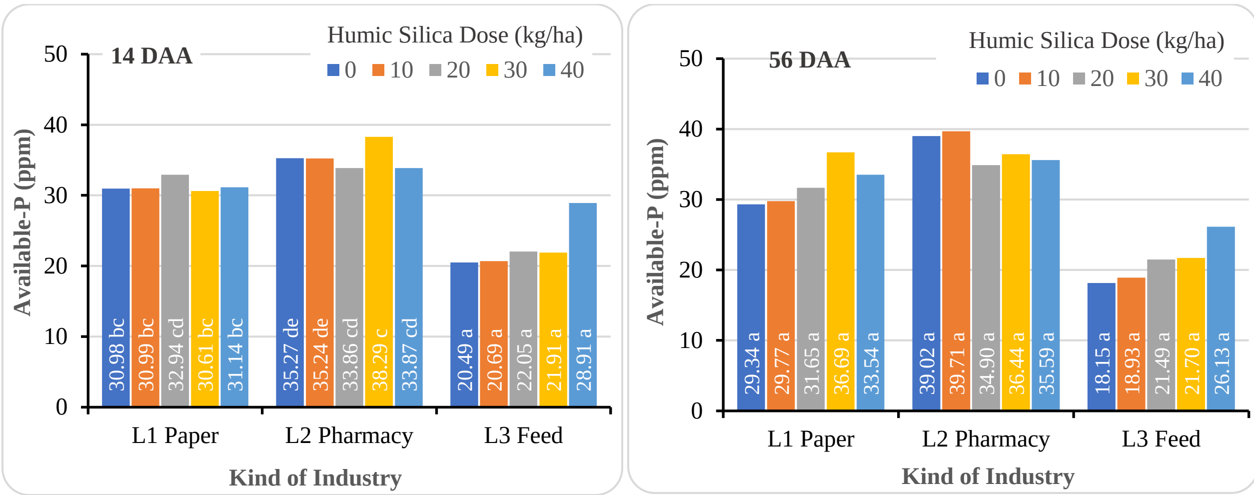


Figure 5. Soil available-P (ppm) after humic silica application. (a) 14 DAA with HSD 5% = 3.53 (significant), (b) 56 DAA with HSD 5% = 8.29 (not significant). Different letters indicate significant differences.

Phosphorus availability at all locations was quite high (Figure 5). This high available-P is due to neutral pH at all locations (Table 3). Phosphorus availability is optimal in the neutral pH range because phosphorus is not easily bound by aluminum (Al) or iron (Fe), which often occurs at lower pH levels, or in alkaline conditions where less soluble phosphorus compounds form with calcium (Debicka, 2024). Humic silica application showed significant effects on soil available-P content across the three industrial waste contaminated locations, with distinct response patterns observed between 14 and 56 DAA (Figure 5a and 5b). At 14 DAA, the feed industry location (L2) demonstrated the highest available-P values, ranging from 35.24 to 38.29 ppm, significantly outperforming pharmaceutical (L1: 30.61-32.94 ppm) and paper industry locations (L3: 20.9-28.1 ppm). Statistical analysis using Tukey's HSD test confirmed these differences, with L2 achieving optimal performance at 30 kg/ha (38.29 ppm), L1 at 20 kg/ha (32.94 ppm), and L3 at 40 kg/ha (28.91 ppm). At 56 DAA, available-P content showed overall improvement across all locations, with L2 maintaining its superiority (34.90-39.71 ppm) and achieving peak values at 10 kg/ha (39.71 ppm). The pharmaceutical location (L1) demonstrated substantial improvement, reaching 36.69 ppm at 30 kg/ha, while the paper location (L3) showed consistent enhancement with maximum values of 26.13 ppm at 40 kg/ha. This temporal improvement indicates that humic silica effects on phosphorus availability intensify over time.

The differential dose requirements among locations reflect the varying industrial waste characteristics and initial soil phosphorus status. The feed industry location (L2), with inherently higher organic matter content and phosphorus levels, demonstrated optimal response at lower doses, particularly evident at 56 DAA where 10 kg/ha proved most effective. This efficiency can be attributed to the synergistic effects between existing organic compounds in feed waste and applied humic silica, facilitating phosphorus solubilization processes. In contrast, pharmaceutical and paper industry locations required higher application rates, with L1 showing progressive improvement up to 30 kg/ha and L3 requiring maximum doses (40 kg/ha) for optimal performance.

The superior phosphorus availability at L2 aligns with findings by Tang *et al.* (2024) who demonstrated that organic-rich environments enhance humic acid effectiveness in phosphorus mobilization. The mechanism involves chelation of metal cations ($Al^{3+}$, $Fe^{3+}$) that typically bind phosphorus, thereby increasing phosphorus bioavailability (Hartemink & Barrow, 2023). The consistent improvement from 14 to 56 DAA across all locations suggests that humic silica creates long-term beneficial changes in soil phosphorus dynamics. The increasing HSD values from 3.53 to 8.29 over time indicate that treatment differences become more pronounced with extended incubation, reflecting the cumulative effects of humic silica on soil phosphorus transformation processes.

### 3.3. Correlation Between Observation Parameters

The correlation analysis results show several important relationships between observation parameters. Based on Table 6, there are negative correlations between soil pH and various soil fertility parameters after the addition of humic silica, such as cation exchange capacity (CEC), total nitrogen total nitrogen (total-N), and available phosphorus (available-P). The negative correlation between pH and CEC (-0.8528) indicates that an increase in soil pH can decrease cation exchange capacity. This may be due to reduced negative charges on soil colloids at higher pH, which play a role in cation exchange. High cation exchange capacity is important for soil fertility because it allows soil to retain and provide nutrient cations for plants (Mustaqim *et al*., 2024).

Table 5. Results of correlation analysis between observation parameters

| | pH | CEC | Total-N | Available-P |
|---|---|---|---|---|
| **pH** | 1 | | | |
| **CEC** | -0.8528 | 1 | | |
| **Total-N** | -0.9165 | 0.8918 | 1 | |
| **Available-P** | -0.8429 | 0.8217 | 0.9581 | 1 |

The very strong negative correlation between soil pH and total-N (-0.9165) shows that an increase in soil pH tends to be followed by a decrease in total-N content. This can occur because at higher pH, the nitrification process increases, converting ammonium to nitrate, which is more easily leached from the soil. Additionally, the negative relationship between soil pH and available-P (-0.8429) shows that increasing pH can reduce phosphorus availability in soil. At higher pH, phosphorus tends to form insoluble compounds, making it less available to plants (Suryokusumo *et al*., 2021). The high positive correlation between total-N and available-P (0.9581) indicates that an increase in total nitrogen corresponds with an increase in phosphorus availability, possibly due to the mineralization process of organic matter that releases both of these nutrients (Bahagia *et al.,* 2022).

### 3.4. Influence of Industry Type on Soil Amendment Effectiveness

The application of silica humate as a soil amendment shows varied responses across three different industrial locations, reflecting the complexity of interactions between soil amendments, initial soil characteristics, and types of industrial pollutants. At the pharmaceutical industry site, soil pH showed optimal response at doses of 10-20 kg/ha, consistent with research by Xu *et al*. (2021) showing that humates can help stabilize soil pH. Aprilia *et al*. (2024) stated that humic acid application can increase soil pH because $H^+$ ions in the soil are bound by the OH activity from carboxyl (-COOH) and hydroxyl groups (-OH). Research by Yohana *et al*. (2013) also showed that silicon from rice husk ash is capable of releasing OH- ions into solution, which contributes to increasing soil pH. The decrease of pH can be caused by the gradual release of carboxyl groups (-COOH) (Amoah-Antwi *et al*., 2022). When added to soil, humic acid can release protons ($H^+$) which directly lower soil pH (Tan, 2014). As a result, pH stability can be controlled by silica humate. The decrease in CEC aligns with the increasing doses at 56 DAA, indicating complex interactions between silica humate and other soil components. During the incubation period, soil micro-organisms produce organic acids due to decomposition of organic matter. These acids can temporarily lower soil pH, causing stronger binding of $H^+$ ions to cation exchange sites, which significantly reduces soil CEC (Rashmi *et al*., 2023).

The linear increase in N-total with dose demonstrates the potential of silica humate to improve nitrogen availability, which may be related to the stimulation of soil microbial activity (Meng *et al*., 2017). Silica application effectively increases soil pH and the availability of several nutrients essential for plants, including plant-available N (nitrate, $NO_3$) due to the presence of silanol and siloxane groups that allow $NH_4^+$ to fill the pore spaces and surface of silica (Rahayu *et al*., 2022; Coasne *et al*., 2010).

At the animal feed industry site, doses of 20-30 kg/ha showed an optimal point for silica humate application. This aligns with findings by Ampong *et al*. (2022) on the non-linear effects of humic materials on soil properties. High CEC and decreased total N at 56 DAA indicate complex dynamics, influenced by interactions between silica humate and organic residues from the animal feed industry.

The paper industry site displayed different response patterns, with consistent pH increases up to an optimal dose of 30-40 kg/ha. This indicates different buffer capacities. Small but consistent increases in total N and significant increases in available P at high doses indicate the potential of silica humate to improve soil fertility, even in environments that may be contaminated with paper industry chemicals.

These variations in response affirm the importance of site-specific approaches in soil amendment applications. The effectiveness of silica humate depends not only on its dosage but is also strongly influenced by initial soil characteristics and types of industrial pollutants. These results align with Mystrioti & Papassiopi (2024) who emphasize the need for tailored remediation strategies for industrially contaminated soils.

## 4. CONCLUSION AND RECOMENDATIONS

Research results show that silica humate was effective in improving the quality of paddy soils contaminated with industrial waste. On soil contaminated by paper industry waste, application of 40 kg/ha significantly increased soil pH, total-N, and phosphorus availability. At doses of 10-20 kg/ha, silica humate were sufficient to increase CEC and phosphorus availability of soil contaminated with wastes from animal feed and pharmaceutical industries. Overall, the optimal silica humate dose recommended based on this research is 10 to 40 kg/ha, depending on the type of industrial contamination and initial soil conditions. Addressing the impact of industrial waste pollution on agriculture requires stricter regulations to ensure industry involvement in the rehabilitation of affected agricultural land. Collaboration between industry, government, and farmers can be facilitated through funding and environmental responsibility programs that support sustainable remediation, ensuring the balance between industrial activities and environmental sustainability can be maintained. Further research should extend the observation period beyond 56 DAA to understand the long-term effects of silica humate on soil properties; assess changes in soil microbial communities over time after silica humate application; and conduct plant growth tests to evaluate the effectiveness of silica humate in improving plant productivity in industrially contaminated soils.

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