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Application of Bentonite-Based Sediment Capping for Eutrophication Control: A Case Study of Lake Batur, Bali

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Abstract
Increasing nutrient inputs, particularly phosphate and nitrogen, have contributed to eutrophication in Lake Batur and increased the risk of water quality degradation. This study evaluated the effectiveness of sediment capping using activated and non-activated bentonite for nutrient removal, including total phosphorus (TP), total nitrogen (TN), nitrate, and ammonia. Characterization using SEM-EDX and FTIR showed that the activation process altered the surface morphology and chemical properties of bentonite, resulting in a more open structure and higher silicon and aluminum contents. Shifts in the absorption bands of –OH, Si–OH, and Si–O–Si groups indicated surface modification without damaging the montmorillonite framework. The results demonstrated that non-activated bentonite achieved the highest removal efficiency for total phosphorus, reaching 87%. Activated bentonite showed better performance in reducing total nitrogen and nitrate, with removal efficiencies of 61% and 79%, respectively. Meanwhile, nitrate removal by non-activated bentonite reached 78%. Ammonia removal remained relatively limited, where activated bentonite reduced ammonia concentration by 30%, while non-activated bentonite showed a slight increase in ammonia concentration of −12%. Overall, both activated and non-activated bentonite exhibited potential as sediment capping materials for controlling nutrient release in aquatic systems.
Keywords*: sediment capping, bentonite, lake batur, phosphate, nitrogen*

Abstrak
Peningkatan masukan nutrien, terutama fosfat dan nitrogen, telah berkontribusi terhadap eutrofikasi di Danau Batur dan meningkatkan risiko penurunan kualitas air. Penelitian ini mengevaluasi efektivitas *sediment capping* menggunakan bentonit teraktivasi dan non-teraktivasi untuk menyisihkan nutrien, meliputi total fosfor (TP), total nitrogen (TN), nitrat, dan amonia. Karakterisasi menggunakan SEM-EDX dan FTIR menunjukkan bahwa proses aktivasi mengubah morfologi permukaan dan sifat kimia bentonit sehingga menghasilkan struktur yang lebih terbuka serta meningkatkan kandungan silikon dan aluminium. Pergeseran pita serapan gugus –OH, Si–OH, dan Si–O–Si mengindikasikan adanya modifikasi permukaan tanpa merusak struktur montmorillonit. Hasil penelitian menunjukkan bahwa bentonit non-teraktivasi mencapai efisiensi penyisihan total fosfor tertinggi, yaitu sebesar 87%. Bentonit teraktivasi menunjukkan kinerja yang lebih baik dalam menyisihkan total nitrogen dan nitrat dengan efisiensi masing-masing sebesar 61% dan 79%, sedangkan penyisihan nitrat oleh bentonit non-teraktivasi mencapai 78%. Penyisihan amonia masih relatif terbatas, di mana bentonit teraktivasi mampu menurunkan konsentrasi amonia sebesar 30%, sedangkan bentonit non-teraktivasi menunjukkan sedikit peningkatan konsentrasi amonia sebesar −12%. Secara keseluruhan, bentonit teraktivasi maupun non-teraktivasi menunjukkan potensi sebagai material *sediment capping* untuk mengendalikan pelepasan nutrien pada sistem perairan.
Kata kunci: *sediment capping, bentonit, danau batur, fosfat, nitrogen*

1. Introduction

Lake Batur, located in Kintamani Subdistrict, Bangli Regency, was formed within the caldera of Mount Batur eruption [1]. Based on the 2009 Bali Agreement, the lake is included among the 15 priority lakes for rehabilitation in Indonesia [2]. Communities surrounding the lake depend on it for various activities, including fisheries, agriculture, and tourism [3]. However, the increasing intensity of these activities has contributed to higher pollutant loads entering the lake from aquaculture, settlements, agricultural runoff, and tourism-related activities [4]. In particular, the rapid development of hotels and restaurants without adequate wastewater treatment systems, along with the extensive application of

fertilizers and pesticides in agricultural areas, has accelerated nutrient enrichment in the lake waters [5]. Excessive nutrient input may stimulate eutrophication, which is commonly indicated by algal blooms, reduced dissolved oxygen concentrations, and deterioration of aquatic ecosystem stability [6] [7].

Several approaches have been applied to control eutrophication in aquatic environments. Dredging is considered effective for removing nutrient-rich sediments, although its implementation is often limited by high operational costs and the risk of contaminant resuspension [8]. Aeration and water circulation systems have also been used to increase dissolved oxygen concentrations and suppress nutrient release from sediments; however, these methods generally require considerable energy and maintenance costs [9]. Bioremediation using microorganisms has shown potential for reducing excess nutrients, yet its performance is strongly influenced by environmental conditions and usually requires a longer treatment period to achieve optimum results [10].

Sediment capping has recently gained attention as an alternative method for controlling internal nutrient loading. This technology involves placing a covering material over the sediment surface to reduce nutrient diffusion into the water column [11]. The mechanism of sediment capping includes physical isolation, adsorption processes, as well as chemical interactions that limit pollutant mobility within sediments [12], Compared with several conventional approaches, sediment capping is relatively simple to implement and has the potential for long-term nutrient control [13].

The effectiveness of sediment capping is strongly influenced by the characteristics of the capping material. Bentonite is considered a promising material because it is widely available in Indonesia and contains a high proportion of montmorillonite minerals with good adsorption capacity [14]. Its adsorption properties are associated with a high cation exchange capacity and fine particle structure. In addition, the dominance of oxygen and silicon compounds in bentonite reflects the presence of a layered silicate structure typical of montmorillonite minerals, which contributes to ion exchange and adsorption processes [15]. Although natural bentonite already exhibits favorable adsorption characteristics, several studies have reported that activation processes can further improve its performance [16]. Chemical or thermal activation may enhance the surface area and porosity of bentonite, thereby increasing its adsorption [17].

Therefore, this study aimed to characterize activated and non-activated bentonite using Scanning Electron Microscope–Energy Dispersive X-ray (SEM-EDX) and Fourier Transform Infrared (FTIR) analyses. In addition, their performance as sediment capping materials was evaluated in reducing total phosphorus (TP), total nitrogen (TN), ammonia, and nitrate concentrations in a laboratory-scale reactor. Water quality parameters were also monitored throughout the experiment to support the evaluation of capping performance. The findings of this study are expected to provide further information regarding the potential application of locally sourced bentonite for nutrient control in tropical lake environments, particularly in Lake Batur, Bali.

2. Research Methods

2.1. Bentonite Preparation

The bentonite used in this study was sourced locally in Indonesia. Prior to use, the bentonite was sieved through a 100-mesh sieve to obtain uniform particle size. After sieving, activated bentonite was prepared by mixing 10 g of bentonite with 1 mL of concentrated sulfuric acid (H_2SO_4, Supelco, 97%) and then heating the mixture at 80°C while stirring for 1 hour. Upon completion of the activation process, the bentonite was rinsed with deionized water until the solution reached neutral pH and subsequently dried at 120°C for 3 hours before being used in the experiments.

2.2. Characterization of Bentonite and Sediment

Both activated and non-activated bentonite were characterized to analyze surface morphology, elemental composition, and functional groups. Surface morphology and elemental distribution were examined using *Scanning Electron Microscopy coupled with Energy Dispersive X-ray* (SEM-EDX), while functional groups were identified via *Fourier Transform Infrared* (FTIR) spectroscopy. The sediment used in the experiments was analyzed using *X-ray Diffraction* (XRD) to determine its mineralogical composition. The results of these characterizations were used to assess the physicochemical properties of bentonite, which play a crucial role in its adsorption capacity and the control of nutrient release during the experiments.

2.3. Laboratory Scale Reactor Preparation and Treatment

In this study, sediment from Lake Batur and artificial wastewater were used. The artificial wastewater was designed to simulate the nutrient-enriched conditions of Lake Batur, with a composition including key parameters such as total phosphorus (TP), total nitrogen (TN), nitrate, and ammonia, adjusted

to reflect eutrophic water characteristics. This artificial wastewater served as the water medium in the sediment reactors, both for reactors treated with non-activated bentonite and activated bentonite. Each reactor had dimensions of 30 × 10 × 10 cm, with a sediment layer of 5 cm and a 2 cm bentonite capping layer. The experimental setup, as shown in **Figure 1**, included a control reactor without capping material, a reactor with activated bentonite, and a reactor with non-activated bentonite.

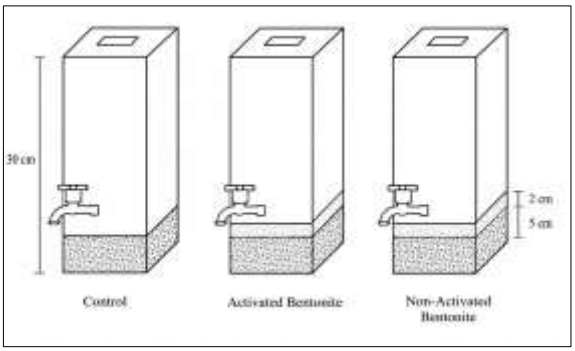


Figure 1. Laboratory scale reactor experimental design

2.4. Nutrient Analysis

During the 21-day experimental period, water quality in the reactors was monitored to evaluate the effectiveness of bentonite in reducing nutrient release from the sediment. The analyzed parameters included total phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-), and ammonia (NH_3).

2.4.1. Total Phosphorus (TP) Analysis

The concentration of total phosphorus (TP) was determined using the ascorbic acid method, based on the formation of a blue-colored complex in the sample, and subsequently measured using a UV-Vis spectrophotometer at a wavelength of 880 nm [18]. TP concentrations were calculated using a linear equation obtained from the calibration curve of phosphate standard solutions ranging from 0.1 to 1 mg/L.

2.4.2. Total Nitrogen (TN) Analysis

Total nitrogen (TN) concentration was determined using the alkaline persulfate–salicylate method, and measurements were performed with a UV-Vis spectrophotometer at a wavelength of 410 nm. TN concentrations (mg/L) were calculated using the following formula [19] :

$$\text{TN (mg/L)} = \frac{\text{Rerata absorbansi-0,016}}{0,74} \text{ x } 10 \qquad (1)$$

2.4.3. Nitrate (NO_3^-) Analysis

Nitrate concentration was analyzed using the method of the [20] with a UV-Vis spectrophotometry technique. Samples were treated with 1 N HCl, and their absorbance was measured at two wavelengths: 220 nm and 275 nm. Nitrate concentrations were calculated using a linear equation obtained from the calibration curve of nitrate standard solutions ranging from 0 to 7 mg/L.

2.4.4. Ammonia (NH_3) Analysis

Ammonia concentration was determined using the method outlined in (SNI. 06-6989.30-2005). The principle of this UV-Vis spectrophotometric analysis is based on the reaction of ammonia with hypochlorite and phenol, forming a colored complex that can be measured at a wavelength of 640 nm. Ammonia concentrations were calculated using a linear equation obtained from the calibration curve of ammonia standard solutions ranging from 0.1 to 1 mg/L.

2.5. Data Analysis

The nutrient removal efficiency (Ef) was calculated to determine the percentage reduction of nutrient concentrations during the experimental process. The calculation was performed using the following equation:

$$\text{Efektivitas (Ef)} = \left(\frac{\text{Co-Ce}}{\text{Co}}\right) \text{ x } 100\% \qquad (2)$$

Where:

Co = initial nutrient concentration (mg/L)
Ce = final nutrient concentration (mg/L)

3. Results And Discussion

3.1. Characterization of Bentonite (SEM-EDX)

The morphology and elemental composition of non-activated bentonite (BNA) and activated bentonite (BA) were examined using Scanning Electron Microscopy–Energy Dispersive X-ray (SEM-EDX) at a magnification of 2500×. SEM analysis was conducted to observe the surface characteristics, particle arrangement, and microstructural features of the materials, while EDX analysis was used to identify the elemental composition of each bentonite sample.

The SEM images revealed noticeable differences between the two materials. Non-activated bentonite showed a relatively compact and dense surface structure. Fine particles appeared closely aggregated with limited visible pore spaces between particles. The surface morphology also tended to be smoother and more uniform, indicating that the natural bentonite structure had not undergone significant structural modification. Similar characteristics of natural bentonite have previously been reported by [22], who described untreated bentonite as having relatively low porosity and a more compact surface texture.

In contrast, activated bentonite exhibited a more irregular and open surface morphology. The particle arrangement appeared less compact, with clearer inter-particle gaps and the presence of small fragmented particles surrounding larger aggregates. Several pore-like structures and rough surface features were also observed after the activation process. These changes suggest that acid activation altered the original structure of bentonite and promoted the development of additional pore spaces.

The formation of a more porous structure is likely associated with the removal of certain mineral components during the activation process. Acid treatment may dissolve exchangeable metal ions and impurities from the bentonite layers, resulting in increased surface roughness and the creation of new active sites. The increase in pore development and surface area is considered beneficial for adsorption processes because it may improve the interaction between bentonite and dissolved nutrients in the water. Comparable findings were also reported by [23], who observed that acid activation contributed to pore formation and structural modification in bentonite materials.

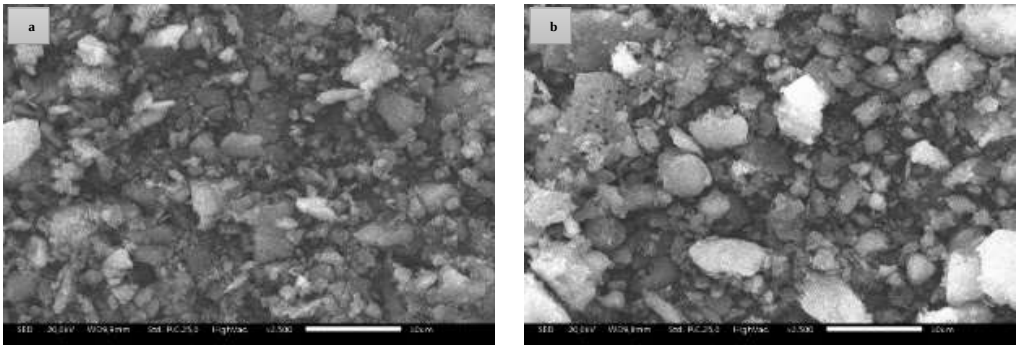


Figure 2. Characterization of bentonite using SEM-EDX (a) non-activated bentonite; (b) activated bentonite

Figure 3 shows the elemental composition of non-activated bentonite (BNA) and activated bentonite (BA) based on SEM-EDX analysis. Non-activated bentonite was predominantly composed of oxygen (45.48%), carbon (42.43%), silicon (8.48%), and aluminum (1.65%). The dominance of oxygen and silicon indicates that montmorillonite was the primary mineral component in the material. However, the lower silicon and aluminum contents compared to activated bentonite suggest that the layered silicate structure of the natural bentonite had not been fully exposed prior to activation.

In the activated bentonite sample, oxygen remained the dominant element at 48.04%, followed by carbon (34.07%), silicon (14.56%), and aluminum (2.04%). The increase in silicon and aluminum contents after activation indicates that the acid treatment modified the bentonite structure and enhanced the exposure of the layered silicate framework. Acid activation may dissolve impurities and exchangeable ions within the clay layers, resulting in structural changes and the formation of additional active sites on the material surface. Previous studies have shown that acid treatment can improve the exposure of silicate layers in montmorillonite minerals and alter their structural properties [15].

The carbon content detected in both samples was relatively high. This condition may be related to the presence of residual organic compounds or carbon-containing substances remaining after the activation process. In addition, the conductive carbon tape used during SEM-EDX sample preparation may also

contribute to the carbon signal detected in the EDX spectrum. Similar observations have been described in previous SEM-EDX analyses using carbon-based mounting materials [24].

Several minor elements, including calcium (Ca), potassium (K), iron (Fe), and titanium (Ti), were identified in concentrations below 1%. The presence of these elements is commonly associated with natural mineral impurities contained in bentonite deposits. Earlier studies indicated that minerals such as quartz, calcite, feldspar, cristobalite, kaolinite, mica, and iron-bearing compounds are frequently found together with bentonite clay materials [25].

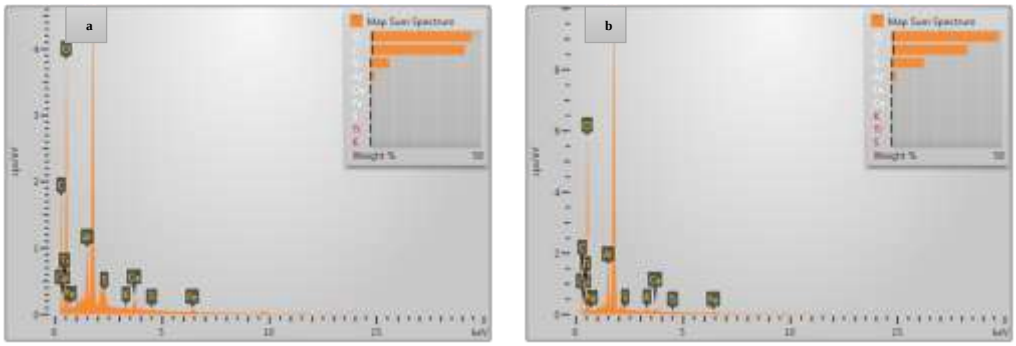


Figure 3. EDX spectrum for elemental identification of bentonite (a) non-activated bentonite; (b) activated bentonite

3.2. Characterization of Bentonite (FTIR)

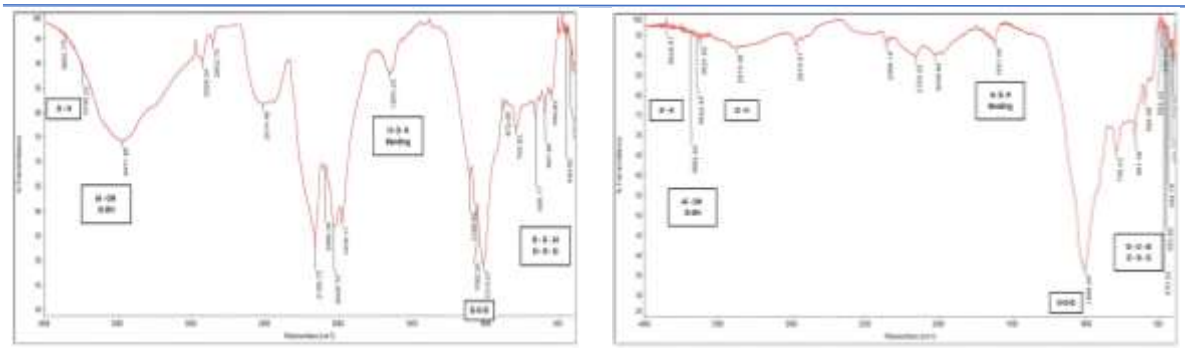
Fourier Transform Infrared (FTIR) analysis within the range of 4000–400 cm^{-1} (Figure 4) identified several characteristic absorption bands associated with montmorillonite in both non-activated bentonite (BNA) and activated bentonite (BA). The presence of free –OH stretching vibrations at approximately 3848–3855 cm^{-1} in both samples indicates that the basic montmorillonite structure remained intact after the acid activation process. Similar characteristics have previously been observed in montmorillonite-based materials following chemical activation treatments [26].

Differences in the absorption regions were identified between the two samples, particularly at 3745–3471 cm^{-1} for BNA and 3684–3624 cm^{-1} for BA. These slight shifts may be related to changes in intermolecular interactions and surface bonding conditions after activation. In addition, the appearance of a new absorption band at 3379 cm^{-1} in the activated bentonite indicates the presence of –OH stretching vibrations associated with interlayer water molecules. This finding suggests that the activation process increased the hydration capacity of the bentonite structure. Comparable observations regarding the formation of hydration-related bands after activation have also been reported in previous studies [27].

A noticeable shift was also observed in the main Si–O–Si stretching vibration band, which changed from 1109 cm^{-1} in non-activated bentonite to 1008 cm^{-1} in activated bentonite. This shift indicates structural modification within the silicate framework, likely caused by ion exchange processes or partial dissolution of mineral components during acid activation. Earlier studies have shown that acid treatment can alter the arrangement of silicate layers and affect the vibrational characteristics of bentonite minerals [28].

Furthermore, the Si–O–Al and Si–O–Si bending vibrations detected within the range of 470–795 cm^{-1} remained present in both samples, indicating that the primary montmorillonite framework was still maintained after activation. However, the activated bentonite exhibited more stable absorption positions at 470 and 445 cm^{-1}, suggesting a more uniform structural arrangement following the treatment process [29].

Overall, the FTIR analysis demonstrates that H_2SO_4 activation did not destroy the montmorillonite structure of bentonite. Instead, the activation process modified several surface functional groups and improved the hydrophilic characteristics of the material. These structural changes are expected to enhance the adsorption performance of bentonite, particularly for nutrient removal applications in aquatic environments.



(a) (b)

Figure 4. FTIR spectra of non-activated bentonite (BNA) and acid-activated bentonite (BA) (a) non-activated bentonite; (b) activated bentonite

3.3. Sediment Characterization (XRD)

Sediment characterization was conducted using X-Ray Diffraction (XRD) analysis to identify the crystalline minerals present before the application of sediment capping technology. Sediments originating from volcanic environments are generally dominated by silicate and clay minerals. As shown in **Figure 5**, quartz (SiO_2) was identified as the dominant mineral component. The presence of quartz reflects the influence of silicate rocks surrounding the lake and its resistance to weathering processes [30].

Other minerals detected in the sediment included plagioclase and aragonite ($CaCO_3$). Plagioclase is a feldspar mineral rich in sodium and calcium that commonly originates from volcanic rock weathering [31]. Meanwhile, aragonite may form through chemical precipitation processes associated with reduced dissolved CO_2 during algal photosynthesis [32].

These minerals naturally have the ability to interact with nutrients in aquatic systems. Quartz can adsorb phosphate through silanol (=SiOH) groups, feldspar provides reactive =SiOH and =AlOH sites, and aragonite contributes through calcium–phosphate precipitation mechanisms [33]. However, their natural adsorption capacities are relatively limited, so their ability to control nutrient release in the water column remains insufficient. Therefore, additional capping materials are needed to improve nutrient retention and reduce eutrophication potential.

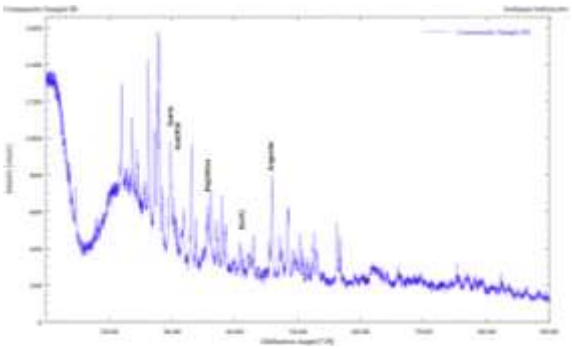


Figure 5. XRD Pattern of Sediment Before the Application of Sediment Capping

3.4. Effect of Sediment Capping on Water Quality

The application of sediment capping technology not only influenced nutrient concentrations but also affected the physicochemical characteristics of the overlying water. Parameters including pH, dissolved oxygen (DO), electrical conductivity (EC), temperature, total suspended solids (TSS), and total dissolved solids (TDS) were evaluated to assess changes in water quality conditions during the experiment. The average values of these physicochemical parameters obtained from each reactor during the 21-day experimental period are summarized in **Table 1**.

The pH variation during the experiment indicated that the application of bentonite as a capping material influenced the acidity conditions of the overlying water. The BA reactor showed pH values ranging from 5.14 to 6.07, whereas the BNA reactor exhibited more acidic conditions, with values ranging from 3.14 to 4.01. The decrease in pH in the BA reactor was likely related to the release of H^+ ions retained within the bentonite structure after activation using H_2SO_4. Although the material was rinsed after the activation process, some protons may have remained adsorbed on the surface or within the interlayer

structure of bentonite [34]. In the BNA reactor, the acidic condition may have been influenced by the natural mineral composition of bentonite, particularly impurity minerals such as Fe, Ti, Ca, and K, which may contribute to proton release through dissolution processes [25].

Table 1. Physicochemical Parameters of Water After Sediment Capping Application

Parameters	Control Reactor (S)	Activated Bentonite (BA)	Non-Activated Bentonite (BNA)
pH	8.4	5.5	3.4
DO (mg/L)	2.3	2,4	2,4
EC (µS/cm)	538	947	2209
Suhu	24.4	24.4	24.5
TSS (mg/L)	81	68	72
TDS (mg/L)	269	472	1099

The dissolved oxygen (DO) conditions were maintained at relatively low levels throughout the experiment through argon gas injection. The use of argon as an inert gas aimed to reduce dissolved oxygen concentrations, thereby maintaining hypoxic conditions within the reactor system. This condition was selected to simulate the natural conditions of the bottom layer of aquatic environments, allowing the hypoxic conditions formed in the reactor to represent the environmental conditions of aquatic sediments. The average DO values in all reactors ranged from 2.3 to 2.4 mg/L **(Table 1**). The movement of argon bubbles through the water column during injection may have influenced the physical conditions of the system by redistributing fine particles from the sediment surface, which subsequently contributed to variations in total suspended solids (TSS) concentrations.

The control reactor showed considerable fluctuations in TSS concentration throughout the experiment. The TSS concentration initially reached 194 mg/L on day 1, decreased during subsequent sampling periods, and increased again to 116 mg/L on day 18. Most TSS values in the control reactor remained above the Class II water quality standard, indicating that the absence of a capping layer allowed fine sediment particles to resuspend more easily into the overlying water. This condition suggests instability within the water column caused by sediment disturbance and diffusion processes. Similar observations regarding sediment resuspension associated with gas movement have also been reported in previous studies [36].

Compared with the control reactor, the reactors capped with activated bentonite (BA) and non-activated bentonite (BNA) generally showed lower TSS concentrations. Initial TSS values in BA and BNA were 46 mg/L and 32 mg/L, respectively, although increases up to 100–114 mg/L were observed at several sampling periods. This increase may be associated with the colloidal properties of bentonite, which can easily disperse in water before aggregation and settling occur [37]. The montmorillonite structure in bentonite tends to form stable aggregates through interlayer interactions, but the release of fine particles may still occur under laboratory-scale conditions.

The average total dissolved solids (TDS) concentration in the control reactor was 269 mg/L, indicating relatively low dissolved solid content. However, a gradual increase in TDS was observed during the experiment, likely caused by the release of dissolved substances from the sediment into the water column in the absence of a diffusion barrier [34]. In the activated bentonite reactor, the average TDS reached 472 mg/L, which remained below the Class II water quality standard of 1000 mg/L. The increase in TDS in BA may be related to the release of residual Na^+ ions remaining within the interlayer structure after the activation process, which is consistent with the ion exchange behavior of montmorillonite minerals [38]. Meanwhile, the non-activated bentonite reactor (BNA) exhibited the highest average TDS concentration, reaching 1099 mg/L. This condition may have resulted from the dissolution of naturally associated minerals and the release of soluble ions from the bentonite material. The higher TDS value observed in the BNA reactor suggests that untreated bentonite contributed a greater amount of dissolved components to the overlying water compared with activated bentonite [39].

3.5. Nutrient Removal Efficiency

3.5.1. Total Phosphorus (TP) Removal Efficiency

Water quality analysis in this study focused on the main nutrient parameters, including total phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-), and ammonia (NH_3), which are closely associated with eutrophication processes in aquatic environments. Changes in the concentrations of these parameters were monitored over a 21-day observation period to evaluate the effectiveness of sediment capping technology in reducing nutrient release into the overlying water.

Two different capping materials were applied, namely activated bentonite (BA) and non-activated bentonite (BNA), and their performance was compared with a control reactor without capping material (S). This evaluation was conducted to assess the ability of bentonite to inhibit nutrient diffusion from the sediment to the water column and to determine its potential in reducing eutrophication risk.

Table 2. Nutrient Removal Efficiency

Parameters	Control	Non-Activated Bentonite (BNA)		Activated Bentonite (BA)	
	(mg/L)	(mg/L)	%	(mg/L)	%
TP	0,57	0,16	87	0,28	76
TN	1,10	1,06	44	0,75	61
NO_3^-	2,40	0,79	78	0,76	79
NH_4^+	0,32	0,90	-12	0,56	30

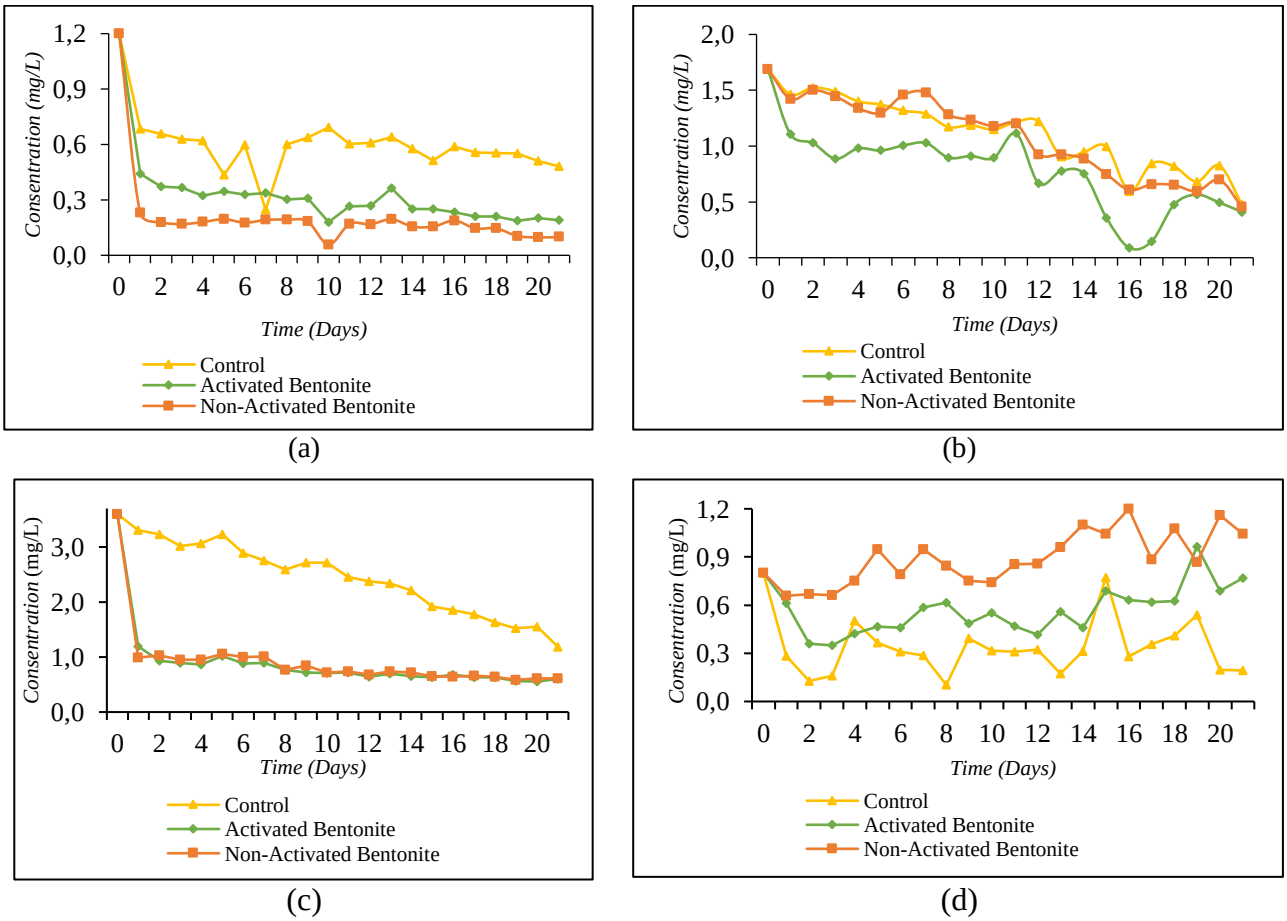


Figure 6. Temporal Variation of Nutrient Concentrations (a) TP; (b) TN; (c) NO_3^- ; (d) NH_4^+

The results showed that the application of sediment capping using bentonite effectively reduced nutrient concentrations in the overlying water. As presented in **Figure 6a**, the initial total phosphorus (TP) concentration of 1.2 mg/L decreased to 0.19 mg/L in the activated bentonite reactor (BA) and to 0.09 mg/L in the non-activated bentonite reactor (BNA). This reduction demonstrates the ability of bentonite to adsorb phosphate released from the sediment, with BNA showing slightly better performance than BA. The acidic conditions observed in both reactors may have supported phosphate adsorption. Under acidic to neutral pH

conditions, phosphate is mainly present as $H_2PO_4^-$, which can interact more easily with positively charged adsorption sites on the bentonite surface [40]. In addition, lower OH^- concentrations reduce competition at active adsorption sites, thereby improving phosphate retention through electrostatic interactions [41].

For total nitrogen (TN), shown in **Figure 6b**, the concentration gradually decreased during the 21-day observation period. The activated bentonite reactor reached a final concentration of 0.41 mg/L, while the non-activated bentonite reactor reached 0.46 mg/L. These results indicate that activated bentonite performed slightly better in reducing TN concentrations. The decrease in TN in the BA reactor was also more stable throughout the experiment, with the lowest concentration observed on day 16. The improved performance of activated bentonite may be related to the activation process, which increases surface area and the number of available active sites for adsorption [42]. Nitrogen removal likely occurred through ion exchange mechanisms involving NH_4^+ ions and other dissolved nitrogen species interacting with the layered structure of bentonite [40].

A decreasing trend was also observed for nitrate (NO_3^-) concentrations, as shown in **Figure 6c**. The initial nitrate concentration of 3.6 mg/L decreased to 0.55 mg/L in BA and 0.59 mg/L in BNA. Nitrate removal may occur through electrostatic attraction, ion exchange, and hydrogen bonding between nitrate ions and functional groups on the bentonite surface. The presence of positively charged sites on bentonite allows interaction with negatively charged nitrate ions, while exchangeable ions within the interlayer structure may also participate in the adsorption process [43]. Functional groups such as Si–OH and Al–OH may further contribute through hydrogen bonding interactions [44]. Although competing ions such as PO_4^{3-} and SO_4^{2-} may reduce nitrate adsorption efficiency, both bentonite materials still showed relatively high nitrate removal performance [45].

Different behavior was observed for ammonia (NH_3), as presented in **Figure 6d**. Compared with the other nutrient parameters, ammonia removal was relatively limited. The initial concentration of 0.8 mg/L decreased only slightly to 0.76 mg/L in the activated bentonite reactor. In contrast, the non-activated bentonite reactor showed an increase in ammonia concentration up to 1.04 mg/L. Under acidic conditions, ammonia in water predominantly exists as ammonium (NH_4^+), following the equilibrium reaction $NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$ [46]. Ammonium ions can theoretically be removed through ion exchange with bentonite surfaces [47]. However, the continuous release of NH_4^+ from the sediment may have exceeded the adsorption capacity of the material. In addition, interactions between NH_4^+, phosphate, and metal ions may lead to precipitate formation that blocks active adsorption sites and reduces adsorption efficiency [48].

Overall, the study demonstrates that bentonite capping was effective in reducing nutrient concentrations in the water column, although different adsorption behaviors were observed for each parameter. Activated bentonite showed better performance for TN and ammonia reduction, while non-activated bentonite achieved higher phosphate removal. These findings provide further insight into the potential application of locally sourced bentonite for nutrient control in tropical lake environments, particularly under conditions influenced by acidic pH and sediment water interactions.

4. Conclusion

Characterization by SEM-EDX and FTIR showed that acid activation modified the surface morphology and chemical characteristics of bentonite, resulting in a more open structure and changes in functional groups that may enhance its adsorption capacity. Laboratory-scale sediment capping experiments demonstrated that both activated and non-activated bentonite effectively reduced nutrient concentrations in the overlying water. Non-activated bentonite achieved higher phosphate removal, whereas activated bentonite showed better performance in reducing total nitrogen. Both materials exhibited comparable nitrate removal efficiencies, while ammonia removal remained relatively limited. Overall, these findings indicate that bentonite-based sediment capping has the potential to control internal nutrient loading and mitigate eutrophication in lake systems. Further studies are recommended to evaluate the long-term effectiveness and environmental safety of bentonite application under field conditions.

5. Acknowledgment

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6. References

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