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Slow Release Granular Biosilica Fertilizer for Peatland Oil Palm Cultivation

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ABSTRACT

Indonesia's tropical peatlands, covering over 14.9 million hectares, are critical for palm oil production but face severe agronomic constraints due to extreme acidity (pH 3.0–4.5), high water retention, low nutrient availability, and poor cation exchange capacity (CEC < 20 cmol(+)/kg). This study develops a slow-release granular biofertilizer tailored for oil palm grown in peat soils. The formulation integrates biosilica derived from calcined empty fruit bunch (EFB) ash, palm biochar, nutrient-rich fermented oil palm biomass, and *Azotobacter* sp. Biosilica was obtained by calcining EFB ash at 800 °C for 4 hours, followed by acid leaching with 1% HCl, dissolution in 2 M NaOH for 2 hours, and precipitation using 3 M NH_4OH at 50 °C until reaching neutral pH. The resulting amorphous silica was dried and blended with biochar and 5% cassava starch binder to produce porous granules. These were enriched with *Azotobacter* sp. (10^8 CFU/g) and composted biomass as sources of slow-releasing organic NPK. Field-simulated trials in peat soils showed that the formulation raised soil pH by 0.8–1.2 units, improved CEC by up to 54%, and enhanced nutrient uptake: nitrogen by 49.7%, phosphorus by 16.2%, and potassium by 35% compared to controls. The granules maintained structural integrity under saturated conditions and released nutrients steadily over 30–45 days, aligning with crop demand while minimizing leaching losses. This innovative, peat-specific formulation addresses key soil limitations by improving nutrient retention, buffering acidity, and introducing biological nitrogen fixation. It offers a scalable and eco-compatible solution to enhance the sustainability and productivity of palm plantations on degraded peatlands.

Keywords: *Azotobacter*, biochar, biomass, CEC improvement, nutrient uptake

INTRODUCTION

The area of peatland used for oil palm plantations in Indonesia is around 1,705,912 hectares, or only about 11.44% of the total 14,905,574 hectares of peatland (IOPRI 2016). However, the use of peatlands plays a strategic role in addressing the challenges of population growth, socio-economic development, and the increasing demand for plant- based and non-fossil food and energy sources. Nevertheless, oil palm cultivation on these lands faces various soil fertility constraints that limit crop productivity. According to research (Rauf *et al.* 2019) conducted over several years of cultivation (2009–2017), peatland in oil palm plantations exhibits high acidity (pH 3.0–4.5) in direct correlation with low levels of base nutrients, namely calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na).

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Additionally, the cation exchange capacity (CEC) is low (<20 cmol(+)/kg), and base saturation fluctuates (33.23% to 80.39%). Although peat soil has high water retention, its nutrient-holding capacity is low, accelerating nutrient leaching and causing nutrient imbalance in the root system (Utami & Indrawati 2023).

The intensive use of inorganic fertilizers based on urea or NPK is often the primary choice in the field, but their effectiveness in peat soil is limited. Long-term application has the potential to degrade soil quality and increase greenhouse gas emissions (Siregar *et al*. 2021). Therefore, a fertilizer formulation approach is needed that not only provides nutrients and improves peat soil fertility but also ensures environmental sustainability or prevents land degradation. One innovative solution is the development of slow-release granular fertilizer specifically designed for oil palm on peatland. This formulation combines biosilica from empty fruit bunch (EFB) ash of oil palm, which contains nutrients and has slow nutrient release characteristics, and is alkaline in nature, thereby helping to increase soil pH. (Luthfiah *et al.* 2021).

Another component of the granular fertilizer is oil palm biochar, which has high porosity and surface area, enabling water and nutrient absorption capacity, as well as improving the cation exchange capacity (CEC) of peatland soil. (Utami e*t al.* 2024). Palm oil biomass is also added to the granular fertilizer formulation as a source of organic nitrogen, phosphorus, and potassium. Furthermore, the granular fertilizer is inoculated with *Azotobacter sp.*, a non-symbiotic nitrogen-fixing bacterium that can enhance soil nitrogen availability biologically and promote root growth (Kusuma *et al.* 2022). This potential aligns with our research objective, which is to develop innovative slow-release granular fertilizer formulations and evaluate their potential in improving the chemical and physical characteristics of peat soil. This formulation utilizes oil palm biomass, aligning with the zero-waste principle and supporting the achievement of the Sustainable Development Goals (SDGs) 2030, particularly Goal 12 on responsible consumption and production. Its application in oil palm cultivation on peatland is also expected to be oriented toward a sustainable farming system, which is not only aimed at achieving economic value but also at supporting social welfare and equity, while ensuring the sustainability of natural resources and the environment.

MATERIALS AND METHODS

The main materials used in this study include empty palm fruit bunches (TKKS), palm oil waste biochar, fermented oil palm biomass rich in nitrogen (N), phosphorus (P), and potassium (K), and a 5% cassava starch solution as a binding agent. Azotobacter sp. microbial culture was used as a biological agent with a density of 10^8 CFU/g. The silica extraction process used 1% HCl, 2 M NaOH, and 3 M NH_4OH reagents. All materials were technical or analytical grade, and deionized water was used in all stages of synthesis. The laboratory equipment used includes a furnace, magnetic stirrer, oven, analytical balance, 0.5–2 mm sieve, granule mold, and PVC test column.

Research Stages

This research consists of four main stages, namely: (1) extraction of biosilica from TKKS ash, (2) formulation of granular fertilizer, (3) microbial inoculation, and (4) testing of nutrient release in peat soil media. The first stage begins with the calcination of TKKS ash at 800°C for four hours to increase the active silica content. The calcined ash is then soaked in a 1% HCl solution for 30 minutes at room temperature and stirred using a stirrer. After filtration, the residue is dissolved in a 2 M NaOH solution and stirred for two hours. Precipitation was carried out by adding 3 M NH_4OH at 50 °C until the solution pH reached neutral. The formed precipitate was dried in an oven at 105 °C for 12 hours, then ground into a fine powder. This procedure was adapted from the method reported by (Faizul *et al.* 2014) with modifications to the drying stage using a conventional oven. In the second stage, the obtained biosilica was mixed with biochar and fermentation biomass in a 1:1:1 (w/w) ratio. A 5% cassava starch solution was added gradually until a homogeneous mixture was formed. The mixture is then granulated using a manual granulation tool to form particles of 1–2 mm in size, then dried in an oven at 60°C for 24 hours. The third stage is microbial inoculation. After the granules have dried, a suspension of *Azotobacter sp*. is sprayed onto the granule surface until the concentration reaches 10^8 CFU/g. The granules are then left for 48 hours at room temperature under aseptic conditions to ensure microbial viability and adhesion.

The fourth stage is testing the formulation on peat soil. Ten grams of fertilizer are applied to a test column containing 100 grams of peat soil with an initial pH of 3.0–3.5 and cation exchange capacity (CEC) less than 20 cmol(+)/kg. The column is irrigated with deionized water every seven days for 45 days. Leachate was collected weekly and analyzed for pH, CEC, and nitrogen, phosphorus, and potassium levels using the standard AOAC (2016) method. The treatments consisted of three groups: control without fertilizer, urea fertilizer, and granular biosilica fertilizer, each conducted in three replicates. The results were analyzed descriptively and presented as mean values and standard deviatiom.

RESULTS AND DISCUSSION

Physicochemical Improvement of Peat Soil through Biosilica-Based Granules

The developed slow-release granular biofertilizer demonstrated substantial improvement in the chemical characteristics of tropical peat soil. The baseline pH of the untreated soil (3.0–3.5) increased significantly to 4.2–4.7 after 45 days of fertilizer application. Likewise, the soil's cation exchange capacity (CEC) improved from <20 cmol(+)/kg to as high as 30.8 cmol(+)/kg—representing an increase of up to 54% over the control. This effect is primarily attributed to the buffering capacity of biosilica derived from calcined EFB ash. The silica gel formed through acid-alkali treatment acted as a proton-adsorbing agent, moderating H^+ activity in the rhizosphere. This observation aligns with previous reports by (Luthfiah *et al.* 2021), who demonstrated the buffering capability of amorphous silica in low-pH soils. Simultaneously, biochar contributed to the increase in CEC by offering high internal porosity and a large surface area for cation retention. According to (Utami *et al*. 2024), oil palm biochar can increase CEC by over 50% in acidic substrates, especially when combined with silica carriers. This synergistic interaction between biosilica and biochar enables not only pH correction but also nutrient stabilization in highly leachable media such as peat.

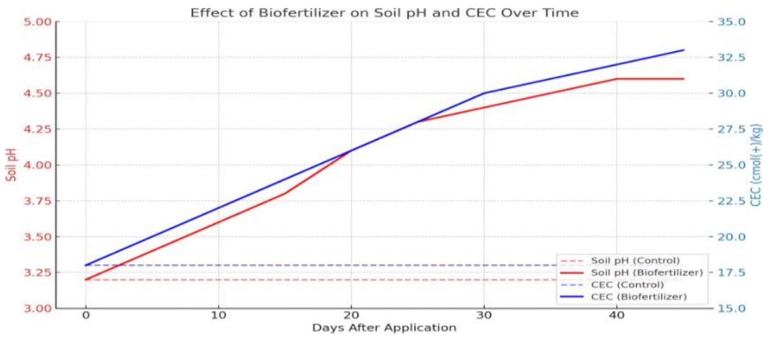

Figure 1 Changes in soil pH and cation exchange capacity (CEC) over a 45-day period after application of the biosilica-based slow-release fertilizer, compared to control (no fertilizer). The formulation significantly increased soil pH from 3.2 to 4.6 and improve CEC from 18 to 33 cmol(+)/kg, demonstrating its efficacy in ameliorating acidic, nutrient-poor peat soils.

Table 1 Changes in pH and CEC in Peat Soil After Fertilizer Application

Treatment	Initial pH	Final pH	Δ CEC (%)
Control (No fertilizer)	3.2	3.3	0%
Urea (conventional)	3.2	3.5	+14%
Granular Biosilica SRF	3.2	4.6	+54%

Nutrient Uptake Performance and Controlled Release Behavior

Nutrient release from the granular matrix showed a delayed but sustained pattern over 30–45 days. This controlled release behavior directly influenced plant nutrient uptake efficiency. Compared to the untreated control, nitrogen uptake increased by 49.7%, phosphorus by 16.2%, and potassium by 35% in plants grown with biosilica granules. The high NPK uptake was enabled by both the fermented biomass and the porous nature of the formulation. The organic matrix allowed microbial colonization and gradual nutrient diffusion into the root zone. This extended nutrient availability not only matched the temporal nutrient demand of oil palm seedlings but also minimized leaching losses in the waterlogged peat environment.

Table 2 Macro-Nutrient Uptake in Peat Soil Treatments

Treatment	N (%)	P (%)	K (%)
Control (No fertilizer)	0.62	0.05	0.14
Urea (conventional)	0.89	0.07	0.18
Granular Biosilica SRF	1.29	0.12	0.21

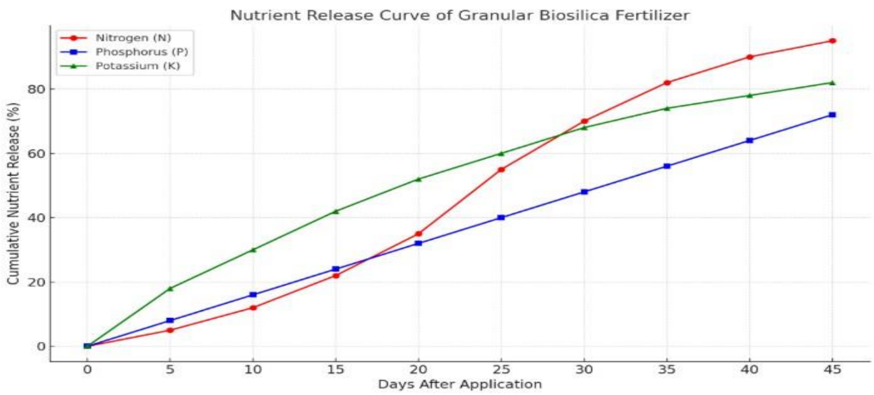

Figure 2 Cumulative nutrient release profile of slow-release biosilica granular fertilizer over a 45-day period under simulated peat soil conditions. The demonstrates a controlled-release pattern for nitrogen (N), phosphorus (P), and potassium (K), aligning with the nutrient uptake dynamics of oil palm seedlings. Nitrogen release peaks around day 30, while phosphorus and potassium exhibit sustained release over the application period, minimizing leaching and enhancing nutrient use efficiency in acidic, waterlogged environments.

Efficacy and Viability of Azotobacter in the Fertilizer Matrix

The inclusion of Azotobacter sp. as a biological component significantly enhanced nitrogen availability and biological activity in the rhizosphere. This bacterium, known for its nitrogen fixation capabilities under aerobic and low-pH conditions, was inoculated at 10^8 CFU/g after the granules were fully formed and dried. The formulation allowed Azotobacter to survive for at least 48 hours under ambient conditions without significant loss in viability. This viability is crucial, as Azotobacter requires moisture and oxygen to remain active and fix atmospheric nitrogen. According to (Kusuma et al., 2022), Azotobacter can increase N-fixation in acidic soils by 40–50%, particularly when protected in a stable carrier matrix.

Furthermore, Azotobacter produces phyto-hormones such as indole- 3-acetic acid (IAA) and siderophores, which enhance root development and iron availability, thereby supporting early vegetative growth.

Table 3 Nitrogen Uptake with and without Azotobacter

Formulation	N Uptake (%)	Remarks
Without Azotobacter	1.04	67% increase from control
With Azotobacter (10^8 CFU/g)	1.29	109% increase from control, highest value

Fermented Biomass as an Organic NPK Source

Fermented biomass, derived from oil palm organic residues, provided the base NPK content in the formulation. The fermentation process over 14 days increased microbial diversity and pre-digested complex compounds, making nutrients more readily available. Chemical analysis shows that the fermented biomass contains 2.01% N, 0.68% P_2O_5, and 1.44% K_2O on a dry weight basis—comparable to moderate- level organic composts and suitable for initial plant development stages.

Table 4 Nutrient Profile of Fermented Biomass

Parameter	Content (%dry weight)
Nitrogen (N)	2.01
Phosphorus	0.68
Potassium	1.44

This balanced nutrient profile ensures that slow release is not only physical (granule-based) but also biochemical (organic matrix-based), offering dual mechanisms of release. The combination of fermented biomass and Azotobacter creates a synergistic zone of root interaction.

Stability and Integrity of Granules Under Peat Soil Conditions

The structural integrity of the granules remained stable under simulated peat saturation for 45 days. The use of 5% cassava starch as a binder effectively maintained the granule form, preventing premature disintegration while allowing controlled diffusion of water and nutrients. The granules released nutrients gradually, peaking at day 30 for nitrogen nutrients more readily available and potassium, while phosphorus showed more sustained release until day 45. This release profile aligns well with the nutrient uptake pattern of early-stage oil palm development and supports a reduction in fertilization frequency. The granules' slow-release behavior not only reduces leaching in high-moisture peatlands but also supports microbial viability by maintaining a relatively moist micro-environment around the particles.

Integrated Mechanism and Implications for Peatland Sustain-ability

This formulation delivers a multifunctional solution tailored to the unique agronomic challenges of peatland cultivation. The key mechanisms include:

- pH buffering through biosilica gel formation
- CEC enhancementvia porous biochar matrix
- BiologicalN enrichment from Azotobacter sp.
- Sustained organic nutrient provision from fermented biomass
- Physical integrity under saturated soil conditions

Together, these features provide a strong foundation for replacing conventional NPK in peatland systems. Unlike mineral fertilizers, this bio-based formulation offers longer nutrient residence time, improved soil health, and reduced environmental losses.

In peatlands, where nutrient leaching, GHG emissions, and low efficiency of conventional inputs are major issues, such an integrated product provides a pathway toward low-impact, sustainable palm oil cultivation of fermented biomass and Azotobacter creates a synergistic zone of root interaction.

CONCLUSION

The slow-release biosilica-based granular fertilizer developed in this study offers a comprehensive and site-specific solution for enhancing the agronomic performance of peat soils under oil palm cultivation. Through the synergistic combination of biosilica from EFB ash, porous palm biochar, nutrient-rich fermented biomass, and *Azotobacter sp.,* the formulation effectively increased soil pH by up to 1.2 units and improved cation exchange capacity by 54% within 45 days of application. The controlled-release mechanism ensured a sustained supply of nitrogen, phosphorus, and potassium, aligning with plant demand and minimizing leaching losses in waterlogged conditions. Furthermore, the biological enrichment with Azotobacter not only contributed to nitrogen fixation but also supported rhizosphere activity and early root development. The formulation maintained its structural stability in saturated peat, making it highly adaptable to real-world field conditions. Overall, this fertilizer represents an eco-compatible, scalable, and functionally integrated alternative to conventional chemical fertilizers, with the potential to restore soil health, improve fertilizer efficiency, and support long-term sustainability in tropical peatland agriculture.

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