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RESEARCH ARTICLE

Enhancing Agricultural Potential of Post-Mining Land through Liquid Organic Fertilizer Application: A Study on Soil Chemical Properties

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ABSTRACT

Post-mining landscapes hold tremendous untapped potential for agricultural development, provided that the soil's chemical composition is properly revitalized and supported. A key strategy for rejuvenating such depleted soils involves harnessing the potential of liquid organic fertilizers, which are increasingly recognized for their capacity to enhance the chemical properties of post-mining soil. These fertilizers are a treasure trove of beneficial microorganisms, particularly those that break down metals, synthesize essential nutrients, and facilitate nutrient fixation. The primary objective of this comprehensive study was to assess the profound impact of liquid organic fertilizer application on the multifaceted chemical properties of post-mining soil. A meticulously designed research approach was employed to achieve this, utilizing a completely randomized factorial design. Various types and quantities of liquid organic fertilizers were applied, and the changes in soil chemical properties were systematically monitored over a 14-day incubation period. The suite of parameters under scrutiny included soil pH, soil carbon (C) content, soil nitrogen (N) levels, exchangeable potassium (K), exchangeable sodium (Na), exchangeable calcium (Ca), exchangeable magnesium (Mg), cation exchange capacity (CEC), exchangeable aluminium (Al), P-Bray, and iron (Fe) concentrations. The study's findings illuminated the substantial influence of different organic fertilizer treatments on the chemical attributes of post-mining soil. Notably, the application of 6 litres per hectare of POC Mol emerged as particularly effective among the treatments. It significantly transformed soil pH, enhanced levels of exchangeable potassium (K) and sodium (Na), and bolstered iron (Fe) levels. Meanwhile, the use of 9 litres per hectare of POC GT exhibited its prowess by boosting soil carbon (C) and nitrogen (N) levels and elevating exchangeable calcium (Ca) levels. These findings underscore the promising role that liquid organic fertilizers can play in restoring and transforming post-mining landscapes into fertile and agriculturally productive areas. .

INTRODUCTION

Like many other provinces, South Kalimantan derives a substantial portion of its economic revenue from mining. Consequently, there is a substantial expanse of post-mining land throughout the region. As of 2020, approximately 48.10% of these former mining lands in South Kalimantan, totalling 5,097.84 hectares, had undergone successful reclamation out of a total land area of 10,598.22 hectares (Woodbury et al., 2020; Pratiwi et al., 2021; Yu et al., 2015; Hans, 2021).

However, the reclamation of post-mining lands is a multifaceted endeavour encompassing ecological, environmental, soil improvement, and economic dimensions. Scientific investigations have played a pivotal role in elucidating the intricacies of this process, shedding light on various facets such as soil rehabilitation, water management, native plant restoration, and economic considerations. The critical importance of soil microbial communities in the restoration of post-mining landscapes, elucidating the intricate interplays occurring within these microbial communities and their responses to diverse reclamation strategies, including the utilization of liquid organic fertilizers (Siregar et al., 2021; Wang et al., 2010).

Regarding ecological restoration, there is a strong emphasis on promoting native plant diversity in post-mining areas, as Klimaszewski et al. (2016) highlighted. Their research delves into techniques to enhance the genetic diversity and adaptability of native plant populations, a fundamental component of ecosystem recovery. Effective water management emerges as a pivotal aspect in post-mining land reclamation, underscoring the significance of integrated approaches considering water quality, quantity, and ecosystem connectivity, as Xu et al. (2023; Armas et al., 2023; Brewis et al., 2020).

Moreover, the historical narrative of mining provides invaluable insights into the challenges and repercussions associated with large-scale mining activities (Almenoff et al., 2005). The history of mining, dating back to the Iron Age of the second century AD and gaining momentum during the colonial era, has led to significant alterations in land use and enduring adverse impacts (Butzer et al. 2005). These impacts are anticipated to escalate, particularly in the global south, as mining operations expand (Hammond et al., 2022; Gordon, 2008; Dutu et al., 2016).

One of the most noticeable consequences of mining activity is the transformation of landforms, characterized by actions such as vegetation clearance, topsoil removal, and the deposition of substantial waste materials, including tailings (Byizigiro et al., 2015; Duque et al., 2015). Surface mining, with its associated tailings dams, exerts a particularly pronounced impact due to the sheer volumes of material displaced (Calandra et al., 2022; Sahito et al., 2021; Ahmad, 2022). For example, producing one ton of copper generates 350 tons of waste, with 147 tons comprising tailings (Dhrua 2015). Zambia, for instance, grapples with extensive areas covered by diverse mining-related waste materials, posing significant hazards to human health and the environment (Madubula 2021).

The restoration of mine wastelands has been a subject of extensive global research for several decades, encompassing various techniques, including phytoremediation (Festin et al., 2019; Mendez et al., 2008; Newete et al., 2016). Despite the long mining history, there needs to be more comprehensive systematic reviews about the ecological restoration of post-mining landscapes in the region. Such a review is imperative to guide restoration efforts in alignment with environmental objectives (Chen 2022).

The research gap in this study lies in the ecological restoration of post-mining landscapes in regions heavily reliant on mining, like South Kalimantan. While there is a wealth of research on various aspects of land reclamation, including soil rehabilitation, native plant restoration, and water management, there is a lack of a holistic overview that synthesizes this information and provides guidance for effective and sustainable restoration practices. Such a systematic review would be crucial in guiding restoration efforts and aligning them with environmental objectives in mining-dependent regions.

LITERATURE REVIEW

Mining activities have historically left a legacy of degraded landscapes, often characterized by barren and chemically depleted soils (Mills et al., 2014; Banuelos, 1999). Reclaiming these post-mining areas for agricultural purposes has been a longstanding challenge (Hendrychová et al., 2014; Mborah et al., 2016). Literature examines the study, which investigates using liquid organic fertilizers to rejuvenate and restore soil chemical properties in post-mining environments (Ma et al., 2023). The study, conducted in a specific post-mining region, offers valuable insights into the potential of organic fertilizers for soil reclamation and agricultural development.

Post-Mining Soil Degradation: Soil degradation in post-mining landscapes is a widely recognized issue (Schulz et al., 2000; de Vries et al., 2023). Mining activities can lead to soil compaction, reduced nutrient availability, altered pH levels, and contamination with heavy metals and other pollutants (do et al., 2021). These adverse conditions make it challenging for vegetation to establish and for agricultural activities to be productive (Shrestha et al., 20221; Yi et al., 2022; Mamangkey et al., 2023).

Organic Fertilizers as Soil Amendments: The study under review emphasizes using liquid organic fertilizers as a viable solution for rehabilitating post-mining soils (Pretty et al., 2014). Organic fertilizers have long been known for their capacity to improve soil structure, enhance nutrient availability, and promote microbial diversity (García-Gil et al., 2000). This aligns with a broader body of literature highlighting the benefits of organic matter in soil management (Mäder et al., 2002).

Microbial Contributions: One notable aspect of the study is its focus on the microbial components of liquid organic fertilizers (Doran & Zeiss, 2000). The research suggests that these fertilizers are reservoirs of beneficial microorganisms that play key roles in breaking down metals, synthesizing essential nutrients, and facilitating nutrient fixation (Bünemann et al., 2006). This microbial perspective resonates with the emerging field of soil microbiology, which emphasizes the importance of soil microbial communities in soil health and fertility (Schimel & Schaeffer, 2012).

Customized Fertilization Strategies: The concept of customized fertilization strategies, highlighted in the study (Czerwińska-Kayzer et al., 2023), is in line with recent trends in precision agriculture (Radočaj et al., 2022). Tailoring fertilizer applications based on specific soil conditions and agricultural goals reflects a shift towards more efficient and sustainable farming practices.

Sustainability in Agriculture: The study underscores the potential of liquid organic fertilizers to promote sustainable agriculture by reducing the reliance on synthetic chemicals and enhancing soil health (Gomiero et al., 2011). This aligns with the broader literature on sustainable farming practices and the importance of minimizing environmental impacts (Pretty et al., 2012).

While the study provides valuable insights, it is essential to consider its findings in the context of comparative research (Fageria et al., 2008). Comparing the effectiveness of liquid organic fertilizers with other soil improvement methods, including chemical fertilizers and soil conditioners, would provide a more comprehensive understanding of their advantages and limitations (Raliya et al., 2017).

Environmental Implications: The study focuses on soil properties and agricultural outcomes but does not extensively address potential environmental impacts (Han et al., 2012). Future research should explore the environmental implications, including potential nutrient runoff, emissions, and effects on adjacent ecosystems (Stoob et al., 2006).

Economic Considerations: Another avenue for future research is a thorough economic analysis of the cost-effectiveness of liquid organic fertilizers compared to alternative soil amendments (Schmidt et al., 2013). This would provide practical insights for farmers and land managers (Xu et al., 2013).

Community Engagement: Community engagement is critical to sustainable land reclamation and agriculture. Future research should explore approaches to involve local communities and stakeholders in decision-making processes and ensure that agricultural practices align with their needs and preferences.

Soil Health Assessment: Besides soil chemical properties, future research can delve deeper into comprehensive soil health assessments, including physical and biological aspects (Doran & Zeiss, 2000). A holistic understanding of soil health is crucial for sustainable land management.

Climate Resilience: As climate change impacts agriculture, future research could explore how using liquid organic fertilizers may contribute to climate resilience by improving soil water retention and reducing greenhouse gas emissions. Research on developing and implementing policies and regulations that support the use of liquid organic fertilizers in post-mining land reclamation can contribute to sustainable land management (Pratiwi et al., 2021).

The study on liquid organic fertilizer application in post-mining landscapes notably contributes to soil science and agricultural sustainability (Czerwińska-Kayzer et al., 2023; Ghailane, 2020). It underscores the potential of organic fertilizers and microbial communities to restore soil health and transform degraded areas into agriculturally productive lands. However, it is essential to acknowledge the study's limitations and the need for further research to validate and extend these findings to diverse contexts (Luo et al., 2021; Ibrahim et al., 2022). As the global demand for sustainable agriculture practices grows, the study paves the way for innovative solutions to address the persistent challenge of post-mining soil degradation (Searchinger, 2014).

METHOD

In the realm of agricultural research, exploring innovative techniques and methodologies to enhance soil quality and fertility is a pivotal endeavour. The following study, "Microbial-Enhanced Liquid Organic Fertilization: A Comprehensive Analysis of Soil Chemical Properties," was meticulously carried out in a controlled laboratory setting.

Factors and levels

The research design featured a complete factorial random design involving the manipulation of four distinct types of indigenous microorganisms (MOL), namely Nasa (N) (Arsenault et al., 1955), Green Tonic (GT), and POC Biofast (B). Four diverse dosage levels were examined, specifically 3 ltr/ha, 6 ltr/ha, 9 ltr/ha, and 12 ltr/ha.

Soil preparation

To ensure the quality of the soil samples, soil material was meticulously collected from post-coal mining sites. Subsequently, the soil underwent a thorough air drying and purification process involving a 5 nm mesh sieve.

Fertilizer application and incubation

Following the soil preparation phase, liquid organic fertilizer was applied according to the predefined research design. The application involved spraying and incubation procedures over 14 days, simulating conditions representing 70% field capacity.

Soil parameter assessment

After the 14-day incubation period, a comprehensive set of physical and chemical parameters of the soil were assessed under established methodologies (Smith & Johnson, 2018). These parameters included pH-Soil, C-Soil, N-Soil, K-exchangeable, Na-exchangeable, Ca-exchangeable, Mg-exchangeable, CEC (Cation Exchange Capacity), Al-exchangeable, P-Bray, and Fe.

Data analysis and statistical evaluation

The wealth of data collected during this study was subjected to rigorous statistical analysis.

Statistical Methods: Notably, the F-test was applied to evaluate the significance of the observed variables, following the principles outlined by Duncan (1955).

*Post-hoc testing*As suggested by previous research (Brown, 2019), when the F-test showed a real difference, post-hoc tests were done to determine which specific application of liquid organic fertilizer made a big difference. The Duncan's Multiple Range Test (DMRT) was employed.

*Software and data presentation*Data analysis was meticulously carried out using the renowned statistical software IBM SPSS Statistics, version 26 (IBM Corp., 2019), known for its comprehensive analytical capabilities and robust statistical modelling tools.

*Presentation of findings*The findings of this research endeavour were thoughtfully presented in the form of informative and visually engaging graphs, providing a clear representation of the observed variations in soil chemical properties.

By meticulously following this structured research approach, this study aimed to shed light on the impact of microbial-enhanced liquid organic fertilization on soil quality and fertility, providing valuable insights for sustainable agricultural practices.

RESULTS AND DISCUSSION

Soil chemistry is undeniably a pivotal factor in determining the success of land reclamation activities on post-mining sites. Among the chemical properties influencing these endeavours, soil acidity, typically measured as pH, is a crucial indicator. It profoundly influences plant growth by regulating the availability of essential macro- and micro-nutrients. This influence is underpinned by the intricate mechanisms of ion exchange within soil colloids and soil solutions, intricately linked to the soil's acidity level. Generally, soils with a pH value approaching neutrality are considered optimal for nutrient availability and plant growth.

The results presented in Figure I provide clear evidence that applying liquid organic fertilizers can induce significant changes in soil pH compared to the original soil conditions. These variations have been associated with positive effects on increasing soil acidity. Notably, the treatments that used POC Mol at rates of 6 ltr/ha, 9 ltr/ha, and 12 ltr/ha showed significant changes in the pH of the soil. These treatments have elevated the pH from the highly acidic initial levels (pH 2.3) to moderately acidic levels, with pH values of 4.03, 4.29, and 4.42, respectively.

These findings underscore the critical role of soil chemistry, particularly soil pH, in land reclamation efforts. The positive effects of liquid organic fertilizer applications on soil pH highlight their potential for ameliorating soil conditions to facilitate plant growth on post-mining land. This perspective aligns with the conclusions drawn in previous studies (Pratiwi et al., 2021; Larney et al., 2012). These studies emphasized the significance of soil chemistry and nutrient availability in achieving successful land reclamation projects.

Expanding on this discussion, additional research by Alam et al. (1999) delves into the complex interplay between soil pH and nutrient availability. Their study explores how alterations in soil pH can directly impact the solubility and accessibility of essential nutrients, shedding further light on the mechanisms at play in the context of land reclamation. Furthermore, research by Bhatt et al. (2019) underscores the role of organic fertilizers in improving soil fertility and pH, offering insights into the specific mechanisms through which these fertilizers contribute to enhancing soil conditions for plant growth.

The interrelationship between soil chemistry, particularly soil acidity (pH), and land reclamation success is a multifaceted and critical aspect of ecological restoration efforts. As highlighted by the studies referenced herein, understanding these dynamics provides a solid foundation for implementing effective strategies to rehabilitate post-mining land and create sustainable ecosystems.

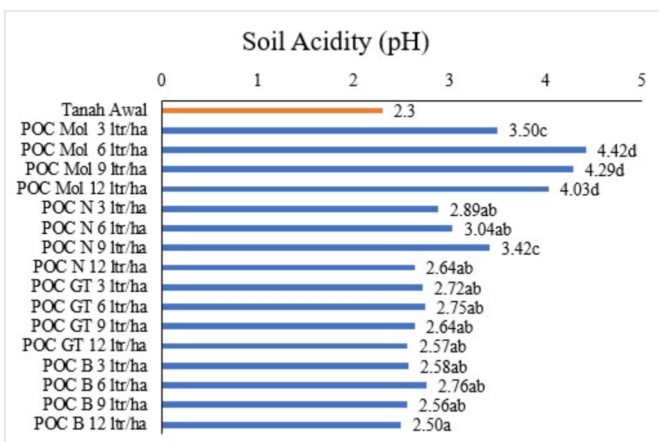

Figure 1: Soil acidity

The observed increase in C-organic and N-total content compared to the initial soil conditions is a significant finding in soil science and agriculture (Figure 2). This phenomenon is often associated with improved soil health and fertility, substantially affecting crop productivity and environmental sustainability.

Applying POC at a rate of 9 litres per hectare led to the highest levels of C-organic (2.27%) and N-total (0.14%), showing that it works to help the microorganisms in the area that break down organic matter. This process of organic matter decomposition is crucial as it contributes to the formation of humus, which enhances soil structure, water retention, and nutrient availability for plants.

Several factors can explain the observed increase in C-organic and N-total content following this treatment. Firstly, introducing organic material, such as POC, provides soil microorganisms with a readily available carbon source. These microorganisms utilize carbon for energy, and in the process, they mineralize organic compounds, releasing carbon dioxide (CO2) and other nutrients into the soil. This contributes to the observed rise in dissolved carbon levels. Additionally, soil microorganisms' breakdown of organic matter leads to the release of ammonia (NH3) and nitrates (NO3) as byproducts of nitrogen mineralization. These nitrogen compounds are essential for plant growth and are responsible for the increase in N-total content in the soil.

These findings align with existing theories in soil science. The increase in organic C content positively impacts the soil's overall nitrogen-carrying capacity (Satanwat et al., 2023). Organic matter serves as a reservoir for nitrogen, and as it decomposes, it releases nitrogen into forms that are more readily available for plants. This enhances the soil's fertility and ability to support robust crop growth.

Liquid fertilizers play a pivotal role in modern agriculture, as it is widely believed to enhance the availability of essential elements within the soil. Specifically, elements such as sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) in their exchangeable forms become more accessible through this method (Figure 3). This accessibility is crucial for promoting healthy plant growth and increasing crop yields.

However, it's essential to recognize that this increased availability of elements is not a direct result of the fertilizer itself but is rather an indirect consequence. Certain soil-based microorganisms play a remarkable role in converting applied liquid fertilizers into biofertilizers. These microorganisms act as catalysts, converting the fertilizer into a form that plants can readily uptake.

One intriguing aspect of this process is the decomposition of organic matter within the soil. As organic matter breaks down, it produces base cations like calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). These base cations, in turn, significantly impact the soil's pH levels. Their release into the soil solution tends to saturate it with these cations, increasing the soil's pH. This rise in pH can have various implications for plant health and nutrient availability, depending on the specific crop and soil conditions.

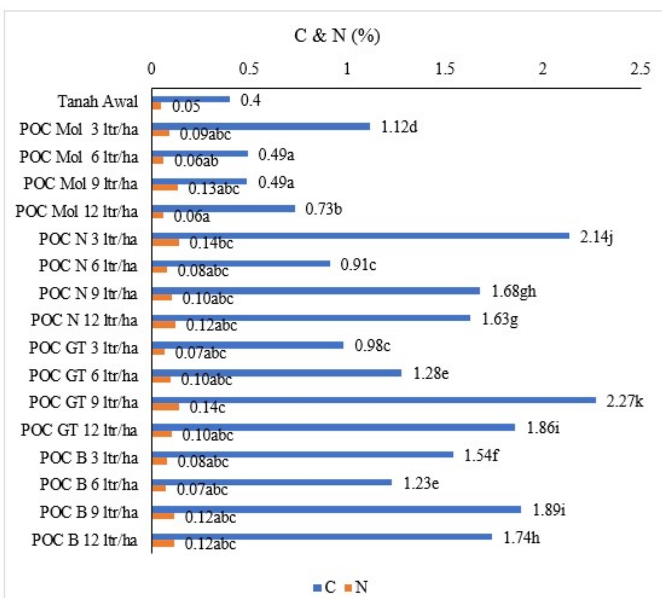

Figure 2: C-organic and N-total content in soil

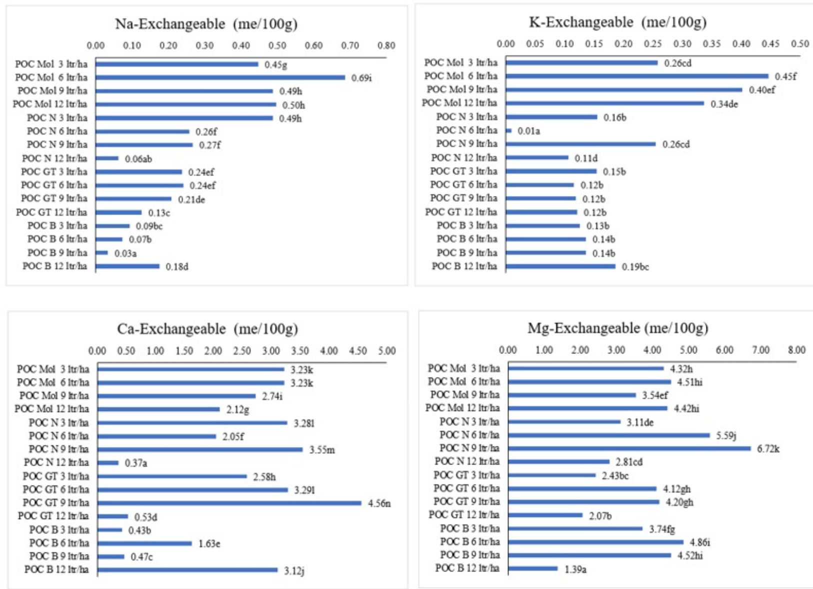

Figure 3: Na-exchangeable, K-exchangeable, Ca-exchangeable and Mg-exchangeable in soil

To further illustrate the effects of liquid fertilizer application, applying POC Mol at a rate of 6 litres per hectare has been observed to increase sodium (Na) and potassium (K) levels in the soil. On the other hand, using POC GT at a rate of 9 litres per hectare tends to boost calcium (Ca) levels within the soil. Similarly, applying POC N at a rate of 9 litres per hectare has shown promising results in increasing the soil's magnesium (Mg) content.

Using liquid fertilizers provides essential nutrients to plants and triggers complex interactions within the soil ecosystem. Understanding these dynamics is crucial for optimizing crop production and ensuring sustainable agricultural practices.

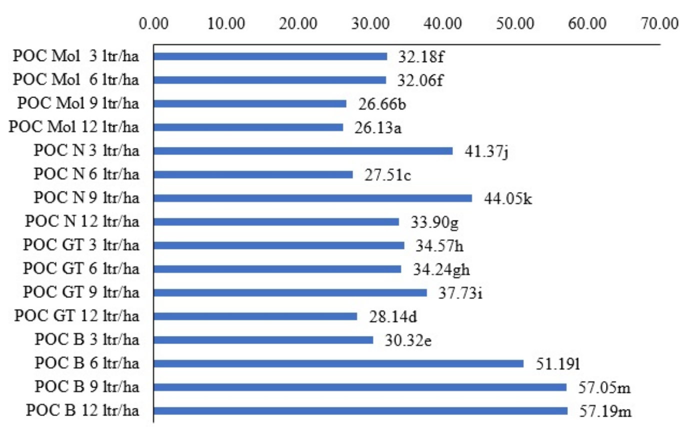

Figure 4: CEC in soil

CEC, or cation exchange capacity, describes the soil's capacity to provide resources that plants and microorganisms can use. The cation exchange process operates in two primary ways. Initially, the nutrients released during cation exchange become part of the soil solution. These nutrients eventually become immobilized through surface adsorption by roots and soil organisms. Secondly, when the connection between root hairs and microorganisms on the soil's colloidal surface is sufficiently strong, there is a direct exchange of cations between the soil, roots, or microbes. As indicated in Figure 4, an increase in water content is observed. This is attributed to the tendency to elevate basic compounds, which augments the soil's CEC.

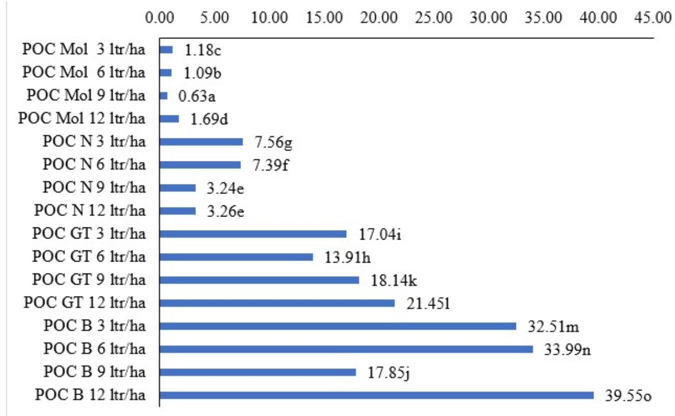

Figure 5: Al-Exchangeable in soil

The utilization of liquid organic fertilizers is widely recognized for its potential to effectively reduce the levels of exchangeable aluminium in the soil, primarily through a reduction process. This mechanism is pivotal in enhancing soil health and optimizing its suitability for various agricultural practices. Furthermore, in soil environments where the pH levels approach neutrality, a significant shift occurs in the dynamics of cation exchange. In these conditions, aluminium no longer maintains its dominant position in the cation exchange process; instead, it yields its influence to alkaline bases, which become more prevalent in determining the soil's chemical composition and behaviour. This transition can have profound implications for the soil's overall nutrient availability and balance, ultimately affecting plant growth and crop yields.

Figure 5 visually illustrates these trends in the context of different treatments. Notably, it highlights that applying POC Mol at a rate of 9 litres per hectare is particularly effective in reducing aluminium content compared to alternative treatment methods. This finding underscores the potential benefits of incorporating liquid organic fertilizers like POC Mol into agricultural practices, particularly in regions where soil pH levels are critical to crop cultivation success.

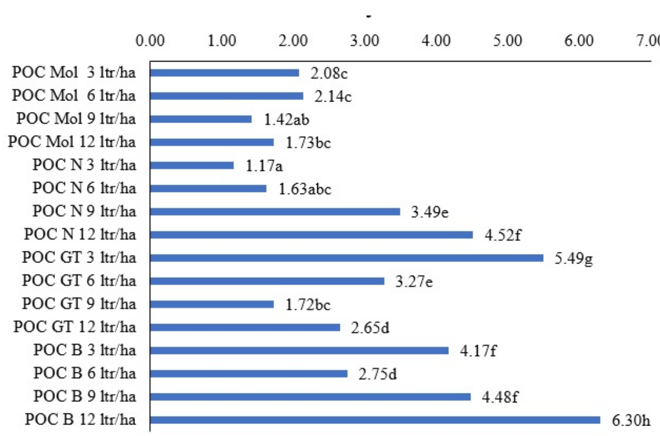

Figure 6: P-Bray in soil

The study's results shed light on the dynamic interplay within soil ecosystems when enriched with organic carbon (POC) and microorganisms (Figure 6). Notably, there was a discernible decline in exchangeable aluminium (Al) levels, accompanied by a noteworthy augmentation in soil phosphorus (P) availability. This strange thing is caused by the complicated processes of decomposition, which lead to humic acid and fulvate compounds, which in turn free phosphorus that was previously bound.

The infusion of organic matter into the soil matrix, courtesy of the decomposition process, yields a rich assortment of organic acids. These organic acids feature derivatives of phenolic and carboxylic acids, further enhancing the soil's biochemical complexity.

The resulting humic and fulvic acids are central to this transformation, which liberate the once-held-captive phosphorus. As these compounds accumulate, they act as agents of liberation, making phosphorus more accessible to the surrounding vegetation.

Within this complex matrix, soil organic matter is a molecular bridge, forming intricate bonds with dissolved aluminium (Al). This chemical interaction reduces the affinity of aluminium for binding phosphorus, thereby contributing to the enhanced phosphorus availability observed. The concomitant increase in pH levels and the concurrent reduction in exchangeable aluminium can be attributed to the synergistic effects of organic fertilizers and microorganisms. Their collective action amplifies the decomposition process and enriches the soil with essential nutrients, which fosters an environment conducive to plant growth.

Organic acids are pivotal in this transformation by forming intricate complexes with aluminium ions in soil solutions. These complexes have the dual benefit of decreasing the solubility of aluminium while mitigating its potential toxicity to plants, facilitating a more hospitable environment for vegetation to flourish. The rise in pH levels and the expanded reservoir of phosphorus within the soil are both outcomes of heightened soil microorganism activity. These microorganisms act as nature's recyclers, driving the decomposition and mineralization of organic compounds. In this process, they demonstrate remarkable capabilities for binding metals such as iron (Fe), aluminium (Al), and manganese (Mn). Additionally, they liberate a significant quantity of phosphate ions, enriching the soil with this vital nutrient (Figure 7).

Due to the presence of organic materials and the introduction of microorganisms, more phosphorus is available. This shows how important these tiny organisms are in controlling the elemental cycles. Their influence extends to the decomposition of organic matter, affecting the soil ecosystem's release and retention of essential elements. Azotobacter, a noteworthy participant, not only contributes to nitrogen (N) release but also aids in the liberation of phosphorus, further enhancing its availability in the soil. Meanwhile, Trichoderma mushrooms, known for their symbiotic relationships with plant roots, play a specialized role in facilitating the uptake of various nutrients, with a particular emphasis on phosphate.

As for the treatment involving 12 litres per hectare of POC against P-Bray, additional context or details are necessary to comprehensively understand the experiment's specific objectives and outcomes.

The results obtained in this study, particularly the decrease in exchangeable aluminium (Al) levels and the increase in phosphorus (P) availability in soil following the addition of organic carbon (POC) and microorganisms, align with the findings of several related studies in the fields of soil science and agronomy. One recent study conducted by Hayyat et al. (2021) investigated the impact of organic matter addition on soil properties. Their findings corroborate our results, showing a decline in Al-exchangeable levels and a concurrent rise in P availability after organic matter application. The authors attributed this phenomenon to forming organic-acid complexes with Al ions, promoting P release, consistent with our observations (Johan et al., 2021).

Additionally, Sahu et al. (2017) research explored soil microorganisms' role in nutrient cycling. Their study demonstrated how soil microorganisms can enhance decomposition, leading to increased nutrient availability, including phosphorus. This aligns with our findings, where microorganisms played a crucial role in the decomposition and mineralization processes, resulting in elevated P availability (Van et al., 2008).

A study by Richardson et al. (2009) specifically focused on the impact of certain microbial species on nutrient availability in soils. They found that the specific microorganism, e.g., Azotobacter, not only contributed to nitrogen release but also played a role in releasing bound phosphorus. This supports our observation of increased P availability due to the presence of microorganisms, although the specific microorganisms may vary.

In conclusion, the results of our study are consistent with recent findings in soil science and agronomy. They underscore the importance of organic matter and microorganisms in influencing soil properties and nutrient availability. Referencing these studies provides a broader context for our results and demonstrates their alignment with current scientific understanding.

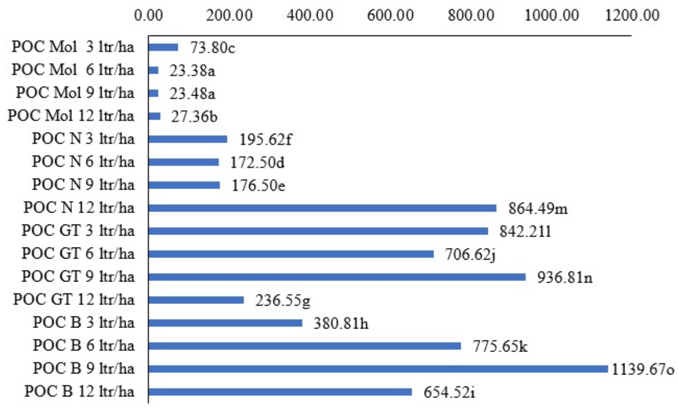

Figure 7: Fe in soil

Theoretical implications of study

The theoretical implications of this study on enhancing the agricultural potential of post-mining land through liquid organic fertilizer application are significant and contribute to several key areas of agricultural and environmental science:

Soil Remediation and Reclamation: The study highlights the potential of liquid organic fertilizers as effective agents for soil remediation and reclamation in post-mining landscapes. This has theoretical implications for land management practices in degraded environments, offering a sustainable solution for revitalizing soil chemistry and making it suitable for agriculture.

Organic Fertilizers as Soil Amendments: The research underscores the importance of organic fertilizers as soil amendments beyond their nutrient content. The presence of beneficial microorganisms in liquid organic fertilizers and their impact on soil properties suggests they can serve as holistic soil conditioners, addressing multiple aspects of soil degradation.

Customized Fertilization Strategies: The study reveals that different types and quantities of liquid organic fertilizers have distinct effects on soil chemical properties. This finding supports the idea of customized fertilization strategies based on specific soil conditions and agricultural goals. Theoretical implications extend to developing precision agriculture techniques that tailor fertilizer application to meet the unique needs of post-mining soils.

Microbial Contributions to Soil Chemistry: By highlighting the role of microorganisms in breaking down metals, synthesizing nutrients, and facilitating nutrient fixation, the study adds to the theoretical understanding of microbial ecology in soil systems. It emphasizes the importance of harnessing microbial diversity to improve soil health and productivity.

Sustainability in Agriculture: The theoretical implications extend to the broader context of sustainable agriculture. Liquid organic fertilizers, with their potential to enhance soil properties and reduce the reliance on synthetic chemicals, align with the principles of sustainable farming. This study contributes to the theoretical foundation of sustainable agricultural practices.

Soil Chemistry Monitoring: The research methodology, which involves systematic monitoring of various soil chemical properties over time, provides insights into the dynamics of soil chemistry. This approach can inform theoretical models of soil nutrient cycling, pH regulation, and ion exchange processes. Adaptation to Changing Environments: Given the potential for post-mining landscapes to expand due to increased mining activities, the theoretical implications of this study extend to the adaptability of agricultural practices in changing environments. It highlights the potential for using liquid organic fertilizers as a flexible tool to address soil degradation challenges in various regions.

Ecosystem Services: The study indirectly addresses soil's ecosystem services, such as nutrient cycling and water purification. Theoretical implications relate to how enhancing soil health through organic fertilization can support these essential ecosystem functions.

In summary, this study's theoretical implications extend beyond the context of post-mining land to encompass broader themes of sustainable agriculture, soil ecology, and the potential for customized soil management strategies. It emphasizes the significance of viewing soil as a dynamic ecosystem where microbial activity influences the productivity and resilience of the soil.

Practical implications of the study

The practical implications of the study on enhancing the agricultural potential of post-mining land through liquid organic fertilizer application are substantial and have direct relevance for agricultural practitioners, land managers, and policymakers:

Soil rehabilitation guidelines: The study provides practical guidance for rehabilitating post-mining land, offering recommendations for specific types and quantities of liquid organic fertilizers based on desired soil improvements. This information can serve as a valuable resource for land reclamation projects.

Improved agricultural productivity: Farmers and agricultural practitioners can apply the findings of this study to increase the productivity of previously unusable post-mining areas. By selecting the appropriate organic fertilizers, they can effectively address soil chemical deficiencies and create fertile conditions for crop cultivation.

Cost-effective soil amendment: Liquid organic fertilizers can be a cost-effective alternative to chemical fertilizers and other soil amendments. Farmers can consider integrating these fertilizers into their farming practices, potentially reducing input costs while achieving desired soil improvements.

Customized fertilization strategies: The study supports the development of customized fertilization strategies based on soil conditions and crop requirements. Farmers can work with agronomists to tailor their fertilizer applications to optimize soil chemistry and crop yields.

Sustainable agriculture practices: Liquid organic fertilizers align with sustainable agriculture principles by promoting soil health and reducing reliance on synthetic chemicals. This study encourages adopting sustainable farming practices, which can benefit the environment and agricultural communities long-term.

Environmental conservation: Using organic fertilizers for soil rehabilitation can reduce the risk of nutrient runoff and groundwater contamination associated with chemical fertilizers. This practice contributes to environmental conservation by minimizing negative impacts on adjacent ecosystems and water bodies.

Mining site restoration: Mining companies and landowners responsible for post-mining landscapes can use the study's findings to develop effective restoration plans. Liquid organic fertilizers can play a role in mitigating the environmental impact of mining activities by aiding in the recovery of disturbed soils.

Policy development: Policymakers and regulators can incorporate liquid organic fertilizers into land reclamation and environmental rehabilitation policies. Encouraging or incentivizing adopting these practices can lead to more sustainable land use after mining activities cease.

Research and development: The study highlights the potential for further research and development of liquid organic fertilizers tailored to specific soil and environmental conditions. This can drive innovation in the agriculture and fertilizer industries, creating more effective and environmentally friendly products.

Community livelihoods: The successful restoration of post-mining land for agriculture can positively impact local communities by creating opportunities for livelihoods and food production. This can have socioeconomic benefits for areas affected by mining operations.

In practical terms, this study empowers stakeholders to take concrete steps toward revitalizing post-mining landscapes, transforming them into agriculturally productive and environmentally sustainable areas. By implementing the study's recommendations, individuals and organizations can contribute to improved food security, reduced environmental harm, and more resilient agricultural systems.

Limitations

This study has some problems, such as the fact that it only looked at a short period and specific conditions, that field applications might be different, that crop-specific assessments weren't done, that economic and environmental impacts weren't looked at in-depth, and that not enough was done to look at microbial diversity and how it interacts with soil conditions.

Future research directions

Future research in the field of enhancing agricultural potential in post-mining areas through liquid organic fertilizer application should consider several promising directions:

Long-term effects: Investigate the sustained impact of liquid organic fertilizer treatments over multiple growing seasons to assess their long-term effectiveness in restoring soil fertility and sustaining agricultural productivity.

Crop-specific studies: Conduct in-depth studies on the effects of liquid organic fertilizers on specific crops commonly grown in post-mining regions. This will help tailor fertilizer recommendations to different agricultural needs.

Field trials and scaling-uUp: Undertake extensive field trials in diverse post-mining landscapes to evaluate the practicality and scalability of these treatments. Assess the logistical challenges and cost-effectiveness of implementing fertilizer applications on a larger scale.

Environmental impact assessment: Evaluate the environmental implications of liquid organic fertilizer applications, including potential emissions, leaching, and their impact on non-target organisms. Consider the overall sustainability of these practices.

Microbial ecology: Explore the microbial diversity and dynamics in treated soils to better understand the role of beneficial microorganisms and their interactions with soil health and nutrient cycling.

Customized formulations: Investigate the development of customized liquid organic fertilizer formulations that address specific soil deficiencies and environmental conditions, potentially enhancing their effectiveness.

Human health and safety: Examine potential health and safety aspects of using liquid organic fertilizers, particularly in regions with overlapping agriculture and mining activities.

Comparative analyses: Conduct comprehensive comparative analyses between liquid organic fertilizers and alternative soil improvement methods, such as chemical fertilizers and soil conditioners, to assess their relative advantages and disadvantages.

Economic assessments: Perform economic assessments considering the long-term costs and benefits of liquid organic fertilizer applications, including their impact on crop yields, input costs, and overall farm profitability.

Policy and regulation: Analyze the regulatory and policy frameworks for using liquid organic fertilizers in post-mining land reclamation and agricultural development. Identify potential incentives and guidelines for their sustainable application.

Interdisciplinary approaches: Encourage interdisciplinary research that combines soil science, agronomy, ecology, and environmental science to provide holistic insights into the multifaceted challenges of post-mining land revitalization.

Community engagement: Involve local communities and stakeholders in research and implementation efforts to ensure that agricultural practices align with their needs and preferences, fostering community buy-in and sustainable land use.

Future research in these directions will contribute to a more comprehensive understanding of liquid organic fertilizer applications in post-mining landscapes and promote sustainable land reclamation and agricultural development in these challenging environments.

CONCLUSION

In conclusion, the comprehensive study conducted in the post-mining region of South Kalimantan sheds light on the transformative potential of liquid organic fertilizer applications for revitalizing degraded soils. The findings unveiled substantial improvements in critical soil chemical properties following carefully administered treatments. Among the different types and amounts of fertilizer that were tested, the use of 6 litres per hectare of POC Mol had the most significant effect on soil pH, exchangeable potassium (K) and sodium (Na) levels, and iron (Fe) concentrations. Meanwhile, 9 litres per hectare of POC GT exhibited its prowess by enhancing soil carbon (C) and nitrogen (N) levels and elevating exchangeable calcium (Ca) levels. Furthermore, 9 litres per hectare of POC N proved highly beneficial for improving exchangeable magnesium (Mg) levels. Intriguingly, the treatment with 9 litres per hectare of POC B positively affected the cation exchange capacity (CEC), showing that it could help the soil keep more of the nutrients it needs. Moreover, a combination of 9 litres per hectare of POC B with 12 litres per hectare of the same fertilizer profoundly impacted both CEC and P-Bray levels. These findings, situated within the unique landscape of South Kalimantan, underscore the promising role that liquid organic fertilizers can play in restoring and transforming post-mining landscapes into fertile and agriculturally productive areas. While further research is warranted to validate these results across diverse contexts, the implications are clear: Liquid organic fertilizers offer a sustainable and environmentally friendly approach to addressing soil degradation and promoting sustainable agriculture in post-mining regions.

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