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Sediment capping technology for eutrophication control and its potential for application in Indonesian lakes: a review

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Abstract: Eutrophication occurs when the lakes become enriched with nutrients. Some nitrogen and phosphorus fractions will settle in sediment, and others will be released back into the overlying water column. Excess nutrients in water bodies resulting in hypoxic to anoxic conditions that can cause a mass fish death. Hence, we need a sediment management strategy to minimize resuspension and transport of sediment back into the water column. Sediment capping is a containment technology to reduce the release of nutrients from sediment as a strategy for eutrophication control. This study aims to provide insight into sediment capping technology, including several considerations in capping design, as well as information on several active materials that have been applied as capping materials and their efficiencies. Capping materials such as calcite, zeolite, bentonite, activated carbon, sludge, biochar, and gypsum from previous studies showed the efficiency of 54–99 % nutrient reduction with capping duration of 10–300 days in some eutrophic lakes. Sediment capping technology has successfully promoted lake ecosystem restoration in other countries, and this technology has the potential to be applied in Indonesian eutrophic lakes as a strategy for eutrophication control and sustainable management of lake ecosystems by considering the selection of the most effective, efficient, easy, inexpensive, and eco-friendly capping materials.

Keywords: sediment capping technology, eutrophication, Indonesian lakes

1. Introduction

Anthropogenic factors associated with industrial, urban, agricultural, domestic, and fish cultivation activities have led to increasing amounts of nutrients in aquatic environments, which led to a condition called eutrophication. Eutrophication occurs when a lake becomes nutrient-enriched (Wetzel, 2001). Some nutrient species like nitrogen and phosphorus fractions will settle in sediment, while other fractions which are redox-sensitive under anoxic conditions such as ammonia-nitrogen (NH_4^+-N), nitrate, organic nitrogen, and phosphorus bound to chemical compounds like iron (Fe) will be released back into the overlying water column (Phillips *et al.*, 2006; Zamparas *et al.*, 2014; Wang et al., 2018; Papera *et al.*, 2021). In this case, sediment acts as both carriers and long-term secondary sources of contaminants in aquatic ecosystems (Zhang *et al.* 2016). Excess nutrients in water bodies can lead to both overgrowth of algae and eutrophication. As dead algae decompose, oxygen is consumed in the process, resulting in low levels of oxygen (hypoxic) and anoxic

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conditions that can cause mass fish death (Jenny *et al.*, 2016). In situ remediation technologies to prevent eutrophication have been studied such as floating treatment wetlands (Coveney *et al.*, 2002; Tanner *et al.*,2011; Henny *et al.*, 2020) that are only effective for water surface remediation. While in situ technologies for contaminated sediment such as dredging (Reddy *et al.* 2007 and Yu *et al.* 2017), chemical precipitation (Gonsiorczyk *et al.*, 1998; Lürling and Oosterhout 2013), in situ chemical injection (Søndergaard *et al.*, 2002; Engstrom et al., 2005; Wang and Jiang, 2016), and hypolimnetic oxygenation (Beutel, 2006; Liboriussen *et al.*, 2009). However, these technologies have some weaknesses, including high cost, ineffective control of nutrient reduction, and toxicological risk to aquatic biota (Reitzel *et al.*, 2013). Indeed, the management strategy for contaminated sediments has become one of the most challenging problems in the aquatic environment.

Sediment management strategies consist of five categories, which are selected based upon an evaluation of specific risks and goals (Apitz and Power, 2002): (1) no action if it is determined that sediment poses no risk; (2) natural recovery monitoring, if the risk is low enough that can be reduced naturally by self-purification; (3) in situ containment, in which sediment contaminants are in some manner isolated from target organisms, though the sediments are left in place ; (4) in situ treatment; and (5) dredging or excavation (followed by ex-situ treatment, disposal, and/or reuse).

The most common and straightforward strategy is dredging, which physically removes contaminants sediment from aquatic systems. However, the dredging strategy is not advisable due to the several disadvantages like the high cost of removal treatment (Hakstege, 2007), remobilization of contaminants that are trapped in the sediments (Martins *et al.*, 2012), environmental degradation (Nayar *et al.*, 2004) and the potential long-term threat for exposure from some remain contamination. No removal technology can remove every particle of contaminated sediment, and post-dredging residual contamination levels have often failed to reach the desired levels (Martins *et al.*, 2012). Although dredging remains a potential strategy for contaminated sediment management, new technologies are needed to develop economical and effective ways to treat sediment contamination.

Sediment capping technology using in-situ capping (ISC) is one development approach that places a layer of clean material over contaminated sediments that is less energy-intensive, cost-efficient, and less disruptive to the environment. The objectives of ISC are to isolate the sediments from the overlying water column and biota (Zhang *et al.*, 2016), and to reduce the contaminant flux of the sediment (Reible *et al.*, 2003). Two types of caps, namely passive and active capping, can be used over contaminated sediments. Passive caps are the conventional type of caps commonly employing clean material like sand, silt, clay, and crushed rock debris. These materials are easily available at relatively low cost, although they have low adsorption capacity due to their dependency on physical retardation mechanisms than on chemical retardation (Eek *et al.*, 2008). The thickness of passive caps is approximately 50 cm (Azcue *et al.*, 1998). Therefore, they are inefficient for use for contaminant removal.

Active caps use chemical reactive materials that sequestrate and or degrade sediment contaminants to reduce their mobility, toxicity, and bioavailability (Zhang *et al.*, 2016). Different from passive caps, active caps use thinner materials. The 12 mm thickness of active materials can theoretically replace 1 m of passive caps such as sand or soil (Olsta, 2007). Active caps can also be applied in areas under diffusion and advection-dominated conditions, thus effectively isolating contaminants in sediment from a bioactive portion of the cap for decades to centuries (Murphy *et al.*, 2006). The objectives of this paper are to provide insights into sediment capping technology, including several considerations in selecting capping materials as the most essential part of sediment capping technology, as well as information on several active materials that have been applied as capping materials and their efficiencies. This study also reveals how this technology can be applied in Indonesian lakes.

2. Materials and Methods

The methods used in the literature review were conducted as follows: (1) searching and selecting appropriate articles regarding sediment capping technology, including theoretical presentations, review articles, and empirical research articles. We explored Google Scholar (https://scholar.google.com) using keywords such as sediment capping and capping material for nutrient removal in eutrophic lakes; (2) analyzing and synthesizing the collection of articles by identifying the important information, integrating them and determining the conclusion that can be drawn from the articles as a group; (3) finding differences in the types of capping materials and their efficiencies in removing nutrient-contaminated sediments. We used Mendeley Desktop (https://www.mendeley.com/) as a tool to organize and annotate all the references.

3. Results and discussion

3.1 Design Considerations for In-Situ Capping of Contaminated Sediments

The guidelines for in-situ capping (ISC) were described by Palermo et al. (1998) which was prepared for the U.S. Environmental Protection Agency (USEPA) under the Assessment and Remediation of Contaminated Sediments (ARCS) Program, administered by USEPA's Great Lakes National Program Office. A recommended sequence of steps involved with the design of an ISC is illustrated in a flowchart in Figure 1. To achieve the remediation goals, a capping project must be treated according to the considered design, construction, and monitoring. Considerations in the design process are summarized as follows:

1. Determination of remediation objective
   Once the objectives are set, the scope of the remediation effort can be defined~~,~~ usually in terms of the areal extent of contamination, contaminant concentration, or volume of material to be remediated. The objective of contaminated sediment remediation may be quite site-specific. ISC is feasible to reduce uptake or toxic effects from a contaminant. However, ISC would not meet an objective to destroy or remove some particular sediment from the aquatic environment.
2. Evaluation of site characterization
   Varying site conditions indicate that sediments are subject to varying biogeochemical processes. Capping performance will be different based on some factors, i.e., water depths, bathymetry, temperature, dissolved oxygen concentration, redox potential, wind energies, current and flow, stagnant or fast-moving water bodies (Zhang *et al.*, 2016), waterways use (water supply, recreation, navigation, and wastewater discharge), geotechnical conditions (stratification of underlying sediment layers, depth to bedrock, and potential for groundwater flow), diffusion and advection (Palermo, 1998).
3. Evaluation of contaminated sediment characteristics
   The physical, chemical, and biological characteristics of the sediments should be determined both horizontally and vertically to determine the areal extent or boundaries of the site to be capped. The characteristics of contaminated sediments are primarily influenced by site-specific conditions. For example, the nature and level of the contamination, the concentrations and bioavailability of those contaminants and their pathways into the aquatic environment and their fate in the lake system. Depending on the type of contaminant, parameters of interest may include organic carbon content, pH, dissolved oxygen, redox potential, ionic strength, and salinity to determine the potential of migration through the capping layer. The physical parameters should include the determination of particle size distribution, organic matter content, water content, plasticity (Atterberg limits), undrained shear strength, slope stability and bearing capacity. In terms of biological parameters, they were focused on bioturbation and ensuring that the capped sediment remains isolated from aquatic biota (EPA, 2012). Moreover, turbulent flow conditions associated with

seasonal flooding can expose anoxic sediment to toxic conditions that may result in significant changes to contaminant speciation and the flux of contaminants from sediments (Riedel *et al*., 1999). Also, groundwater discharge will cause significant widespread continuous flow through the sediment and lead to the release of contaminants (Liu *et al*., 2001).

4. Determination of preliminary feasibility
   Following the remediation objective, site and sediment characteristics, a preliminary determination of the overall feasibility of ISC at the target site should be conducted. The cost and effort involved in long-term monitoring and potential management actions should be evaluated as part of the initial feasibility study.

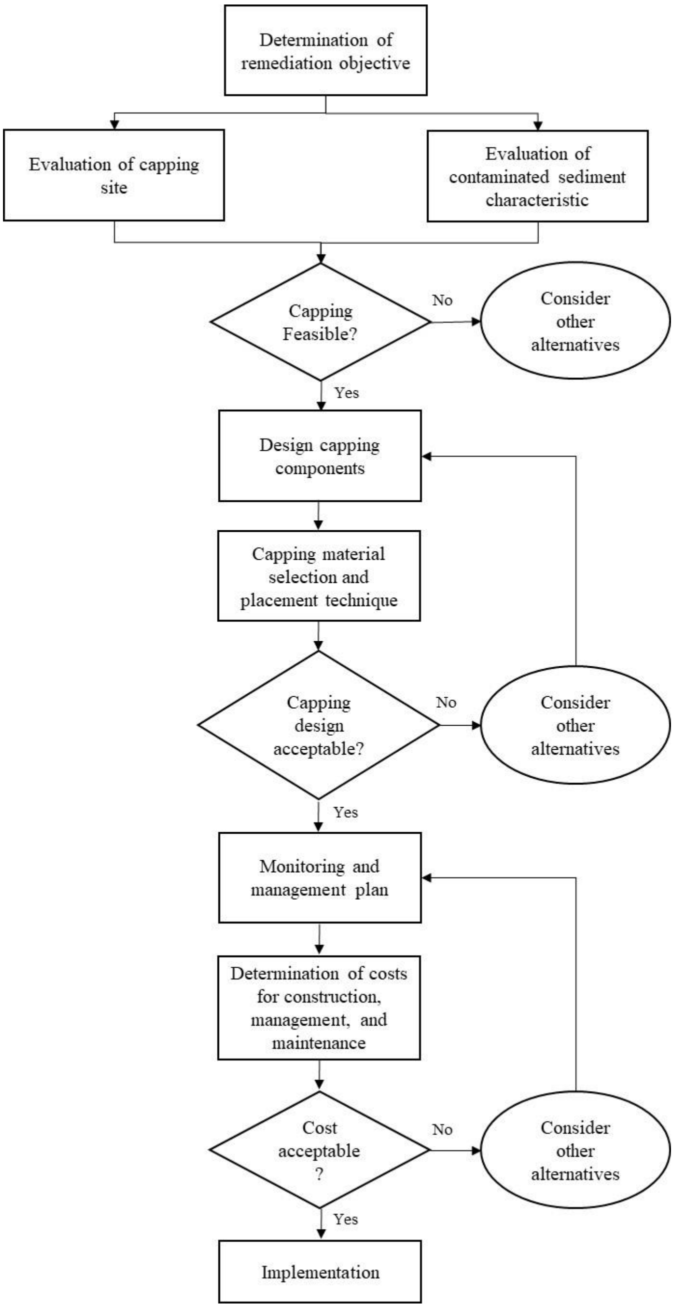

Fig.1 Flowchart showing the design sequence of an in-situ capping project (modified from Palermo, 1998)

5. Capping component design
   The composition and thickness of cap materials can be referred to as the cap design by considering physical isolation, sediment stabilization, and reduction of dissolved contaminant flux (EPA, 2012). The design must also be compatible with the available construction and placement techniques, consideration for effective short and long-term chemical isolation of contaminants, adsorption, bioturbation, consolidation, erosion, and other pertinent processes. The standard cap design for ISC is illustrated in Figure 2. The recent state-of-the-art cap designs involve a combination of laboratory experiments, knowledge of local species and their bioturbation behavior; wind forces circulation, analytical evaluations, hydrodynamic, sediment transport and erosion modeling (Palermo *et al*., 1998), as well as advective and diffusive contaminant transport process modeling (Go *et al*., 2009).

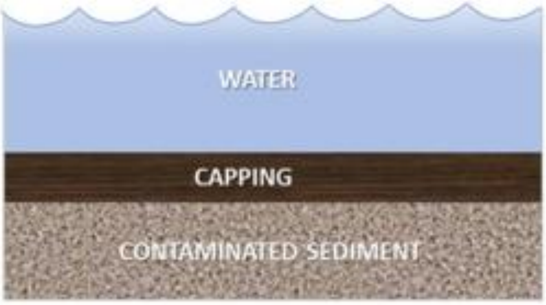

Figure 2. In-situ capping (ISC) design

6. Capping materials and placement technique
   The consideration for cap materials is the most important since these materials will generally represent the overall project cost. The selection among several potential cap materials must be determined by subsequent analysis using laboratory experiments. Most ISC projects have used sediment or soil materials, either dredged from nearby waterways or obtained from upland sources, including commercial quarries. Granular materials, i.e., sandy sediment or soil, should contain an organic fraction to act as an effective containment layer. Other materials, such as armor stone or geotextiles, should be considered in erosive environments (Palermo, 1998).
7. Monitoring and management plan
   When the capping design and materials have been accepted, then a monitoring program should be required to ensure that the cap is placed as intended and performing the basic functions (physical isolation, sediment stabilization and chemical isolation) as required to meet the remedial objectives. Specific parameters that may be monitored include cap thickness, cap consolidation, the need for cap nourishment, benthic recolonization, and chemical migration potential (Palermo, 1998). Furthermore, intensive monitoring is necessary at capping sites during and immediately after construction, followed by long-term monitoring at less frequent intervals.
8. Determination of costs for construction, management, and maintenance
   The important aspect that must be considered is the necessary costs for ISC, including material costs and long-term monitoring during ISC implementation. An economic study is required to consider the capping duration and the maintenance of materials.

3.2 Active Capping Materials

A summary of active capping materials for nutrient reduction applied in a number of previous studies is presented in Table 1. Apparently, their distinct characteristics depend on the type of material and adsorption capacity. Active materials play different roles in active capping technology, including target contaminant, capping duration, and their efficiencies in nutrient reduction (Zhang *et al*., 2016).

Table 1. Several active capping materials

No.	Capping material	Contaminant	Capping duration	Finding	Application	Reference
1.	Calcite-zeolite mixtures	Phosphorus, ammonium	72 days	93 % reduction of the phosphorus fluxes and 99 % reduction of ammonium fluxes using batch and sediment incubation experiment	Sediment and water sample from a eutrophic, polluted small landscape waterbody in Shanghai, China	(Lin *et al*., 2011)
2.	Rohrbach calcite	Phosphorus	70 - 230 days	80 % reduction of soluble reactive phosphorus flux using batch and sediment incubation experiment	Sediment and water sample from eutrophic Lake Epple and Lake Muggle, Germany	(Berg *et al*. 2004a)
3.	Manufactured calcite (U1)	Phosphorus	300 days	No phosphorus release in a 4.5 cm of U1 thickness using batch and sediment incubation experiment	Sediment and water sample from eutrophic Lake Epple and Lake Muggle, Germany	(Berg *et al*., 2004)
4.	Calcite-modified Fe (FMCA)	Phosphorus	86 days	In batch experiment, FMCA show better adsorption process than unmodified-calcite, and the efficiency increase as well as Fe addition.	Sediment samples were collected from a eutrophic lake in Pudong, China	(Bai *et al*., 2021)
5.	Calcite/Zeolite modified Fe	Nitrogen and phosphorus	135 days	77,8–99,7% of soluble phosphorus reduction and 54,0–96,7% of ammonium reduction using batch and microcosm incubation experiment	Sediments sample from a lake in Pudong New Area, Shanghai, China	(Zhan *et al*., 2020)
6.	Fe-modified bentonite	Phosphate	90 days	68 % reduction of the phosphate flux from the sediment	Aitoliko Lagoon, Western Greece	(Zamparas *et al*, 2013)
7.	Bentonite humic-acid composite material (Bephos)	Phosphorus, ammonium	92 days	96.6% reduction of the phosphate flux and 75.2% reduction of the ammonium flux from the sediments	Aitoliko Lagoon, Western Greece	(Zamparas *et al*., 2014)
8.	Bentonite clay and Bauxsol	Phosphorus	300 days	Bentonite clay effectively reduce phosphorus in oxic/anoxic condition (~82 %)	Lake Ainsworth, Australia	(Akhrust *et al*., 2004)
9.	Bentonit, Illite, and Zeolite	Nitrogen and phosphorus	60 days	Illite showed the highest efficiency (90 %) in reducing phosphate and total phosphorus.	Highly eutrophic lake in Anseong City, Korea	(Gu *et al*., 2019)
10.	Magnetite/bentonite modified fabric-wrapped zirconium (M-ZrFeBT)	Phosphorus	120 days	M-ZrFeBT can bind P with efficiency of 96.5–98.2%.	Eutrophic water body in Pudong New District, China	(Lin *et al*.,2020)
11.	Bentonite-modified zirconium (ZMBT)	Phosphorus	170 days	When the P concentration increased, ZMBT was able to prevent the released P with efficiency of 95 %	Shallow water body in Pudong District, China	(Zhan *et al*., 2020)
12.	Zeolite-modified gypsum	Phosphorus	10 days	90 % of phosphorus release reduction using batch experiment	Artificial eutrophic water and sediment	(Yun *et al*., 2007)

No.	Capping material	Contaminant	Capping duration	Finding	Application	Reference
13.	Zeolite, ceraicite and light porous media	Nitrogen	90 days	The highest efficiency of N reduction was performed by zeolite (90-100%), followed by ceraicite and light porous media (59 %)	Eutrophic lake in Xi'an, China	(Huang *et al.*, 2011)
14.	Zeolite, activated carbon and non-woven fabric mats	Nitrogen and phosphorus	60 days	Capping efficiency 94-98% for N and 74-79% for P	Eutrophic Lake in Anseong City, Korea	(Hong *et al.*, 2019)
15.	Dolomite and zeolite	Nitrogen and phosphorus	60 days	96-100 % prevent the release of N and P by considering the placement	Sediment and lake water samples from a highly eutrophic lake in Anseong City, Korea	(Alvarado *et al.* 2020)
16.	Zeolite-modified lanthanum (LMZ)	Phosphorus	20 days	LMZ as an inactivation agent to prevent P release from sediment (91 %)	Lake Taihu, China	(Li *et al.* 2019)
17.	Water clarifier sludge	Phosphorus, ammonium	60 days	The adsorption capacity of sludge sintered at 600 °C was 2.2 times higher than unsintered sludge (~80 %)	Mandai pond, a eutrophic pond in Osaka City, Japan	(Ichihara and Nishio 2013)
18.	Activated carbon and non-woven fabric mats	Nitrogen and phosphorus	210 days	The used of NFWM upper the capping material show more efficient to reduce nutrient (88–94%)	Sediment and lake water samples from lake in Anseong City, Korea	(Gu et *al.*,2017)
19.	Biochar	Ammonia-nitrogen	30 days	Reducing the ammonia in sediment up to 70.8 – 87.2 %.	Baiyangdian Lake, China	(Zhu *et al.*, 2019)
20.	Powdered-gypsum and granular gypsum	Phosphorus	45 days	Batch experiment show 80 % reduction of phosphorus for both powdered-gypsum and granular-gypsum	Eutrophic lake in Korea	(Kim *et al.*, 2007)[b]

3.3 Potential of sediment capping technology for Indonesian lakes

By considering the application of sediment capping technology using some materials in several lakes in other countries in Table 1, we summarized the positive and the negative impact of sediment capping technology as a scenario for eutrophication control. The positive impact of this technology includes good efficiency in reducing nutrients and preventing eutrophication; easy to apply by distributing uniformly over the surface of the waterbody or the area targeted for application; also, by knowing the duration of capping, the long-term monitoring during ISC implementation can be well-managed. Regarding the effect of sediment capping on the aquatic biota, several studies have proven that there is no lethal or sublethal toxicity produced by materials used such as activated carbon, apatite, zeolite, and organoclay (Özkundakci *et al.*, 2011; Paller and Knox, 2010; Rosen *et al.*, 2011). However, there was a change in feeding behavior and a decrease in growth rate using calcite and biopolymer materials for Rotifers, Cladocera and water insect species (Ghadouani *et al.*, 1998 and Galvez-Cloutier et al., 2012). The potential for toxicity to organoclays should not be overlooked due to their significant harmful effects on living organisms (Sarkar *et al.* 2013).

Furthermore, research conducted by Cho *et al.* (2009) observed no negative impact, while Cornelissen *et al.* (2011) and Jonker *et al.* (2009) reported the potential ecotoxicological minor impacts on benthic communities using activated carbon material. This is related to the characteristics of the sedimentary environment and the occurrence of physical or chemical changes in the capping material, such as changes in composition that depend on the type of activated carbon (raw or modified activated carbon) and particle size (75–300 µm) (Janssen and Beckingham 2013). Generally, sediment capping technology is an innovative proprietary water remediation technology with clear environmental benefits for healthy waterways to support economic, recreational and humanitarian well-being.

However, this technology has some negative impacts due to the limitations and undesirable effects of the technology. According to Public Service and Procurement Canada (Vallee, 2017), the primary disadvantage of sediment capping technology is that contaminants remain in place, resulting in an ongoing risk of contaminant loss, re-exposure, or disturbance of the contaminated sediment. Other limitations of using sediment capping as a remedial strategy as follows: (1) the risk of contaminant migration through diffusion and advection, particularly when contaminants easily transported through interstitial water and low association with sediment grain size; (2) the stability of a sediment cap can be disturbed by extreme weather events (such as storms, flooding and earthquakes); (3) local regulations may not allow capping in some areas; (4) long-term monitoring and maintenance of the cap is required. In addition, some temporary potential adverse effects include increased turbidity or suspended sediment within the water column, resuspension of contaminated sediments, and alteration of benthic habitat due to the placement of capping materials. To minimize the negative impacts, it is necessary to determine the most suitable and effective capping materials.

Sediment capping technology with various materials in Table 1 was applied in several lakes, including some batch experiments using water and sediment from the lakes. Those lakes have similarities with Indonesian lakes in terms of trophic state, except for surface area, depth and water volume. The trophic state of those lakes was eutrophic to hypereutrophic with the value of total nitrogen was > 750 µg/l, total phosphorus was > 30 µg/l, chlorophyll-a was > 5 $mg/m^{3,}$ and Secchi depth was < 2.5 m according to trophic classification from Regulation of Ministry of Environment 28/2009. The trophic state was similar with several lakes in Indonesia that is eutrophic to hypereutrophic (Ministry of Environment Republic of Indonesia, 2014). Most of the lakes in Indonesia are experiencing environmental problems, water quality decline and eutrophication because of the enhancement of tourism, industry, agriculture/plantation, settlement/domestic and fish cultivation using floating net cages.

However, there has been no effective effort to restore the water quality up to this time, especially for eutrophication issue. Hence, sediment capping technology has the potential to be implemented for eutrophication control in Indonesian lakes, and it has been recommended in Yuniarti *et al.* (2021). It is necessary to carry out laboratory tests to assess the characteristics of water quality and internal loading of nutrients and to determine the most suitable capping material to reduce nutrients. In addition, it is necessary to consider the selection of the most effective, efficient, easy, inexpensive, and eco-friendly capping materials. The selection of capping material must consider the potential positive and negative effects before this technique is applied to more extensive field-scale studies.

4. Conclusion

Several types of active capping materials such as calcite, zeolite, bentonite, activated carbon, sludge, biochar, and gypsum can be used to reduce the release of nutrients from sediment with an efficiency of 54–99 % and capping duration of 10–300 days in some eutrophic lakes. Sediment capping technology showed a promising result for lake ecosystem restoration in other countries. Therefore, this technology has the potential to be applied in Indonesian eutrophic lakes as a strategy for eutrophication control and sustainable management of lake ecosystems by considering the selection of the most effective, efficient, easy, inexpensive, and eco-friendly capping materials.

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Author Contributions

AS conducted the investigation, formal analysis of the literature review and preparation of the manuscript, **PS** and **ABS** were involved in conceptualization as well as reviewed the manuscript. All the authors read and approved the final manuscript.

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