JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(10), 238–251
https://doi.org/10.12911/22998993/205825
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.05.16
Accepted: 2025.07.15
Published: 2025.07.22

Optimizing aquaculture sustainability: Synergistic role of bio-silica fertilization and soil remediation in improving water quality and plankton productivity in acid sulfate soil

Nur Asia Umar[1*], Muh. Hatta[2], Agustin Rustam[3], Sutia Budi[1], Tarunamulia[4], Kamariah[4]

[1] Aquaculture Study Program, Faculty of Agriculture, Bosowa University, Makassar, 90231, Indonesia
[2] Marine Science Study Program, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[3] Research Centre for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency Bogor, 16911, Indonesia
[4] Research Center for Fisheries, National Reseach and Innovation Agency, Bogor, 16911, Indonesia
* Corresponding author's e-mail: nurasia.umar@universitasbosowa.ac.id

ABSTRACT

Acid sulfate soils pose ongoing obstacles in sustainable aquaculture, primarily due to their high acidity and elevated levels of toxic metals that deteriorate water quality. This study investigated the potential of bio-silica fertilization and soil remediation to improve soil and water conditions and promote plankton growth in such acidic environments. A factorial experimental design was used to evaluate both individual and combined effects of these interventions on water quality parameters and plankton diversity. Parameters were systematically monitored, including pH, toxic metal concentrations, and nutrient availability. Data were analyzed using Analysis of Variance (ANOVA), with significant differences among treatments determined at $p < 0.05$ using Duncan's Multiple Range Test. Pearson's correlation analysis was employed to examine relationships among soil and water quality, while hierarchical clustering was performed to classify plankton species based on abundance profiles. Results demonstrated that the integrated application of bio-silica and soil remediation significantly increased soil pH, reduced toxic metal levels, and enhanced nutrient bioavailability. These improvements contributed to better water quality and higher plankton abundance. In particular, the growth of diatom species such as *Nitzschia* sp. and *Skeletonema* sp. played a crucial role in supporting zooplankton populations and fostering ecosystem stability. Correlation analysis and hierarchical clustering confirmed the differential responses of plankton functional groups, with diatoms emerging as key bioindicators of treatment efficacy. The study concludes that the combination of bio-silica fertilization and soil remediation offers a promising, sustainable strategy for restoring aquaculture systems impacted by acid sulfate soils. Further research is recommended to explore the long-term ecological effects of these methods across different aquaculture environments.

Keywords: bio-silica fertilization, degradation, bioremediation, aquaculture sustainability, acid sulfate.

INTRODUCTION

Acid sulfate soils pose critical challenges to the sustainability of aquaculture systems, particularly in tropical regions. Characterized by extreme acidity and high concentrations of toxic metals such as iron and aluminum, these soils severely degrade water quality, disrupt nutrient dynamics, and impair the survival and growth of aquatic organisms (Asif, 2025). The resulting environmental stress significantly limits ecosystem productivity and threatens the viability of aquaculture operations. In countries like Indonesia, where aquaculture drives economic growth and food security, the degradation caused by acid sulfate soils represents a formidable barrier to sectoral development. Therefore, effective soil acidity and toxic metal accumulation management is imperative to support resilient and sustainable aquaculture practices, ensuring both ecological stability and socio-economic benefits (Michael, 2020; Mehmood et al., 2023; Zhou et al., 2024).

Research has documented the negative impacts of acid sulfate soils on aquaculture ecosystems. These soils contribute to water quality degradation, characterized by low pH and elevated levels of toxic metals such as iron and aluminum, diminishing aquatic biodiversity and productivity (Hasnawi et al., 2020; Hidayat and Fahmi, 2020). Conventional remediation techniques, such as liming, have been employed to mitigate these issues; however, they often fail to address soil acidity and nutrient deficiencies (Imanudin et al., 2021; Roveda et al., 2024). Recent innovations have explored alternative solutions, including the application of agricultural byproducts like bio-silica derived from rice husk ash. These materials have shown promise in improving nutrient availability and promoting the growth of beneficial plankton, which are essential for maintaining ecosystem balance (Bhattacharjya et al., 2020; Hatta et al., 2022).

Diatoms, such *as Nitzschia* sp. and *Skeletonema* sp., are widely recognized as essential components of aquatic food webs, playing a critical role in nutrient cycling and contributing to water quality enhancement. Silica supplementation has been shown to stimulate diatom growth, thereby supporting overall aquatic productivity and promoting ecosystem health (Umar et al., 2024; Tafdrian et al., 2024). In parallel, soil remediation strategies, including controlled oxidation, washing, and amendment techniques, have effectively reduced soil acidity and toxic metal accumulation (Lee et al., 2024; Roveda et al., 2024; Zhou et al., 2024). The integrated application of bio-silica fertilizers alongside soil remediation presents a promising strategy for achieving sustainable aquaculture while minimizing economic and environmental costs (Zhou et al., 2024). However, limited research has explored the synergistic effects of combining bio-silica fertilization with soil remediation in acid sulfate soils. While the individual benefits of these interventions are well-documented, their combined impact on aquaculture productivity and ecosystem stability remains underexplored, particularly regarding soil-water-plankton interactions. In addition, the role of diatoms, important microscopic algae that help recycle nutrients and maintain ecosystem balance, has not been fully explored. It is still unclear how bio-silica and remediation treatments influence diatom populations and their impact on overall aquaculture ecosystem health. Therefore, this study aims to investigate how combining bio-silica fertilization with soil remediation can improve soil and water quality, increase plankton abundance, and support sustainable aquaculture in acid sulfate soils. By addressing these gaps, this research will contribute to developing affordable and eco-friendly solutions for aquaculture practices in regions affected by soil acidity.

MATERIALS AND METHODS

This study used a rectangular aquarium with a water capacity of approximately 50 liters. The aquarium was placed within a transparent plastic enclosure to allow adequate light penetration, supporting photosynthesis for phytoplankton and benthic algae. Acid sulfate soil was added to fill one-third of the aquarium's vertical height at the base. Seawater used in the experiment was sourced from the Marana Subdistrict, Maros Regency, and filtered through a 0.5 μm filter to remove impurities. Bio-silica fertilizer was synthesized from rice husk ash, containing silica concentrations ranging from 15% to 20%, with 1 kg of rice husk used as the raw material.

Experimental design

The experiment followed a completely randomized design (CRD) in a factorial arrangement with two factors at two levels each. Factor A: Soil Remediation (A0 = without remediation, A1 = with remediation). Factor B: Bio-Silica Fertilization (B0 = without bio-silica, B1 = with bio-silica)

Acid sulfate soil was characterized in situ using pHF, pHFOX, and redox potential measurements (Ahern et al., 2004). Further analysis was conducted at the BRPBAP3 soil laboratory to determine key soil parameters and guide liming and fertilization requirements. The soil was air-dried for seven days for remediation until cracks and iron oxide appeared on the surface. The soil was then submerged in water for 24 hours and rinsed twice. Lime dosage for acidity neutralization was calculated using methods from Boyd (1990) and SPOCAS (Ahern et al., 2004). After liming, the soil was left for seven days to allow complete reaction before fertilization.

Fertilization involved adding filtered brackish water to a depth of 5 cm, allowing evaporation until near desiccation. Water was then replenished to a height of 10 cm, followed by uniform application of Urea, TSP, and bio-silica fertilizers. The nutrient ratios followed an N: P: Si proportion of approximately 16:1:15 (N: Si = 1:1). Bio-silica application ranged from 150–200 mg/L, adjusted based on the initial silica content in the seawater.

Phytoplankton proliferation was allowed for five days, indicated by water discoloration. Afterwards, each aquarium was filled with up to two-thirds of its height with seawater. The diatom *Skeletonema costatum* was introduced as an inoculum to promote uniform plankton growth.

Variables measurement

Soil sampling was conducted at the experiment's beginning and end to assess treatment effects over time. Water quality parameters and plankton abundance were measured on five occasions: the first measurement on day six, followed by subsequent measurements every three days. Initial measurements were taken prior to treatment application to establish baseline values for all variables. Characteristics of acidic sulphate soil and water quality variables before treatment of biosilica and soil remediation are presented in Table 1 and 2.

The soil quality parameters measured included: field pH (pHF), peroxide pH (pHFOX), differential pHF-pHFOX, redox potential (mV), salinity potential (Sp, %), KCl-extractable sulfur (SKCl, %), soluble sulfur (SPOS, %), total potential acidity (TPA, Mol H^+/ton), total actual acidity (TAA, Mol H^+/ton), total sulfur acidity (TSA, Mol H^+/ton), total nitrogen (N-total, %), phosphate (PO_4, ppm), organic carbon (C-organic, %), iron (Fe, ppm), aluminum (Al, ppm), and pyrite content (%). Water quality parameters assessed included pH, temperature, salinity, ammonia nitrogen (NH_3-N), nitrate (NO_3-N), nitrite (NO_2-N), phosphate (PO_4), and total organic matter (TOM), following standardized methods (Walter, 2011; APHA, 2005). Silica concentration (SiO_2) was determined using atomic absorption spectroscopy (AAS).

Data analysis

Soil quality data were analyzed descriptively and presented as mean values with corresponding standard deviations in tabular format. To evaluate the effects of soil remediation and biosilica fertilization on water quality and plankton abundance, the data were subjected to Analysis of Variance (ANOVA). Differences among treatment groups were further analyzed using Duncan's Multiple Range Test at a 5% confidence level ($p < 0.05$) using IBM SPSS Statistics version 25. Pearson's correlation analysis was conducted to explore the interrelationships among parameters in soil and water quality. Furthermore, hierarchical clustering analysis was

Table 1. Characteristics of acidic sulphate soil quality variables before treatment of biosilica and soil remediation

Variables	Value	Field Indicators
pH_F	6.72	Mangrove. swamp fern. and green kyllinga. Iron rust on the edge of the pond
pH_{FOX}	2.06	
pH_F-pH_{FOX}	4.67	
Redox potential (mV)	-40.43	
S_p (%)	1.63	
S_{KCl} (%)	0.33	
S_{POS} (%)	1.29	
TPA (mol H^+/ton)	342.13	
TAA (mol H^+/ton)	0.00	
TSA (mol H^+/ton)	342.13	
N-total (%)	0.23	
PO_4 (ppm)	537.69	
C-organic (%)	3.90	
Fe (ppm)	5,314.83	
Al (ppm)	446.83	
Pyrite (%)	1.53	

Table 2. Characteristics of water quality in sulfuric acid soils before treatment of biosilicates and soil remediation

Variables	Value
Temperature (°C)	26.80
Dissolved oxygen (mg/L)	3.03
Salinity (ppt)	33.53
pH	8.01
NH_3-N (mg/L)	0.19
PO_4-N (mg/L)	0.004
NO_2-N (mg/L)	0.001
NO_3-N (mg/L)	0.19
Dissolved organic matter (mg/L)	150.23
SiO_2 (mg/L)	7.98

performed to visualize species grouping patterns based on abundance profiles. Both correlation matrices and dendrograms were generated using R Studio version 4.2.2 with the packages "corrplot" for correlation analysis and "stats" (hclust, dist) for clustering procedures.

RESULTS AND DISCUSSION

Soil and water quality after treatment of soil remediation and bio-silica fertilization

The acid sulfate soil exhibited persistent acidity, particularly without any treatment or bio-silica fertilization (A0B0). Under these untreated conditions, the soil quality remained essentially unchanged from its initial degraded state and, in some cases, deteriorated further (Table 3).

In contrast, the application of bio-silica fertilization alone (A0B1), soil remediation alone (A1B0), or a combination of both (A1B1) led to noticeable improvements in soil quality parameters when compared to baseline conditions. However, these improvements did not extend to organic carbon and total nitrogen levels, which remained relatively stable across treatments. Initially, the acid sulfate soils demonstrated severe acidity, with a pHF-pHFOX differential exceeding 3, alongside elevated concentrations of iron and aluminum and low phosphate availability. These findings aligned with Hasnawi et al. (2020), highlighting the detrimental impacts of toxic metals and nutrient deficiencies on aquaculture ecosystems. Although moderate levels of organic carbon and nitrogen were present, they were insufficient to mitigate soil acidity or improve nutrient dynamics.

Following treatment, substantial improvements in soil quality were observed, particularly under the combined treatment of remediation and bio-silica fertilization (A1B1). This integrated approach effectively reduced soil acidity and enhanced nutrient availability. Applying bio-silica notably increased soil silica concentrations, supporting diatom growth and promoting nutrient cycling (Hasan et al., 2022; Tafdrian et al., 2024; Zhou et al., 2024).

Soil remediation through liming and washing effectively reduced acidity and lowered concentrations of toxic metals such as iron and aluminum. These results agree with studies by Vehanen et al. (2022) and Mehmood (2023), emphasizing the necessity of acidity neutralization for supporting aquaculture productivity. This study's remediation alone (A1B0) improved pHF values and reduced pyrite and iron concentrations, demonstrating its beneficial impact. However, adding bio-silica fertilizer (A1B1) yielded even greater improvements, likely due to its role in stabilizing soil nutrients. Silica enhances soil structure, facilitates phosphorus retention, and increases the availability of essential nutrients for aquatic organisms (Huang et al., 2022). The combined treatment of soil remediation and bio-silica fertilization emerged as the most effective strategy, offering synergistic benefits in reducing soil toxicity and optimizing nutrient dynamics. This integrated approach is particularly valuable for managing total suspended matter (TSM) and improving overall ecosystem health, supporting sustainable aquaculture practices.

The initial assessment of water quality in sulfuric-acid-dominated soils indicated a moderate potential for aquaculture but also revealed several critical limitations (Table 4).

The recorded temperature of 26.8 °C fell within the optimal range for many aquaculture species, suggesting that temperature was not a primary stressor in this study. This observation aligns with Hasnawi et al. (2020), who highlighted the supportive role of temperature in aquaculture systems affected by acidic conditions, despite nutrient deficiencies posing a more significant constraint. However, dissolved oxygen (DO) levels were low at 3.03 mg/L, approaching hypoxic conditions that can stress aquatic organisms. This finding is consistent with Yusoff et al. (2024), who reported oxygen depletion in acidic

Table 3. The soil quality of acidic sulfate soil after soil remediation treatment and bio-silica fertilization at the end of the study

Variables	Treatments			
	A0B0	A0B1	A1B0	A1B1
pH_F	6.89±0.41	6.96±0.20	7.22±0.21	6.97±0.29
pH_{FOX}	2.56±0.43	2.77±0.47	2.89±0.36	3.08±0.21
pH_F-pH_{FOX}	4.33±0.44	4.19±0.41	4.32±0.18	3.89±0.14
Redox potential (mV)	-40.60±9.47	-45.80±12.05	-34.67±8.42	-18.13±4.31
S_p (%)	1.53±0.04	1.52±0.006	1.53±0.04	1.49±0.05
S_{KCl} (%)	0.23±0.02	0.26±0.003	0.25±0.007	0.25±0.03
S_{POS} (%)	1.29±0.06	1.26±0.003	1.28±0.01	1.24±0.07
TPA (mol H^+/ton)	354.67±7.97	281.67±16.27	259.17±34.80	257.83±23.69
TAA (mol H^+/ton)	0.00	0.00	0.00	0.00
TSA (mol H^+/ton)	354.67±7.97	281.67±16.27	259.17±34.80	257.83±23.69
N-total (%)	0.25±0.01	0.27±0.002	0.25±0.001	0.28±0.00
PO_4 (ppm)	118.99±4.92	121.00±9.70	102.53±6.06	116.92±13.83
C-organic (%)	5.57±0.25	5.77±0.56	5.86±0.86	6.73±1.14
Fe (ppm)	5,373.17±71.66	5,207.50±341.30	4,945.17±250.41	4,881.83±293.35
Al (ppm)	444.33±40.19	403.67±26.58	396.17±33.04	388.33±31.47
Pyrite (%)	1.58±0.04	1.26±0.007	1.16±0.16	1.15±0.11

Note: A0B0 – no remediation and no biosilica fertilization – control; A0B1 – no remediation with bio-silica fertilization; A1B0 – remediation without bio-silica fertilization; A1B1 – remediation witht bio-silica fertilization.

Table 4. Water quality of acidic sulfate soil treated with soil remediation and bio-silica fertilization

Variable	Treatment			
	A0B0	A0B1	A1B0	A1B1
Temperature (°C)	27.59 ±0.31^a	27.81 ±0.43^a	28.73 ±1.06^a	27.24 ±0.48^a
Dissolved oxygen (mg/L)	3.09 ± 1.70^a	3.01 ± 1.20^a	2.87 ± 0.06^a	3.00 ± 0.31^a
Salinity (ppt)	33.38±0.10^a	33.40±0.06^a	33.39±0.10^a	33.13±0.10^a
pH	7.98±0.10^a	8.05±0.050^a	8.03±0.03^a	7.99±0.08^a
NH_3-N (mg/L)	0.5508±0.0235^a	0.5852±0.0132^b	0.6763±0.0151^a	0.5211±0.0762^a
PO_4-N (mg/L)	0.0063±0.0019^a	0.0056±0.0020^a	0.0103±0.0307^b	0.0110±0.0051^a
NO_2-N (mg/L)	0.009±0.0025^a	0.0044±0.0010^c	0.0227±0.0047^b	0.0103±0.0052^a
NO_3-N (mg/L)	0.0802±0.019^a	0.0701±0.078^c	0.1868±0.0837^b	0.0948±0.0167^a
Dissolved organic matter (mg/L)	157.78±1.52^a	162.75±7.46^a	165.11±5.65^b	171.69±6.27^a
SiO_2 (mg/L)	0.5188±0.0804^a	4.3769±0.194^c	0.1022±0.1770^b	10.4152±0.1735^d

Note: Data are presented as mean ± standard deviation (SD). A0B0 – no remediation and no biosilica fertilization – control; A0B1 – no remediation with bio-silica fertilization; A1B0 – remediation without bio-silica fertilization; A1B1 – remediation witht bio-silica fertilization. Different lowercase superscript letters within the same row indicate statistically significant differences among treatments at $p < 0.05$, as determined by Duncan's multiple range test.

ecosystems due to organic matter decomposition. The salinity level of 33.53 ppt indicated a brackish environment, suitable for moderately tolerant species (Tafdrian et al., 2024).

The chemical composition of the water revealed imbalances in key nutrients. Although the pH was slightly alkaline (8.01), this could be attributed to buffering effects from the water source or management interventions, as suggested by Hidayat and Fahmi (2020). Ammonia concentrations (NH_3-N) measured at 0.192 mg/L were moderate but could inhibit sensitive species (Bayramova et al., 2023). Phosphate (PO_4-P) levels were critically low at 0.004 mg/L, indicating phosphorus limitation that restricts phytoplankton growth, particularly for diatoms (Egge and Aksnes, 1992; Bayramova et al., 2023). Nitrate (NO_3-N) levels were adequate at 0.197 mg/L, while nitrite (NO_2-N) was negligible (0.001 mg/L), posing no toxicity concerns. Dissolved organic matter (DOM) was high at 150.23 mg/L, suggesting active organic breakdown that could further deplete oxygen but contribute to nutrient cycling (Roveda, 2024). Silica (SiO2) concentrations of 7.98 mg/L were sufficient for some diatom growth but below optimal levels for dominance (Egge and Aksnes, 1992; Xiao et al., 2019). These findings underscore the need for targeted interventions to address nutrient deficiencies, improve oxygenation, and enhance silica availability. Previous studies have shown that bio-silica fertilization and soil remediation can effectively improve aquaculture systems' water quality and plankton diversity (Mehmood et al., 2023; Tafdrian et al., 2024).

Water quality parameters such as temperature, DO, salinity, and pH remained relatively stable across treatments (Table 4). This stability was attributed to controlled experimental conditions, including freshwater supplementation and aeration. Nevertheless, salinity increased over time due to evaporation. Ammonia levels varied among treatments. The highest concentrations were observed in the remediation-only treatment (A1B0), while the combination of remediation and bio-silica (A1B1) resulted in the lowest ammonia levels (Figure 1).

Statistical analysis revealed significant differences ($P < 0.05$), suggesting that bio-silica fertilization effectively reduced ammonia accumulation, likely by enhancing nutrient retention and microbial balance (Akbarurrasyid et al., 2022). While temperature and salinity remained stable, ammonia reduction was most effective in bio-silica treatments. This supports Yusoff's (2024) findings on bio-silica's role in improving nitrogen dynamics. Though generally low, phosphate levels increased slightly in remediation treatments, likely due to decreased phosphate binding by iron and aluminum post-washing, as reported by Vehanen et al. (2022). Managing ammonia toxicity is crucial for maintaining a healthy aquaculture environment (Boyd, 2014).

Nitrite levels, part of the nitrogen cycle, peaked on day 12 in the A1B0 treatment, coinciding with a temperature rise. In contrast, the A0B1 treatment maintained minimal nitrite levels. Similarly, nitrate levels peaked in A1B0 on day 12 and were lowest in A0B1 (Figure 1F). These trends highlight the importance of microbial activity in nitrogen transformation processes, influenced by temperature and treatment type (Akbarurrasyid et al., 2022). Phosphate levels followed a similar pattern, peaking on day 12 in A1B0 and declining thereafter, suggesting the need for follow-up fertilization before day 15 to sustain phytoplankton productivity. Organic matter levels were higher in A1B0 than in the control, likely due to enhanced plankton biomass (Figure 1). While organic matter is vital for nutrient cycling, excessive accumulation can lower DO levels, posing risks to aquatic life (Silva et al., 2025). The addition of bio-silica supported diatom proliferation and enhanced silica availability, critical for plankton growth (Kamariah et al., 2023). The study also found that bio-silica treatments reduced nitrite concentrations, indicating their stabilizing effect on microbial processes and nitrogen dynamics (Akbarurrasyid et al., 2022). The highest nitrate levels were observed in A1B0, demonstrating the role of remediation in facilitating nitrogen cycling (Wang et al., 2022). These findings emphasize the importance of integrated nutrient management strategies to optimize nitrogen availability while minimizing toxicity risks.

Plankton abundance

The plankton community analysis revealed that *Nitzschia* sp. was the most dominant species, particularly in the soil remediation treatment without bio-silica fertilization (A1B0), followed by *Skeletonema* sp. (Table 5).

The phytoplankton and zooplankton growth patterns in acidic sulfate soil media water treated with soil remediation and bio-silica fertilizer are clearly illustrated in Figure 2 and 3.

Both species were also abundant in the combined treatment of soil remediation and bio-silica fertilization (A1B1). In contrast, *Navicula* sp., *Oscillatoria* sp., and *Pseudonitzschia* sp. were consistently observed in lower abundances across all treatments, regardless of bio-silica application. Diatom populations were highest in the A1B1 treatment, with *Nitzschia* sp. as the prevailing species. This result aligns with prior studies demonstrating that silica availability is crucial for diatom growth and overall ecosystem function (Egge and Aksnes, 1992; Lü et al., 2020; Saxena et al., 2022). Diatoms require

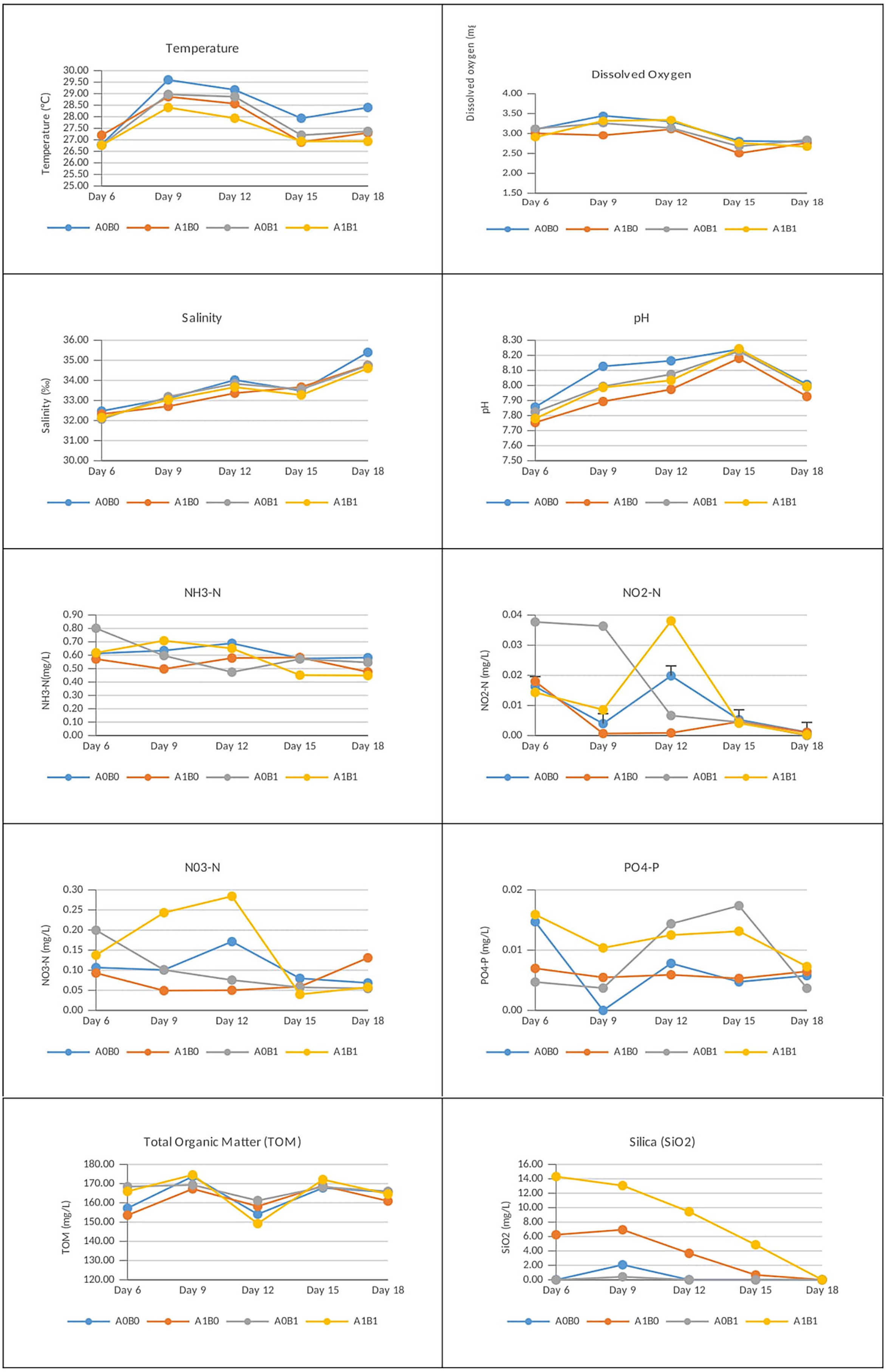

Figure 1. Changes in water quality of acidic sulfate soil treated with soil remediation and bio-silica fertilization

Table 5. Abundance of phytoplankton and zooplankton on acidic sulfate soils treated with remediation and fertilization

Types of plankton	Abundance of plankton (ind/L)			
	A0B0	A0B1	A1B0	A1B1
Phytoplankton				
Navicula sp.	3	5	2	2
Oscillatoria sp.	5	7	0	0
Nitzschia sp.	97	14	837	115
Pseudonitzschia sp.	8	1	1	0
Prorocentrum sp.	5	1	14	1
Skeletonema sp.	78	41	291	172
Zooplankton				
Tintinopsis sp.	1	1	0	0
Copepoda sp.	0	1	0	2
Euplotes sp.	1	2	0	0
Apocyclops sp.	1	0	0	0

Note: A0B0 – no remediation and no biosilica fertilization – control; A0B1 – no remediation with bio-silica fertilization; A1B0 – remediation without bio-silica fertilization; A1B1 – remediation witht bio-silica fertilization.

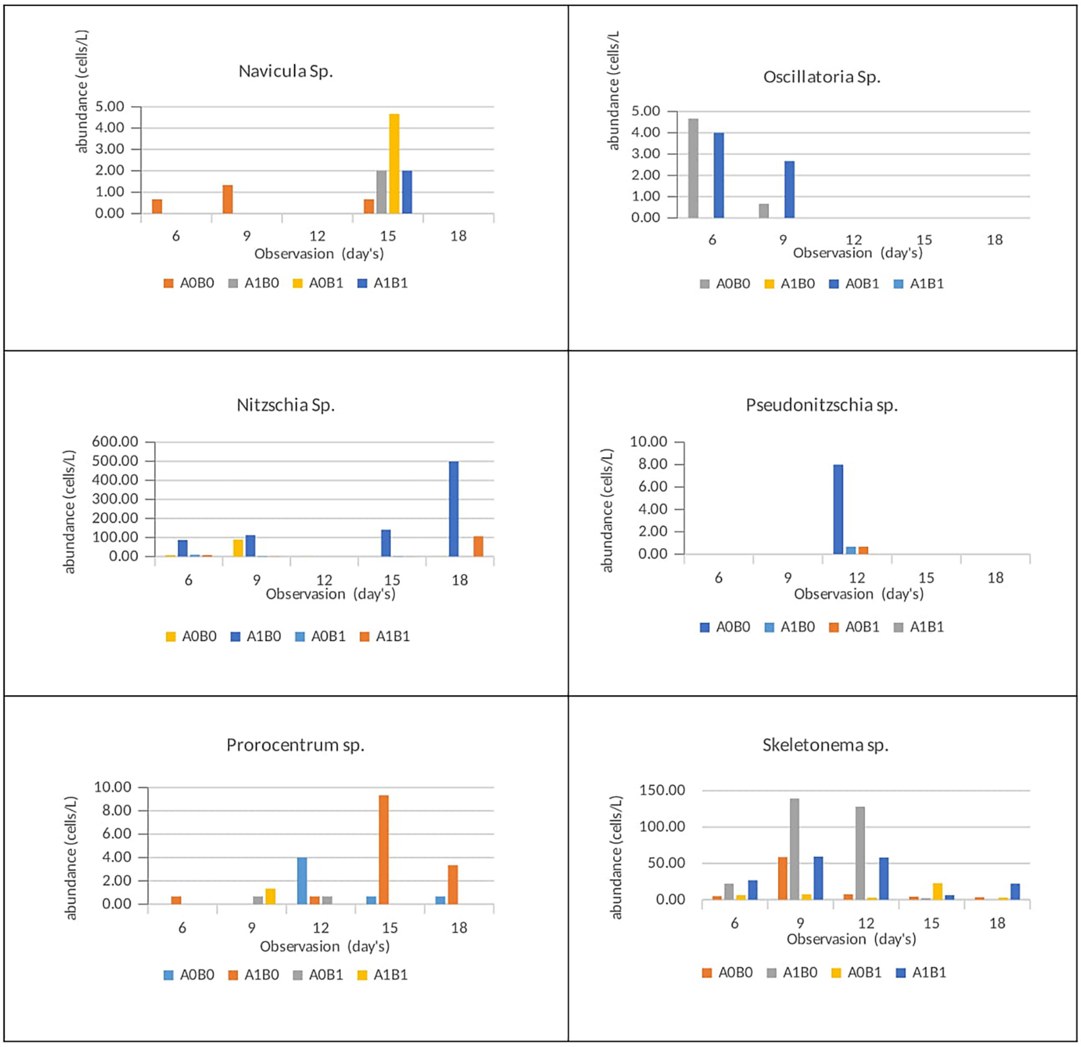

Figure 2. Phytoplankton growth patterns in acidic sulfate soil media water treated with soil remediation and bio-silica fertilizer

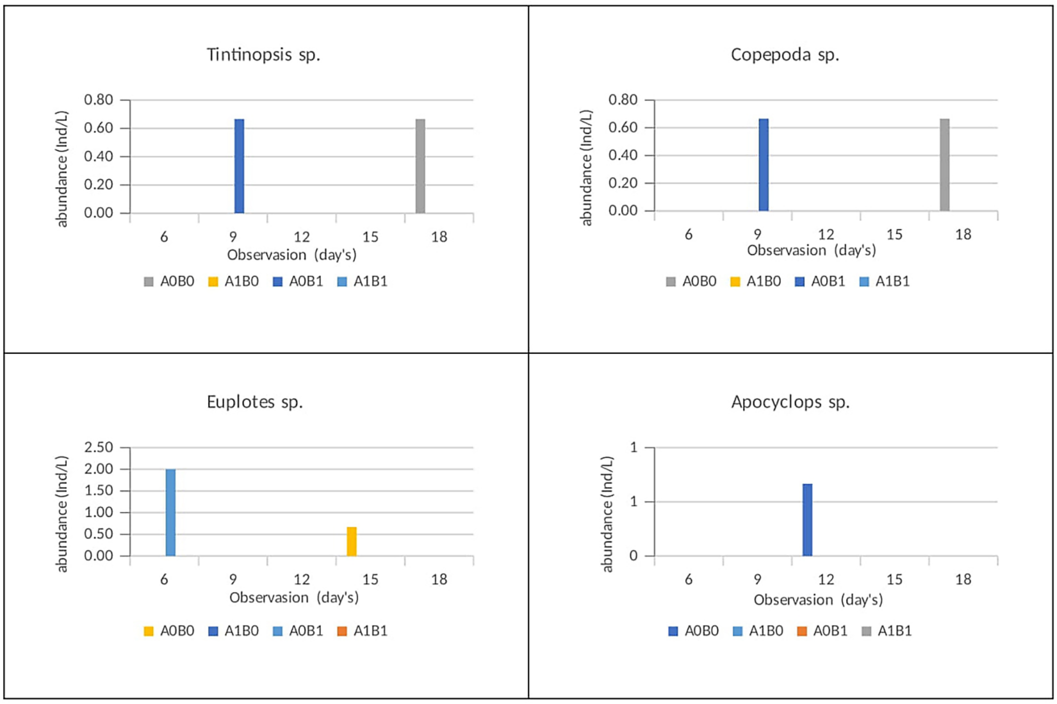

Figure 3. Zooplankton growth patterns in acidic sulfate soil media treated with soil remediation and bio-silica fertilizer

silica for frustule (cell wall) formation, and their growth rate is closely tied to silica uptake and deposition, which is essential for their cell cycle progression (Zepernick et al., 2021; Umar et al., 2024; Saxena et al., 2022).

The study on the 15th day of observations indicated that Navicula sp. was present in all treatments, albeit in low quantities. This suggests that while remediation efforts improved general plankton diversity, particular species remained less competitive under the existing environmental conditions. Various remediation techniques have been employed to address the challenges of acid sulfate soils in aquaculture (Ahmad et al., 2022; Sarangi et al., 2022). Liming remains a widely used approach to neutralize soil acidity, while hydrological interventions, such as water table management using weirs and modified floodgates, have effectively prevented pyrite oxidation (Indraratna et al., 2011). Innovative methods, including permeable reactive barriers composed of recycled concrete, have shown promise in neutralizing acidic groundwater (Abdel Rehman et al., 2023). For aquaculture ponds, remediation strategies like forced oxidation, flooding, and flushing have enhanced soil pH and nutrient availability (Zhou et al., 2024; Nair et al., 2025). However, despite the widespread application of liming, its effectiveness is sometimes limited. For instance, limestone drain systems used for acid sulfate soil remediation have encountered operational issues related to aluminum accumulation (Mafane et al., 2025). Moreover, adding organic matter has been explored as an alternative strategy to reduce soil acidity and inhibit sulfidic soil oxidation under varying moisture conditions (Afzal et al., 2024).

Correlation among parameters on soil quality and water quality

The correlation analysis in Figure 4 revealed significant improvements in acidic sulfate soil quality following remediation and bio-silica application, demonstrated by strong interrelations among pH, redox potential, sulfur fractions, metals, and nutrients. Increases in pH_{FOX} were strongly associated with reductions in Fe (r = -0.96), Al (r = -0.93), and S_{POS} (r = -0.95), reflecting effective mitigation of soil acidity and metal toxicity. Redox potential showed a positive correlation with S_{KCl} (r = 0.93).

However, it was negatively associated with pH_F (r = -0.78) and S_{POS} (r = -0.63), indicating enhanced oxidation processes facilitated by bio-silica that promote the transformation of sulfides into more stable sulfate forms. Despite these

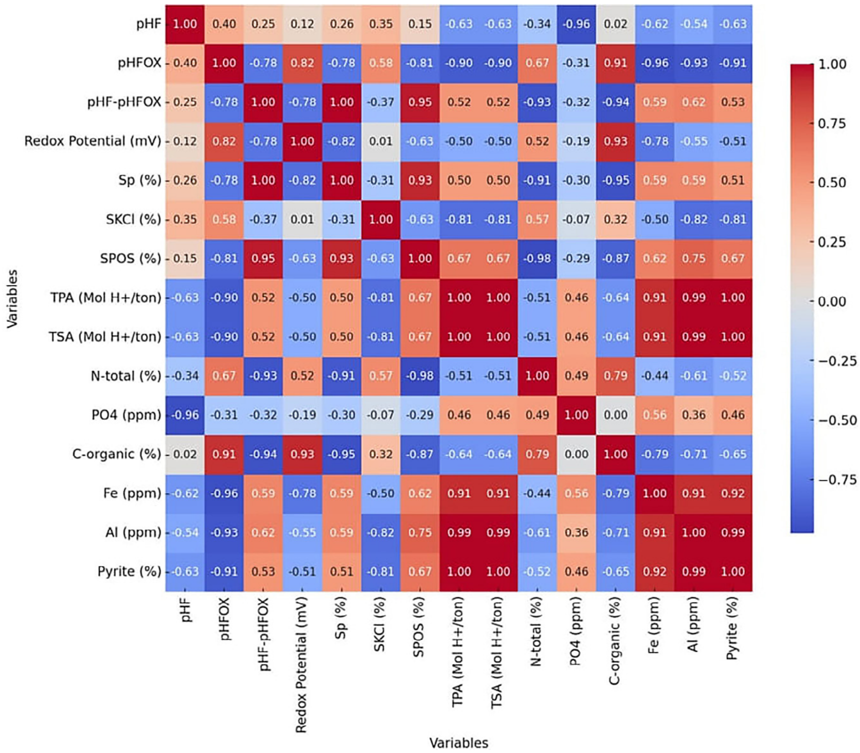

Figure 4. Correlation among parameters on soil quality

improvements, TPA and TSA remained highly correlated with Fe, Al, and Pyrite (r > 0.90), suggesting that residual sulfide minerals continue contributing to latent acidity potential. Organic carbon (C-organic) positively correlated with pH_{FOX} and redox potential (r = 0.91–0.93), underscoring its buffering role in stabilizing soil conditions through improved aeration and microbial activity. Additionally, N-total exhibited inverse correlations with S_{POS} (r = -0.92) and redox potential (r = -0.93), indicating that nitrogen cycling improved under oxidizing conditions. Though weaker, the correlation between PO_4 and N-total (r = 0.49), alongside its inverse relationship with Fe (r = -0.44), suggests that phosphorus availability also benefited from reduced iron solubility. These patterns confirm that the combined application of soil remediation and bio-silica fertilization significantly improves acidic sulfate soil quality by elevating pH, stabilizing redox conditions, reducing the mobility of iron and aluminum, and enhancing nutrient availability. These findings align with previous studies. Thangavelu et al. (2024) found that silicon fertilizers enhanced redox conditions by accelerating sulfide oxidation. Huang et al. (2024) also highlighted improved nitrogen cycling under better aeration and redox balance. Persistent correlations between sulfide minerals and acidity indicators reflect long-term challenges, as Asif et al. (2025) noted, requiring ongoing management. The persistent influence of residual sulfide minerals indicates that continuous monitoring and long-term management are required to mitigate latent acidity risks and ensure sustainable soil recovery fully.

The correlation analysis (Figure 5) highlights key interdependencies among water quality parameters, elucidating the impacts of soil remediation and bio-silica fertilization on acid sulfate soil-affected aquatic environments. Dissolved oxygen (DO) exhibited strong negative correlations with temperature (r = -0.80), NH_3-N (r = -0.82), and NO_3-N (r = -0.90), indicating that oxygen depletion is closely associated with nutrient accumulation and elevated organic matter activity.

Silica (SiO_2) concentrations positively correlated with dissolved organic matter (r = 0.80), reflecting its role in enhancing microbial activity and supporting organic matter stabilization processes. Conversely, salinity showed inverse correlations with SiO_2 (r = -0.89), DO (r = -0.08), and dissolved organic matter (r = -0.82), suggesting dilution effects linked to remediation interventions. Additionally, strong positive correlations among nitrogenous species, notably between NO_2-N and NO_3-N (r = 0.99), indicate active nitrogen cycling, likely

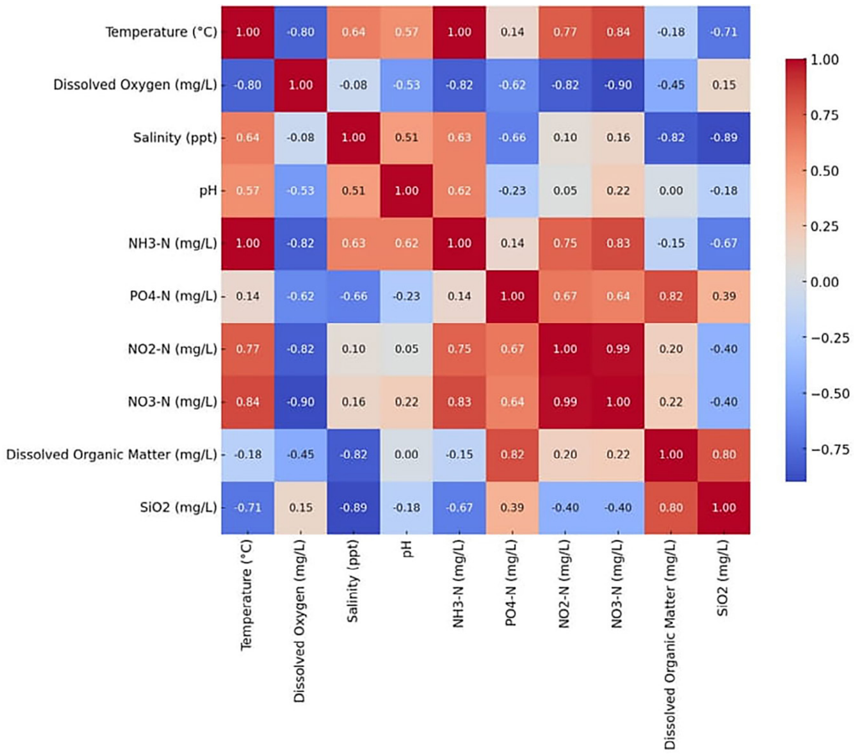

Figure 5. Correlation among parameters on water quality

facilitated by improved redox dynamics. These findings are consistent with previous studies. Mustafa et al. (2024) reported that silicon amendments enhanced microbial-mediated nitrogen cycling and improved water quality in acid sulfate wetlands. Similarly, Khodabandeh et al. (2025) observed that silica application boosted dissolved oxygen levels by stimulating microbial oxidation of reduced sulfur compounds. The inverse relationship between salinity and SiO_2 is also supported by Szklare et al. (2022), highlighting the role of silica in promoting freshwater influx and reducing ionic strength. These patterns confirm that combined remediation and bio-silica strategies effectively modulate biogeochemical processes and improve aquatic environments impacted by acid sulfate soils. These patterns collectively indicated the effectiveness of remediation strategies and bio-silica application in modulating key biogeochemical processes and enhancing overall water quality in acidic sulfate soil environments.

Clustering of plankton species based on abundance patterns across treatments

The dendrogram illustrates the hierarchical clustering of phytoplankton and zooplankton species based on their abundance patterns under soil remediation and bio-silica fertilization treatments. Two distinct clusters are evident as presented in Figure 6.

The first cluster comprises bloom-forming diatoms, *Nitzschia* sp. and *Skeletonema* sp., which exhibit notably higher abundances under silica-enriched conditions, reaching up to 837 and 291 ind/L in the A1B0 treatment, and maintaining substantial populations even with combined treatments. This reflects their ecological preference for elevated silica availability, which supports frustule formation and rapid proliferation in nutrient-enriched environments. The second, broader cluster includes less dominant phytoplankton species (*Navicula* sp., *Oscillatoria* sp., *Pseudonitzschia* sp., *Prorocentrum* sp.) and zooplankton taxa (*Tintinopsis* sp., *Copepoda* sp., *Euplotes* sp., *Apocyclops* sp.), all of which exhibited relatively stable and lower abundance values across treatments, typically ranging from 0 to 14 ind/L. Their aggregation into a single cluster indicates limited responsiveness to silica amendments and remediation efforts, likely due to niche specialization and competitive suppression by dominant diatom species. The clustering threshold, indicated by the red dashed line, clearly separates these functional groups, highlighting the differential ecological responses within

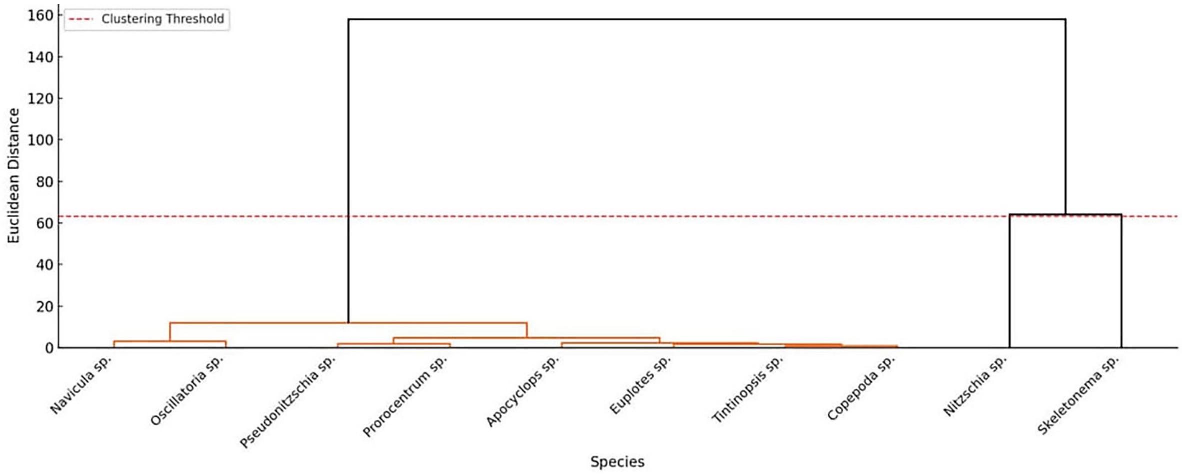

Figure 6. Dendrogram of hierarchical clustering of plankton species based on abundance patterns

the plankton community. These findings align with previous observations by Giri et al. (2022), who reported that diatom blooms, particularly *Nitzschia* and *Skeletonema*, are strongly driven by silica enrichment, often outcompeting other phytoplankton through rapid frustule formation and nutrient assimilation. Similarly, studies by Panwar et al. (2019) demonstrated that bio-silica applications in estuarine systems favored diatom proliferation while exerting minimal impact on zooplankton and cyanobacterial populations, as observed in this study. Overall, this analysis highlights the role of diatoms in mediating ecosystem dynamics in acid sulfate soil-affected waters, while also revealing the resilience of background planktonic species to environmental interventions.

CONCLUSION

This study shows that synergizing bio-silica fertilization with soil remediation effectively improves soil and water quality in areas affected by acid sulfate soils. The integrated treatment raised soil pH, reduced toxic metals (Fe, Al), and enhanced nutrient availability, leading to better water quality and higher plankton productivity. Notably, diatom species such as *Nitzschia* sp. and *Skeletonema* sp. increased significantly, indicating ecosystem recovery. Applying bio-silica fertilizers and remediation strategies has emerged as a practical and sustainable solution to support aquaculture productivity. Further research is needed to evaluate its long-term effectiveness and application on a larger scale.

REFERENCES

1. Abdel Rahman, R. O., El-Kamash, A. M., Hung, Y. T. (2023). Permeable concrete barriers to control water pollution: a review. *Water, 15(21),* 3867. https://doi.org/10.3390/w15213867
2. Afzal, M., Muhammad, S., Tan, D., Kaleem, S., Khattak, A. A., Wang, X.,..., Tan, Z. (2024). The effects of heavy metal pollution on soil nitrogen transformation and rice volatile organic compounds under different water management practices. *Plants*, *13*(6), 871. https://doi.org/10.3390/plants13060871
3. Ahern, C. R., Blunden, B., Sullivan, L. A., McElnea, A.. (2004). Soil sampling, handling, preparation and storage for analysis of dried samples. In Acid sulfate soils laboratory methods guidelines B1-1–5. Indooroopilly, Queensland, Australia.
4. Ahmad, A. L., Chin, J. Y., Harun, M. H. Z. M., Low, S. C. (2022). Environmental impacts and imperative technologies towards sustainable treatment of aquaculture wastewater: A review. *Journal of Water Process Engineering*, *46*, 102553. http://dx.doi.org/10.1016/j.jwpe.2021.102553
5. Akbarurrasyid, M., Prajayati, V. T. F., Nurkamalia, I., Astiyani, W. P., Gunawan, B. I. (2022). Hubungan kualitas air dengan struktur komunitas plankton tambak udang vannamei. *Jurnal Penelitian Sains, 24(2),* 90. https://doi.org/10.56064/jps.v24i2.688
6. APHA. (2005). *Standard Methods for the Examination of Water and Wastewater* (*21st ed.*). American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.
7. Asif, M. R., Ye, B., Ye, C. (2025). Acid sulfate soils: formation, identification, environmental impacts, and sustainable remediation practices. *Environmental Monitoring and Assessment*, *197*(4), 484. https://doi.org/10.1007/s10661-025-13919-5

8. Bayramova, E. M., Bedoshvili, Ye. D. Likhoshway, Ye. V (2023). Molecular and cellular mechanisms of diatom response to environmental changes. *Limnology and Freshwater Biology 2023(1),* 20–30. https://doi.org/10.31951/2658-3518-2023-A-1-20
9. Bhattacharjya, R., Kiran Marella, T., Tiwari, A., Saxena, A., Kumar Singh, P., Mishra, B. (2020). Bioprospecting of marine diatoms Thalassiosira, Skeletonema and Chaetoceros for lipids and other value-added products. *Bioresource Technology, 318,* 124073. https://doi.org/10.1016/j.biortech.2020.124073
10. Boyd, C. E. (1990). *Water quality in ponds for aquaculture*. Alabama, 482.
11. Boyd, C. E. (2014). *Silicon, Diatoms In Aquaculture.* Global Aquaculture Advocate, 39.
12. Egge, J. K., Aksnes, D. L. (1992). Silicate as regulating nutrient in phytoplankton competition. *Marine Ecology Progress Series, 83*(2–3), 281–289. https://doi.org/10.3354/meps083281
13. Giri, T., Goutam, U., Arya, A., Gautam, S. (2022). Effect of nutrients on diatom growth: a review. *Trends in Sciences*, *19*(2), 1752–1752. http://dx.doi.org/10.48048/tis.2022.1752
14. Hasan, J., Chandra Shaha, D., Rani kundu, S., Ahmed, M., Haque, S. M., Haque, F., …, Salam, M. A. (2022). Outwelling of nutrients into the Pasur River estuary from the Sundarbans mangrove creeks. *Heliyon, 8(12),* e12270. https://doi.org/10.1016/j.heliyon.2022.e12270
15. Hasnawi, Utojo, Tarunamulia, Kamariah. (2020). Species composition and individual abundance of plankton in acid sulfate soil brackishwater ponds in Kotabaru Regency, South Kalimantan Province. *IOP Conference Series: Earth and Environmental Science, 564*(1). https://doi.org/10.1088/1755-1315/564/1/012001
16. Hatta, M., Umar, N. A., Rustam, A. (2022). Perbandingan Klorofil-a dan Kelimpahan Plankton di Perairan Pantai Kabupaten Pinrang Provinsi Sulawesi Selatan. *Jurnal Kelautan Nasional*, *17*(1), 37–46.
17. Hidayat, A. R., Fahmi, A. (2020). Impact of Land Reclamation on Acid Sulfate Soil and Its Mitigation. BIO Web of Conferences, 20, 01002. http://dx.doi.org/10.1051/bioconf/20202001002
18. Huang, Y., Li, L., Li, R., Li, B., Wang, Q., Song, K. (2024). Nitrogen cycling and resource recovery from aquaculture wastewater treatment systems: a review. *Environmental Chemistry Letters*, *22*(5), 2467–2482. http://dx.doi.org/10.1007/s10311-024-01763-x
19. Huang, Y., Shen, Y., Zhang, S., Li, Y., Sun, Z. (2022). Characteristics of phytoplankton community structure and indication to water quality in the lake in agricultural Areas, *Frontiers in Environmental Science*, *10*, 1–14. https://doi.org/10.3389/fenvs.2022.833409
20. Imanudin, M. S., Tarunamulia, S., Sammut, J. (2021). Restoration of abandoned shrimp ponds affected by acidic sulfate soils in Southeast Asia. *Sustainable Aquaculture Journal, 20*(3), 159–172.
21. Indraratna, B., Regmi, G. L. D. N., Golab, A. (2011). Geo-environmental approaches for the remediation of acid sulphate soil in low-lying floodplains. *Geo-Frontiers, 856–865*. http://dx.doi.org/10.1061/41165(397)88
22. Kamariah, K., Umar, N. A., Budi, S. (2023). Explorasi rasio optimum silikon dan nitrogen (Si/N) untuk pertumbuhan fitoplankton jenis diatom skeletonema costatum. *Journal of Aquaculture and Environment*, *6*(1), 22–29.
23. Khodabandeh Lu, N., Alamdari, H., Rashedi, H., Yazdian, F., Pourmadadi, M., Rahdar, A., Romanholo Ferreira, L. F. (2025). Photocatalytic Bioreactors in Water Treatment: Mechanisms, Challenges, and Innovations in Microbial Inactivation. *Water, Air, & Soil Pollution*, *236*(5), 1–28. http://dx.doi.org/10.1007/s11270-025-07919-x
24. Lee, H., Sam, K., Coulon, F., De Gisi, S., Notarnicola, M., Labianca, C. (2024). Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review. *Science of the Total Environment, 912*(July 2023), 168769. https://doi.org/10.1016/j.scitotenv.2023.168769
25. Lü, J. J., Zhang, G. T., Zhao, Z. X. (2020). Seawater silicate fertilizer facilitated nitrogen removal via diatom proliferation. *Marine Pollution Bulletin, 157*(May), 111331. https://doi.org/10.1016/j.marpolbul.2020.111331
26. Mafane, D., Ngulube, T., Mphahlele-Makgwane, M. M. (2025). Anaerobic bioremediation of acid mine drainage using sulphate-reducing bacteria: current status, challenges, and future directions. *Sustainability*, *17*(8), 3567. https://doi.org/10.3390/su17083567
27. Mehmood, S., Ahmed, W., Mahmood, M., Rizwan, M. S., Asghar, R. M. A., Alatalo, J. M., …, Shaheen, S. M. (2023). Aquaculture sediments amended with biochar improved soil health and plant growth in a degraded soil. *Marine Pollution Bulletin, 191*(December 2022), 114899. https://doi.org/10.1016/j.marpolbul.2023.114899
28. Michael, P. (2020). Management of acid sulfate soils under aerobic and anaerobic soil conditions revolves around organic matter and live plant macrophytes. *Annals of Tropical Research, 42*(1), 1–22. https://doi.org/10.32945/atr4211.2020
29. Mustafa, G., Hussain, S., Liu, Y., Ali, I., Liu, J., Bano, H. (2024). Microbiology of wetlands and the carbon cycle in coastal wetland mediated by microorganisms. *Science of The Total Environment*, 175734. https://doi.org/10.1016/j.scitotenv.2024.175734

30. Nair, C. S., Manoharan, R., Nishanth, D., Subramanian, R., Neumann, E., Jaleel, A. (2025). Recent advancements in aquaponics with special emphasis on its sustainability. *Journal of the World Aquaculture Society*, *56*(1), e13116. https://doi.org/10.1111/jwas.13116
31. Panwar, V., Dutta, T. (2019). Diatom biogenic silica as a felicitous platform for biochemical engineering: Expanding frontiers. *ACS Applied Bio Materials*, *2*(6), 2295–2316. https://doi.org/10.1021/acsabm.9b00050
32. Roveda, M., de Menezes, C. C. A., Bolívar-Ramírez, N. C., Owatari, M. S., Jatobá, A. (2024). Acidifying remediation and microbial bioremediation decrease ammoniacal nitrogen, orthophosphates, and total suspended solids levels in intensive Nile tilapia farming under biofloc conditions. *Aquaculture, 580*(August 2023). http://dx.doi.org/10.1016/j.aquaculture.2023.740292
33. Sarangi, S. K., Mainuddin, M., Maji, B. (2022). Problems, management, and prospects of acid sulphate soils in the Ganges Delta. *Soil Systems*, *6*(4), 95. https://doi.org/10.3390/soilsystems6040095
34. Saxena, A., Kumar Singh, P., Bhatnagar, A., Tiwari, A. (2022). Growth of marine diatoms on aquaculture wastewater supplemented with nanosilica. *Bioresource Technology, 344*(PA), 126210. https://doi.org/10.1016/j.biortech.2021.126210
35. Silva, M. I. B. D., Brandão, L. P. M., Brighenti, L. S., Staehr, P. A., Barros, C. F. D. A., Barbosa, F. A. R., Bezerra-Neto, J. F. (2025). Nutrient, Organic Matter and Shading Alter Planktonic Structure and Density of a Tropical Lake. *Limnological Review*, *25*(2), 16. https://doi.org/10.3390/limnolrev25020016
36. Szklarek, S., Górecka, A., Wojtal-Frankiewicz, A. (2022). The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution-A review. *Science of The Total Environment*, *805*, 150289. https://doi.org/10.1016/j.scitotenv.2021.150289
37. Tafdrian, M. K. I., Subhan, U., Mulyani, Y., Iskandar. (2024). Optimizing plankton growth and diversity in biofloc systems through silica supplementation. *Asian Journal of Fisheries and Aquatic Research, 26(8),* 75–82. https://doi.org/10.9734/ajfar/2024/v26i8797
38. Thangavelu, R. M., da Silva, W. L., Zuverza-Mena, N., Dimkpa, C. O., White, J. C. (2024). Nano-sized metal oxide fertilizers for sustainable agriculture: balancing benefits, risks, and risk management strategies. *Nanoscale*, *16*(43), 19998–20026.
39. Umar, N. A., Arnol, M. (2024). Investigating the optimum silicon to nitrogen ratio (Si/N) for diatom (*Chaetoceros sp.*) culture. *Aquaculture, Aquarium, Conservation & Legislation*, *17*(6), 2557–2568.
40. Umar, N. A., Hatta, M., Indrawati, E., Rumoey, D. S. (2024). Comparison of Phytoplankton Composition and Abundance (River, Estuary dan Coast) as Potential Water Contamination Bio-Indicators in Tallo Watershed Area. *Journal of Environmental and Agricultural Studies*, *5*(3), 1–11. https://doi.org/10.32996/jeas.2024.5.3.1
41. Vehanen, T., Sutela, T., Aroviita, J., Karjalainen, S. M., Riihimäki, J., Larsson, A., Vuori, K. M. (2022). Land use in acid sulphate soils degrades river water quality – Do the biological quality metrics respond? Ecological Indicators, 141(March). https://doi.org/10.1016/j.ecolind.2022.109085
42. Walter, W. G. (2011). *Standard Methods For The Examination Of Water And Wastewater.* https://doi.org/10.2105/AJPH.51.6.940-a (11th ed., Vol. 51). American Public Health Association. https://doi.org/10.2105/AJPH.51.6.940-A
43. Wang, T., Cao, X., Chen, M., Lou, Y., Wang, H., Yang, Q., …, Zhuge, Y. (2022). Effects of soil acidification on bacterial and fungal communities in the Jiaodong Peninsula, Northern China. *Agronomy, 12*, (4). https://doi.org/10.3390/agronomy12040927
44. Yusoff, F. M., Umi, W. A. D., Ramli, N. M., Harun, R. (2024). Water quality management in aquaculture. Cambridge Prisms: Water, 2. https://doi.org/10.1017/wat.2024.6
45. Zepernick, B. N., Gann, E. R., Martin, R. M., Pound, H. L., Krausfeldt, L. E., Chaffin, J. D., Wilhelm, S. W. (2021). Elevated pH conditions associated with *Microcystis* spp. blooms decrease viability of the cultured diatom fragilaria crotonensis and natural diatoms in Lake Erie. *Frontiers in Microbiology, 12 (February),* 1–12. https://doi.org/10.3389/fmicb.2021.598736
46. Zhou, Q., Wu, K., Yao, L., Chen, R., Liu, S., Xing, H., …, Wu, Z. (2024). Bio-ecological remediation of freshwater aquaculture environments: A systematic review and bibliometric analysis. *Water Biology and Security, 3*, 100229. https://doi.org/10.1016/j.watbs.2023.100229