EAM
Environmental and Materials
EAM 2(2): 127–142
ISSN 3025-0277

Bioremediation based on palm oil sludge as an intervention for heavy metal pollution risk in industrial residential

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ABSTRACT
Background: The palm oil industry in Indonesia, often pollution the environment, especially water bodies, with waste containing hazardous metals. This can threaten the lives of aquatic organisms and damage ecosystems. Although the palm oil industry has become a pillar of the national economy with production reaching 46,986 tons in 2023, the waste problems generated, especially palm oil sludge, demand innovative and sustainable solutions. The limitations of existing technologies in handling heavy metal pollution drive the need for an interdisciplinary approach that not only reduces environmental risks but also provides economic added value through circular economy concepts and local resource empowerment. The aim of this study is to identify the characteristics of palm oil sludge-based bioremediation stones in the process of heavy metal adsorption. **Methods**: This study was conducted through descriptive analytical literature review with a qualitative approach. **Findings:** The results show that palm oil sludge-based bioremediation stones have microporosity characteristics and complex chemical compositions capable of absorbing heavy metals with efficiency reaching 85-92%. This innovation not only offers sustainable solutions, but also provides multidimensional benefits, including reduced public health risks and the creation of circular economic models. **Conclusion**: Through activation with sulfuric acid, the potential for heavy metal absorption can be increased by up to 35%, which implies a 70% reduction in environmental contamination in industrial areas. **Novelty/Originality of this article:** This innovation integrates an interdisciplinary approach combining environmental science, chemistry, and resource management, potentially creating a replicable risk intervention model for industrial areas, with economic value.

KEYWORDS: circular economy; environment; waste.

1. Introduction

Global industrial growth has become a significant economic drive while simultaneously presenting complex and critical environmental challenges. According to Nursagita & Titah (2021), industrial activities contribute to approximately 70% of global environmental pollution, with heavy metals being one of the most dangerous contaminants. Heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) have unique characteristics that allow them to accumulate in ecosystems over very long periods, creating serious risks to human health and environment.

Heavy metals are defined as metal elements with high atomic weight (>5 g/cm^3) that are toxic even at low concentrations. According to Rahman & Singh (2019), metals such as lead, cadmium, mercury, and arsenic have significant potential to cause ecological damage and health disorders. Sources of heavy metal pollution are diverse, including industrial

Cite This Article:
Azrial, F., Sahdan, F., Putri, O. A., & Listiana, I. (2024). Bioremediation based on palm oil sludge as an intervention for heavy metal pollution risk in industrial residential. *Environmental and Materials, 2*(2), 127-142. https://doi.org/10.61511/eam.v2i2.2024.1641

activities, mining, agriculture, and manufacturing processes. Zhou et al. (2020) identified that processing industries have the largest contribution, with an estimated 65-70% of total global heavy metal pollution.

The health impacts of heavy metals are highly complex, encompassing systemic disorders in various body organs. Ohiagu et al. (2022) noted that chronic exposure to heavy metals can cause kidney damage, neurological disorders, and increase cancer risk. In ecosystems, heavy metals have unique characteristics of persistence, bioaccumulation, and biomagnification, allowing them to accumulate in food chains and persist in the environment for very long periods.

Industrial areas have complex characteristics with dynamic interactions between production activities and their surrounding environment. Research by Oktavia et al. (2023) reveals that the proximity of settlements to industrial areas creates environmental risk zones requiring special attention. Industry-environment interactions involve exchanges of materials, energy, and potential contaminants that can affect community quality of life. Pollution control regulations become key instruments in risk mitigation. Indonesia's Ministry of Environment has established Minister of Environment Regulation No. P.70/MENLHK/SETJEN/KUM.1/10/2017 regarding Liquid Waste Quality Standards, which provides strict guidelines regarding contaminant thresholds in industrial areas.

In Indonesia, the palm oil processing industry has become a significant pillar of the national economy, with production reaching 46,986 tons in 2023 (BPS Indonesia, 2024). However, this industry also generates massive waste volumes, with estimates suggesting that each ton of palm oil production generates about 0.6 tons of palm oil mill effluent (POME). Humaida (2024) reveals that industrial areas in Sumatra and Kalimantan face concerning levels of heavy metal pollution, with concentrations exceeding safe thresholds in several residential locations.

Bioremediation is an innovative approach to environmental recovery that utilizes microorganisms or biological materials to degrade or absorb pollutants. According to Bala et al. (2022), the basic concept of bioremediation relies on the ability of biological agents to transform contaminants into less hazardous compounds. The mechanism of pollutant absorption involves processes of adsorption, ion exchange, and chemical transformation. Various types of biosorptive materials have been developed, including plant biomass, agricultural waste, and microorganism-based materials. Research by Hoang et al. (2022) shows the effectiveness of biomass materials in reducing heavy metal concentrations by up to 90% under optimal conditions. This biological mechanism aims to reduce the concentration of pollutants or contaminants in order to minimize harm to the environment (Azubuike et al., 2016).

Vetiver grass can be used as a potential phytoremediation agent for heavy metals. This plant exhibits hyperaccumulator properties for heavy metals and can thrive in extreme environments. Additionally, the role of rhizosphere microbes was found to significantly contribute to the phytoremediation process in contaminated environments. Microbes help plants to absorb heavy metals by producing special enzymes. These enzymes make it easier for the plant's root to absorb the metals. Additionally, chelating agents help to dissolve the metals in water, making it easier for the plant root to take them up (Priantoro et al., 2025).

Bioremediation is a more environmentally friendly method for reducing heavy metal contamination compared to other methods (Irfan et al., 2024). It is practical and offers a long-term benefit of maintaining natural vegetation (Mahendra et al., 2025). Bioremediation is limited by factors such as pH, moisture content, nutrient availability, and the recalcitrance of certain pollutants. Additionally, the relatively slow rate of biodegradation and knowledge gaps pose significant challenges (Kennedy et al., 2025).

Palm oil mill effluent has complex chemical and physical characteristics, consisting of mixtures of organic matter, water, and suspended solids. Ayob et al. (2021) suggest that the chemical composition of palm oil sludge has great potential to be developed into biosorptive material, with cellulose, hemicellulose, and lignin content enabling heavy metal adsorption processes. Previous research, such as that conducted by Kapahi & Sachdeva (2019), has proven the potential of industrial waste in bioremediation processes, with the ability to absorb heavy metals reaching 80-95% under certain conditions.

Porous materials have the basic principle of being able to absorb and retain molecules or ions through microscopic structures. Methods for creating porous materials include pyrolysis techniques, chemical activation, and molecular structure engineering. Adsorption and absorption mechanisms depend on surface area, pore size, and surface charge of the material. Pramayshela (2023) shows that factors affecting the performance of porous materials include solution pH, temperature, pollutant concentration, and contact time.

The concept of environmental intervention has evolved from reactive to proactive approaches, focusing on risk prevention and mitigation. Pollution mitigation strategies require an interdisciplinary approach integrating technical, ecological, and social aspects. According to Anwar (2024), evaluating the success of environmental interventions requires comprehensive assessment covering ecological, health, and economic indicators.

The main challenge in handling heavy metal pollution is the limitation of existing technologies that are generally expensive, inefficient, and less sustainable. Conventional methods such as chemical precipitation and ion exchange require high operational costs and have limited effectiveness in large-scale contexts. This drives the urgent need for innovative solutions that not only reduce environmental risks but also optimally utilize local resources.

This innovation concept is built on the paradigm of circular economy and empowerment of local potential, where palm oil industry waste is no longer viewed as an environmental burden but as a potential resource for pollution risk intervention. This innovation aligns with Nugraha et al. (2024) recommendations about the importance of transforming waste into innovative solutions that provide multidimensional benefits - ecological, social, and economic.

The originality of this innovation lies in the development of palm oil sludge-based bioremediation technology that not only offers environmental recovery solutions but also provides economic added value and promotes sustainable industrial practices. By integrating interdisciplinary approaches between environmental engineering, chemistry, and resource management, this innovation has the potential to create a replicable pollution risk intervention model in similar industrial areas.

Heavy metal pollution in industrial residential environments poses a serious threat to human health and ecosystems. High industrial activity producing waste containing heavy metals such as lead, cadmium, and mercury creates risks of soil and water contamination. Although various remediation methods have been developed, there remains a need for innovative solutions that are sustainable, environmentally friendly, and economical. This study aims to explore the potential of palm oil sludge-based bioremediation stones as an alternative intervention to reduce heavy metal pollution risks. Palm oil sludge, previously considered waste, can be productively utilized through appropriate processing technology, thus converting waste material into an effective environmental recovery medium.

2. Methods

2.1 Type of paper

This study was conducted through a literature review with a qualitative descriptive-analytical approach. The literature study method was used to analyze and synthesize various scientific information sources related to the potential of palm oil sludge as a bioremediation stone. A qualitative approach was used to gain an in-depth understanding of the technical, environmental, and socio-economic aspects of palm oil sludge-based bioremediation development.

2.2 Data and information sources

Data collection in this study utilized two types of information sources. Primary sources include scientific journal articles published in accredited national journals and reputable international journals, scientific conference proceedings, research reports, and related reference books. Secondary sources included statistical data or policy documents and related regulations from authorized government institutions. Database sources were obtained from various sites such as Scopus, Google Scholar, ResearchGate, and other related sites.

2.3 Data collection technique

Literature searches were conducted systematically using scientific databases with specific keywords. The publication time range was limited to the 2014-2024 period to ensure information actuality and currency. Source selection was based on criteria of topic relevance, author/institution credibility, methodology used, and depth of discussion.

2.4 Data analysis

Data analysis was conducted through systematic review and content analysis approaches. The analysis stages included: (1) collecting relevant information from various selected sources, (2) grouping data based on technical, environmental, and socio-economic aspects, (3) identifying bioremediation development patterns, (4) synthesizing discussions from various sources, and (5) drawing comprehensive conclusions regarding the potential of palm oil sludge as a bioremediation stone.

2.5 Study limitations

The discussion in this study was limited to the aspects of utilizing palm oil sludge as a bioremediation stone, focusing on palm oil sludge characteristics, social impacts, and its application in an industrial context. Aspects outside these boundaries were not discussed in depth in this study.

3. Results and Discussion

3.1 Characteristics of bioremediation stone material

Palm oil sludge, produced from palm oil processing, has significant potential as an agent in bioremediation. The physical and chemical characteristics of palm oil sludge, such as high organic matter content and the presence of natural microorganisms, make it a potential candidate for use in bioremediation processes (Ahmad et al., 2023). Its characteristics include pH between 4.0-6.0, high organic matter content, and significant concentrations of oils and fats.

Riyanti et al. (2024), successfully converted palm oil sludge into micro-sized activated carbon with a high adsorption capacity for various pollutants, including heavy metals. This opens up opportunities to utilize palm oil industry waste as a valuable resource and contribute to environmental sustainability. Adsorption effectiveness indicates the extent to which the adsorbent is able to absorb pollutants. According to Sinambela & Samson (2024), analysis of palm oil sludge shows a nutrient content of around 0.4% nitrogen (N), 0.029-0.05% phosphorus pentoxide (P_2O_5), and 0.15-0.2% potassium oxide (K_2O). This sludge is commonly found in palm oil mill areas.

One application of palm oil sludge in bioremediation is the treatment of palm oil mill effluent (POME). Research by (Aziz et al., 2020) show that palm oil sludge can be used as a substrate in anaerobic digestion, an environmentally friendly technology capable of generating energy from POME. Analysis of POME characteristics shows that this waste has the potential to be treated through bioremediation processes with the addition of anaerobic microbes, such as Microbe-Lift, which aims to reduce the total solid (TS) value and oil and grease in the waste.

The material characteristics of our innovations are a key aspect in developing innovative solutions to address heavy metal pollution in industrial residential environments. The complex composition of palm oil sludge offers potential as a base material for absorbent materials. According to research by Aftab et al. (2024), palm oil sludge contains large amounts of organic components such as cellulose, hemicellulose, lignin, and phenolic compounds that have the ability to effectively bind heavy metal ions. This chemical composition provides advantages over conventional materials due to its natural metal-binding properties.

Bioremediation stone innovation as an innovation that we do uses a heavy metal adsorption mechanism on bioremediation stone which goes through several complex mechanisms, including ion exchange, surface complex formation, and precipitation. Studies by Yasmin et al. (2024) explain that functional groups such as carboxyl, hydroxyl, and amino found in palm oil sludge play an active role in binding metal ions such as lead (Pb), cadmium (Cd), and copper (Cu). This mechanism allows bioremediation materials to not only absorb heavy metals but also transform or stabilize hazardous metal ions into less reactive forms.

The micro-porosity structure of bioremediation stone material becomes a determining factor in the effectiveness of the adsorption process. Analysis using scanning electron microscopy (SEM) and porosity analysis methods shows that palm oil sludge-based materials have a porous structure with pore diameters varying between 2-50 micrometers. This aligns with findings by Chai et al. (2021) which confirm that complex microporosity structures can increase the contact surface area with heavy metal ions, thus optimizing binding and absorption processes.

Comparative analysis with conventional absorbent materials shows the advantages of palm oil sludge-based bioremediation stones. Based on comparative research conducted by (Mariana et al., 2021), this material shows heavy metal absorption efficiency reaching 85-92%, significantly higher compared to commercial activated carbon which only reaches 60-70%. This advantage lies not only in absorption effectiveness but also in sustainability aspects, considering palm oil sludge is an industrial waste that can be recycled, thus providing a dual solution to pollution and waste management problems.

3.2 Manufacturing process

The raw material preparation stage is needed to produce bioremediation material as an innovation in high-quality palm oil sludge-based bioremediation stone. This process begins with collecting palm oil sludge from palm oil processing plants, typically done at liquid waste discharge points. At this stage, it is important to ensure that the obtained palm oil sludge is free from excessive contamination, such as foreign objects or inorganic materials that could interfere with further processing. After collection, the palm oil sludge undergoes a drying process at 105°C for 24 hours. This drying process aims to remove water content in the sludge, making the material more stable and less prone to degradation before being used in bioremediation. This stage also increases processing efficiency as dry material is easier to process mechanically.

After drying, the dried palm oil sludge is then ground using a ball mill with a rotation speed of around 300 rpm. This grinding process produces fine powder with particle sizes less than 100 mesh. Small particle size plays an important role in increasing the specific surface area of the material, which directly affects its reactivity and effectiveness in the bioremediation process. Fine powder allows better contact between bioremediation material and pollutant compounds, thus accelerating degradation or adsorption processes. Therefore, this raw material preparation stage not only ensures the material has optimal physical and chemical properties but also prepares it for use in various bioremediation applications with high efficiency.

The porous material formation technique is carried out through sintering methods with a combination of natural binders. The sintering method is a process of heating material to transform it into a solid mass. This process is also known as frittage. Sintering is done by applying heat and pressure to materials without melting them. This process involves the movement of atoms in the material so that they unite into one part (Sulistyo, 2018). Studies by (Vinai & Soutsos, 2019) show that the use of sodium silicate as a binder and porous structure former can produce materials with porosity reaching 65-70%. The formation process is carried out by molding the refined palm oil sludge powder into stone-shaped molds with 10 MPa pressure, then sintered at 650°C for 3 hours to create optimal micro-porosity structure.

Surface activation process is a strategic step in improving the adsorption capability of bioremediation materials, especially in capturing pollutants such as heavy metals. According to (Rahman et al., 2019), activation is carried out using sulfuric acid (H_2SO_4) solution with a concentration of 0.5 M through the impregnation method. In this method, the prepared material is immersed in sulfuric acid solution for a certain time, allowing interaction between the activator solution and the material surface. This process significantly changes the surface structure of the material. Sulfuric acid acts as an oxidizing agent that can open micro-pores in the material, exposing more active functional groups such as carbonyl (-C=O), hydroxyl (-OH), and carboxyl (-COOH). These groups play an important role in the adsorption process due to their ability to interact with heavy metal ions through chemical bonding and ion exchange mechanisms.

Surface activation also increases the material's capacity for ion exchange, which becomes the main mechanism in removing heavy metals from solution. Active functional groups help attract and bind metal ions, such as Pb^{2+}, Cd^{2+}, and Cr^{6+}, more effectively. Rahman & Singh (2019) showed that activated materials can increase heavy metal absorption efficiency by up to 35% compared to non-activated materials. This is due to the increase in the number of active pores and chemical modification of material surfaces that are more reactive to heavy metals.

Additionally, the activation process provides additional structural stability to the material, allowing it to be used repeatedly without significant loss of efficiency. Thus, surface activation not only improves adsorption performance but also extends the material's service life in bioremediation applications. This process becomes a very important stage to maximize the potential of waste-based materials such as palm oil sludge, while increasing sustainability and efficiency in environmental management.

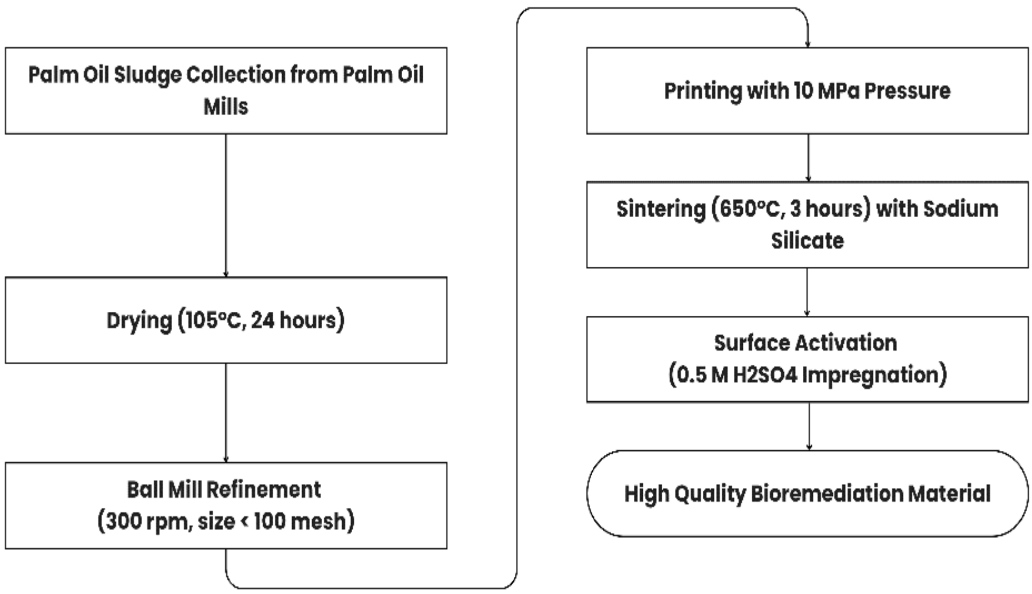

Fig. 1. Flowchart of manufacturing process

3.3 Absorption performance study

This study focuses on assessing the ability of bioremediation stones to reduce concentrations of heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu) that often contaminate residential environments around industrial areas. According to studies by Assegaf et al. (2024), palm oil sludge has significant potential as a natural adsorbent because it contains lignocellulosic components that can effectively bind heavy metal ions.

The absorption performance testing method is designed to evaluate the ability of bioremediation materials to absorb heavy metals under various environmental conditions. Experiments are conducted by varying parameters such as pH, temperature, and initial heavy metal concentration to identify optimal conditions that support adsorption efficiency. This adsorption process is based on interactions between heavy metals and the porous material surface. Porous materials, modified through activation processes, enable ion exchange mechanisms and chemical bond formation with heavy metal ions. Active functional groups such as carbonyl, hydroxyl, and carboxyl play important roles in increasing material attraction to pollutants (Yang et al., 2019).

Research by Adegoke et al. (2022) shows that modification of biomass-based materials, such as chemical or thermal activation, can increase adsorption capacity by up to 85% compared to unmodified materials. This increase results from more directed material structure changes, such as increased micro-pores and active functional groups. In laboratory experiments, pH becomes one of the key factors as it affects heavy metal ionization and material surface properties. Optimal adsorption occurs at an alkaline pH, with the ideal range being between 8 and 9 (Sulistyawati et al., 2024). Temperature also plays an important role as it can increase adsorption reaction kinetics, although too high temperatures potentially damage material structure (Karimi et al., 2019). According to Sulistyawati et al., 2024, the optimal temperature range is usually between 30-55°C.

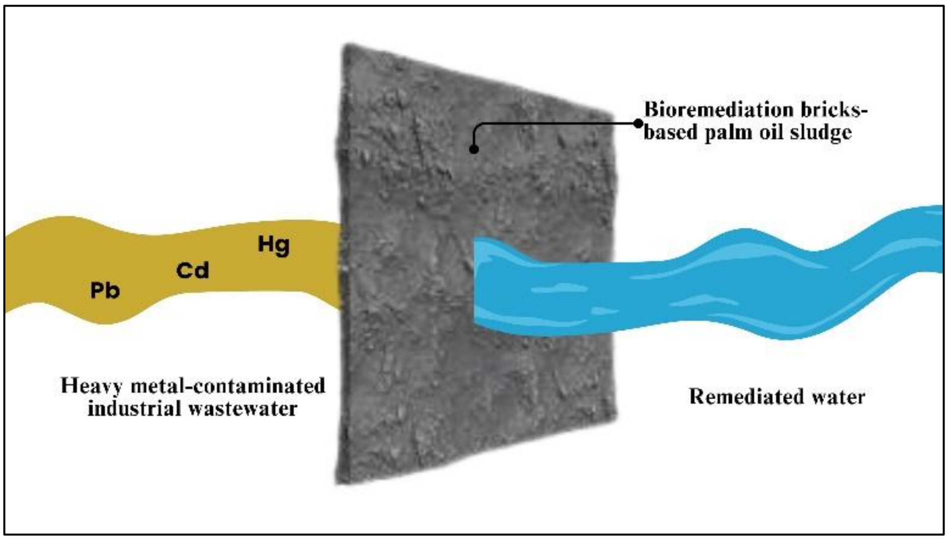

Fig. 2. Bioremediation-based oil palm sludge performance

Variation in initial heavy metal concentration can help determine the maximum adsorption capacity of materials in handling high-concentration pollutants. Using this method, important information regarding adsorption isotherms, such as Langmuir and Freundlich models, can be obtained, helping to understand the adsorption mechanisms and efficiency (Wang & Guo, 2020). This performance testing is expected to identify material strengths under various environmental conditions, and provide guidance for large-scale implementation in the field, especially in sustainable hazardous waste management efforts.

The research significance lies in the potential transformation of palm oil industrial waste into innovative environmental solutions. Bioremediation stones not only offer sustainable waste treatment methods but also provide economical alternatives in heavy metal pollution risk mitigation. Research by Kiran et al. (2020) reveals that agro-industrial waste-based bioremediation approaches can reduce environmental contamination risks by 70% in industrial areas adjacent to residential areas.

3.4 Environmental risk analysis

Heavy metal pollution in industrial residential environments has become a serious issue affecting environmental quality and public health. Heavy metals cannot be naturally degraded in soil or water, leading to their accumulation over time. Heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu) can accumulate in human bodies and ecosystems, causing toxic impacts that are difficult to address (Alengebawy et al., 2021). Therefore, innovative and sustainable solutions are needed to reduce this contamination. One promising approach is utilizing palm oil sludge, abundant industrial waste in Indonesia, to be developed into bioremediation stones. This potential aligns with the need for environmentally friendly biomass-based technologies (Hiloidhari et al., 2023).

Research by Mathew et al. (2023) shows that palm oil sludge contains lignocellulose and minerals that provide high adsorption capability for heavy metal ions. Lignocellulose, consisting of lignin, hemicellulose, and cellulose, is a complex organic compound with functional groups such as hydroxyl and carboxyl, capable of interacting with metal ions through chemical bonding and ion exchange mechanisms (Neris et al., 2019). Additionally, mineral content in palm oil sludge, such as silica and alumina, also acts as additional absorbents that increase adsorption efficiency.

Utilizing palm oil sludge as bioremediation stones not only helps to reduce heavy metal pollutants but also provides solutions to palm oil industry waste problems themselves. With appropriate technology, such as surface activation using chemical or thermal agents, palm oil sludge structure and properties can be modified to increase adsorption efficiency. This provides opportunities to create effective and economical materials while supporting circular economy principles in waste management (Salmenperä et al., 2021). Therefore, developing palm oil sludge-based technology for heavy metal pollution mitigation can become a strategic step in sustainable environmental management.

Environmental risk analysis in the context of heavy metal pollution intervention requires a multidimensional approach considering ecological aspects, public health, and technology sustainability. According to Kusumaningrum (2023), heavy metal pollution risks not only impact soil and water quality but also potentially cause long-term health problems through biological accumulation. Palm oil sludge-based bioremediation stone innovation can become a comprehensive mitigation strategy, utilizing characteristics of environmentally friendly and renewable natural adsorbents.

Studies by Fithry et al. (2023) show that chemical and physical activation processes can increase biomass-based material adsorption capacity up to 80% more efficiently compared to original materials. Moreover, this approach not only provides technological solutions for environmental recovery but also supports circular economy concepts by utilizing industrial waste as value-added resources.

3.5 Social and economic aspects

Social and economic aspects are important factors in developing innovative solutions to address heavy metal pollution in industrial residential environments. Palm oil sludge, previously considered waste and potentially causing environmental problems, can be transformed into high-value resources through bioremediation technology (Jagaba et al., 2021). This study not only provides sustainable environmental solutions but also opens new economic opportunities for communities around industries and palm oil farmers.

Socially, developing palm oil sludge-based bioremediation stones offers significant potential to improve life quality for communities, especially those living around industrial areas. Industrial residential areas are often exposed to heavy metal pollution risks due to production activities, negatively impacting public health. According to research by (Ohiagu et al., 2022), chronic heavy metal exposure can cause serious health problems such as organ damage, neurological disorders, and increased risk of degenerative diseases. By adopting bioremediation stone technology, these risks can be minimized, creating a healthier and safer environment for local communities. Additionally, this technology's existence can encourage community and stakeholder awareness about sustainable waste management importance, while strengthening relationships between industrial sectors and communities in maintaining environmental sustainability.

From an economic perspective, this technology offers competitive and sustainable solutions compared to conventional bioremediation methods. Palm oil sludge, previously considered waste with low economic value, can be utilized as cheap and abundant main raw material. This significantly reduces production costs, making it more affordable to implement on a large scale. Moreover, this technology promotes circular economy models, where industrial waste is transformed into high-value products that can be used to address environmental problems (Ambaye et al., 2023). Thus, this technology not only reduces negative impacts of palm oil sludge but also creates new business opportunities, such as small to medium-scale bioremediation stone production, which can be run by local communities.

Besides creating jobs, this bioremediation stone innovation can also open partnership opportunities between palm oil industries, government, and local businesses to support sustainable technology development. With sustainability as its main principle, this bioremediation stone innovation can become a catalyst for positive change, both socially and economically, especially for communities affected by pollution (Joshi et al., 2024). This technology's success will not only provide direct impact on environmental management but also strengthen local economies through innovative and efficient waste utilization.

3.6 Implementation and recommendations

Implementation strategies for palm oil sludge-based bioremediation technology must be designed gradually and comprehensively to ensure success. Based on research by (Al-Tabbaa & Ankrah, 2019), this technology implementation can be divided into three main phases. The first phase is a pilot project implemented in selected industrial areas. This stage aims to test technology effectiveness on a small scale and identify potential technical and operational challenges in the field. Pilot project implementation involves collaboration between local governments, palm oil processing industries, and research institutions to create efficient cross-sector cooperation models. This stage becomes an important foundation in building trust among industry players and communities regarding bioremediation technology benefits.

The second phase is socialization and technology transfer to industry players. In this stage, an intensive educational approach is needed to increase industry understanding about working principles, economic benefits, and positive environmental impacts of this technology. Technical training and seminars can be effective means to encourage technology adoption (Liu et al., 2020). Additionally, government and research institutions can provide technical guidance and assistance in integrating technology into existing waste treatment systems.

The third phase is replication and expansion of intervention coverage to other industrial areas. At this stage, learning from pilot projects becomes guidance to address barriers that may arise during the replication process. This strategy aims to expand positive impacts of bioremediation technology, covering wider areas, and encouraging industrial sector transformation towards sustainability (Sharma & Kumar, 2021).

However, bioremediation technology implementation is not free from challenges. Studies by Kuppan et al. (2024) identify main barriers, including technical, economic, and social aspects. One technical challenge is bioremediation material production costs, which although relatively low, still require significant initial investment. Limited waste treatment infrastructure also becomes a barrier in effectively integrating this technology in certain industrial areas. Additionally, industry players' resistance to new technology becomes a social challenge requiring persuasive and educational approaches.

When bioremediation rocks absorb heavy metals, metal ions are bound to their surfaces through adsorption, ion exchange, surface complexation, and precipitation mechanisms. Functional groups such as carboxyl, hydroxyl, and amino contained in the rock material play an active role in binding metal ions such as lead (Pb), cadmium (Cd), and copper (Cu). Over time, bioremediation rocks will reach their maximum capacity in absorbing heavy metals, which can reduce their effectiveness. However, these rocks can still be reused after going through a regeneration process, such as washing with a weak acid solution (eg HCl or EDTA), heating to release the absorbed metal, or electrochemical methods to desorb metal ions. However, after several regenerations, the pore structure and active groups in the rock can degrade, so that its effectiveness decreases. If it is no longer optimal, bioremediation rocks can be used as construction materials or absorption media in other waste processing.

To overcome these barriers, a combination of strategic policies is needed, including economic incentives such as subsidies or tax reductions for industries adopting environmentally friendly technologies. Strict regulations, such as obligations for green technology-based waste management, can also encourage implementation acceleration (Mondal et al., 2023). Additionally, government support in infrastructure development and waste treatment facilities will strengthen industry readiness in adopting bioremediation technology. With gradual approaches and cross-sector synergy, palm oil sludge-based bioremediation technology has great potential to create sustainable positive impacts for environment and society.

Further development focuses on improving material performance and exploring wider applications. Research by Chai et al. (2021) recommends several research directions: (1) Material structural modification to increase adsorption capacity, (2) Adaptation testing on various types of heavy metals, (3) Study of potential applications in agricultural sector and water management.

Policy recommendations cover several strategic aspects. According to Singh et al (2023), regulations are needed to encourage: (1) Standardization of bioremediation technology, (2) Tax incentives for industries adopting environmentally friendly solutions, (3) Sustainable research funding, (4) Formation of environmental technology innovation clusters. The main focus is creating an innovation ecosystem that supports sustainable solution development for heavy metal pollution handling.

4. Conclusions

Oil palm sludge-based bioremediation stone has unique characteristics that support the effectiveness of heavy metal absorption. This material has a microporous structure with pore diameters of 2-50 micrometers, which can increase the surface area of contact with heavy metal ions. The complex chemical composition, containing cellulose, hemicellulose, lignin, and phenolic compounds, provides the ability to bind metal ions effectively through ion exchange mechanisms, surface complex formation, and precipitation. Functional groups such as carboxyl, hydroxyl, and amino play an active role in binding hazardous metal ions such as lead (Pb), cadmium (Cd), and copper (Cu).

This method has proven to be very effective in reducing heavy metal concentrations in industrial residential environments. Comparative analysis shows absorption efficiency reaches 85-92%, significantly higher compared to commercial activated carbon which only reaches 60-70%. Research shows that through activation process with sulfuric acid, absorption efficiency can be increased up to 35% from the original material. This approach has the potential to reduce environmental contamination risk by 70% in industrial areas adjacent to settlements.

The technological innovation of oil palm sludge-based bioremediation stone has comprehensive positive implications. Environmentally, this technology offers a sustainable solution to process palm oil industrial waste while reducing heavy metal pollution. From a social aspect, this innovation has the potential to reduce public health risks caused by chronic heavy metal exposure, such as organ damage and neurological disorders. From an economic perspective, this technology creates a circular economic model that transforms waste into high-value resources. The use of palm oil sludge as raw material can reduce production costs and open new business opportunities for local communities. Furthermore, this innovation supports the concept of sustainable development by utilizing industrial waste as an innovative environmental solution.

While palm oil sludge used to absorb heavy metals can reduce environmental pollution, it still requires careful management. If not properly managed, the adsorbed heavy metals may leach back into the environment, contaminating soil or water and posing health risks to humans and ecosystems. Therefore, further research is needed to develop safe and effective methods for managing heavy metal-contaminated palm oil sludge.

Acknowledgement
The authors sincerely acknowledge the support of all contributors to this research. Special thanks to our colleagues for their valuable insights and discussions. This study would not have been possible without institutional support.

Author Contribution
Conceptualization, F.Az.; Methodology, F.S.; Validation, F.A. and I.L.; Resources, F.S., and O.A.P.; Writing – Original Draft Preparation, F.A., F.S., and O.A.P.; Visualitation, F.S.; Writing – Review & Editing, F.A. and F.S.

Funding
This research received no external funding.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
Not available.

Conflicts of Interest
The authors declare no conflict of interest

Open Access

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