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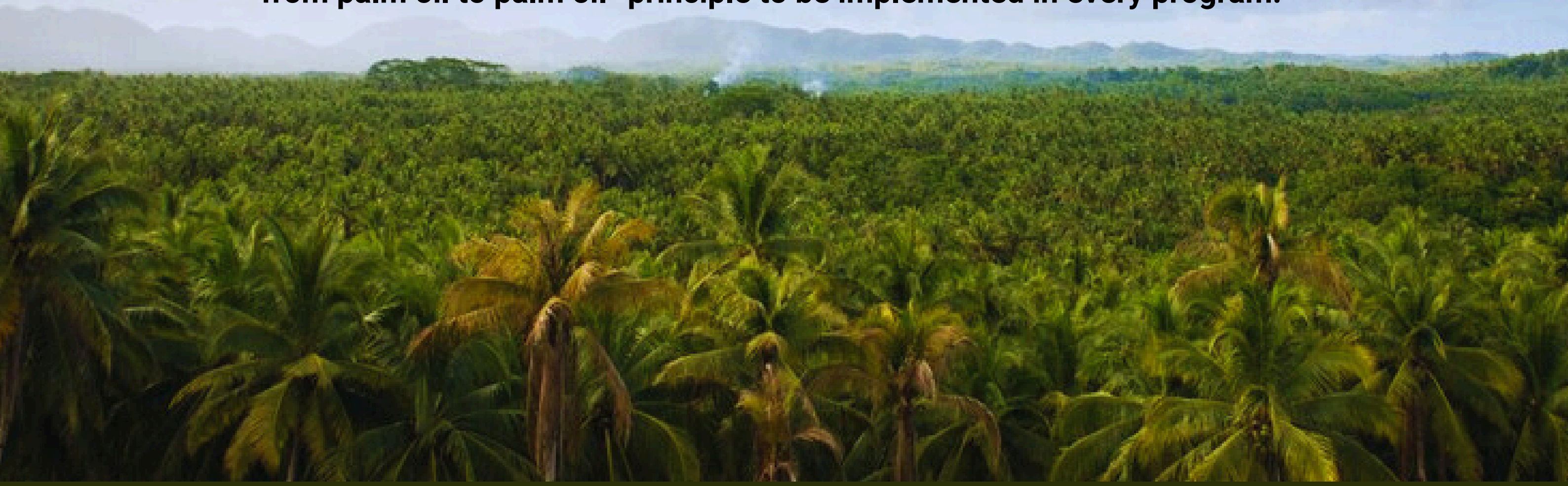

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Circular Economy in The Palm Oil Industry: Global Trends, Potentials, and Opportunities for Green Economy in Indonesia

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ABSTRACT

The palm oil industry in Indonesia plays a crucial role as a foreign exchange earner but faces criticism for its environmental impacts, such as deforestation and carbon emissions. This study aims to analyze global trends in the circular economy within the palm oil sector and explore the potential of a green economy in Indonesia through a mixed-methods approach involving bibliometric and ex-post facto analyses. The findings reveal fluctuating trends in scientific publications, with Malaysia and Indonesia as the main contributors. There has been significant growth in research on this topic, with an annual publication increase rate of 43.45% from 2017 to 2024. International collaboration is vital, with nearly 50% of publications involving cross-border cooperation. Malaysia dominates global contributions with over 35% of total publications, followed by Indonesia, which is also active in international partnerships. Global trends indicate that although the volume of publications has stabilized, the topic of the circular economy is transitioning from an exploratory phase to more advanced technological applications and developments. Terms such as circular economy, sustainable development, and bioenergy are increasingly prominent. Implementing a circular economy in Indonesia holds great potential for transforming palm oil waste into renewable energy. Indonesia's high Crude Palm Oil (CPO) production generates significant volumes of waste, such as empty fruit bunches (EFB) and palm oil mill effluent (POME). Technologies like pyrolysis, which converts EFB into bioenergy and anaerobic digestion to produce biogas from POME can reduce greenhouse gas emissions and reduce reliance on fossil fuels. Adopting a circular economy approach could help Indonesia achieve its greenhouse gas emission targets outlined in the Paris Agreement. Technological support and collaboration are essential to empowering smallholder plantations, aiding the palm oil industry's sustainability and fostering a green economy's growth.

Keywords: palm oil, circular economy, trends, opportunities, green economy

INTRODUCTION

Agriculture contributes greatly to food security and economic growth (Firdaus *et al.* 2024). The palm oil industry in Indonesia plays a significant role in driving economic growth and is crucial in generating foreign exchange revenue while expanding employment opportunities (Anggraeni & Hukom 2023). According to the Ministry of Agriculture (2024), in 2023, Indonesia's palm oil exports amounted to 38.23 million tons, contributing USD 25.61 billion in foreign exchange revenue. It

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solidifies Indonesia's position as the world's largest palm oil exporter, commanding a 52.55% share of the global palm oil market (Kementan 2024). However, the industry also brings detrimental environmental impacts, such as deforestation, which leads to ecosystem destruction and a reduction in biodiversity (Enala *et al.* 2024). Forests are frequently converted into palm oil plantations, disrupting habitats and resulting in the loss of endemic flora and fauna (Senaro *et al.* 2024).

Deforestation exacerbates carbon emissions due to excessive logging, aggravating global climate change (Situmorang 2022). Palm oil often produces hazardous chemical waste, contaminating rivers and local water sources (Pakpahan 2020). Additionally, using pesticides and chemical fertilizers in palm oil plantations contributes to soil degradation (Hidayat *et al.* 2022). Water and soil pollution from palm oil industries threatens ecosystems' sustainability and endangers public health, particularly for communities relying on groundwater for daily needs.

Inefficient management of palm oil waste can have adverse environmental consequences and diminish the potential economic benefits derived from such waste (Syamriati 2021). The inefficient utilization of palm oil waste and resources hampers the sector's potential to create a sustainable green economy (Abogunrin-Olafisoye *et al.* 2024). The United Nations Environment Programme (UNEP) defines a green economy as a sustainable economic system that enhances human well-being reduces social inequality and does not compromise environmental integrity or create resource scarcity for future generations (Handoko & Widyasanti 2023).

Palm oil remains one of Indonesia's largest foreign exchange commodities, with 24.99 million tons exported in 2022 (BPS 2023). The rapid growth in palm oil exports has accelerated the expansion of palm oil processing facilities (Ziaulhaq 2022), converting a significant portion of non-palm oil land into plantations. Despite Indonesia's strong presence in the global palm oil market, international observers have criticized its unsustainable plantation management practices, which are seen as environmentally damaging (Liana *et al.* 2023). The high volume of palm oil production correlates with increased waste, such as palm oil mill effluent, mesocarp fibres, palm kernels, and empty fruit bunches, which can disrupt environmental equilibrium (Nurmilatinaa *et al.* 2023). Therefore, interventions are needed to address the negative environmental impacts of palm oil processing and promote sustainability through green economy initiatives.

In response, adopting a circular economy is viewed as a viable strategy to minimize waste, reduce environmental degradation, and support sustainable development goals (Malihah 2022). A circular economy aims to enhance economic growth by maintaining the value of resources while minimizing environmental damage (Sari *et al.* 2023). Its concept, which emphasizes recovery, recycling, and reuse, is vital to reducing carbon emissions and securing natural resources (Nurmilatinaa *et al.* 2023).

Numerous studies have explored the potential of a circular economy in the agricultural sector. For instance, research by Sari *et al.* (2023) highlights the empowerment of Aceh Tamiang communities by using palm leaf waste to produce broomsticks, thereby boosting the local economy. Isnaeni & Arista (2022) investigated the use of waste from the indigo dye industry for compost and biogas production, reducing water pollution and increasing financial returns. Tsani *et al*. (2023) explored circular economy efforts by processing used cooking oil waste, reducing waste and enhancing market value. However, prior research on circular economy in agriculture has been limited to local use cases, with palm oil waste management primarily focused on lighter waste processing in Aceh.

A study by Abdul-Hamid *et al.* (2021) explored the integration of circular economy principles into the Malaysian palm oil industry through IoT, big data, and AI technologies, transforming palm oil waste into high-value products. Rajakal's (2023) research emphasized optimising the palm oil sector by integrating various industries to create economic circulation. Abdul-Hamid *et al.* (2022) further emphasized the fusion of modern technologies with circular economy principles to foster sustainability in the palm oil industry. While many studies have highlighted the potential of a circular economy in the palm oil sector, none specifically focus on the industry in Indonesia.

MATERIALS AND METHODS

The research adopts a mixed-method approach, incorporating both quantitative and qualitative analyses. Two essential analytical methods address the research questions: bibliometric analysis and ex-post facto analysis. The bibliometric analysis draws from the Scopus database to reflect global trends. At the same time, data from Indonesia's Central Bureau of Statistics (BPS) is used to assess the potential of the circular economy within Indonesia's palm oil industry. The findings from these analyses are integrated to explore the opportunities for advancing a green economy in Indonesia. The research framework is illustrated in Figure 1.

Bibliometrics Analysis

Bibliometric analysis is a precise statistical approach to explore and analyze extensive scientific data, revealing variations and highlighting the development within a particular field (Donthu *et al.* 2021). The purpose of employing bibliometric analysis in Its research is to identify global trends related to the circular economy within the palm oil industry. The bibliometric analysis follows three steps: defining the objective, selecting the sample, and conducting statistical analysis.

Defining the Objective

Bibliometric analysis encompasses several quantitative characteristics of publications, including the number of articles retrieved, citation frequency, keyword usage, subject categories, and contributing countries. The volume of publications and citation frequency reflect changes in scientific attention over a specified time frame. Keyword frequency illustrates the primary topics addressed in the research. Subject categories and contributing countries demonstrate the breadth of research application across various disciplines and regions.

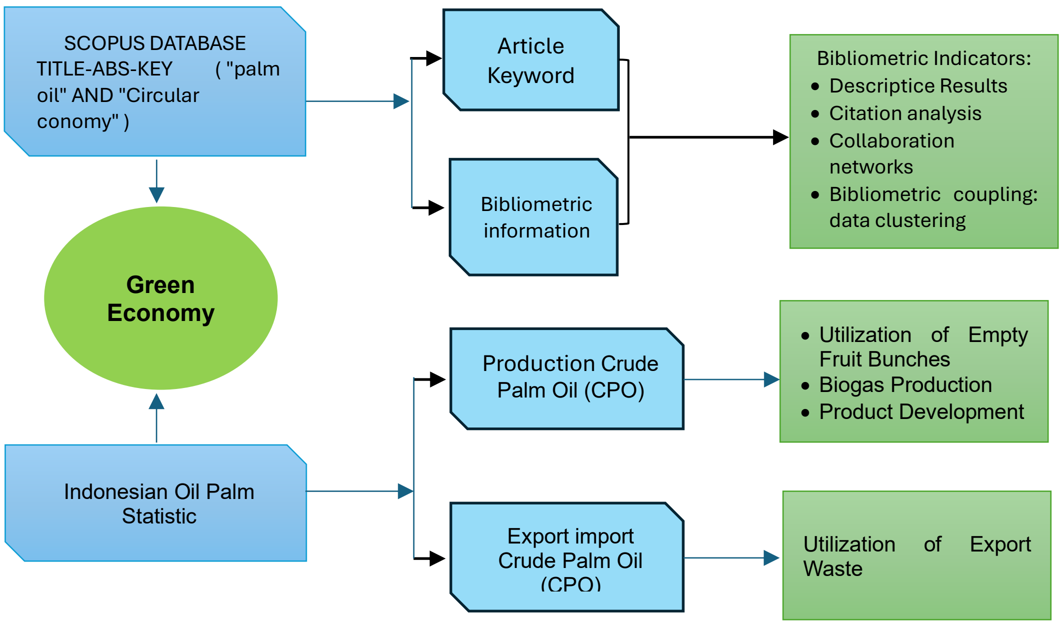

Figure 1 Research framework design

Selecting the Sample

The study utilizes documents from the Scopus database, covering 2017-2024. Sample selection involved searching the article titles, abstracts, and keywords using “Palm Oil” AND “Circular Economy.” The search yielded 121 research documents between 2017 and 2024 without restriction on publication years. The articles were exported in BibTeX format; however, one document failed to meet the bibliometric metadata requirements and was excluded, resulting in a final sample of 120 papers for analysis.

Statistical Analysis

The research employs R Studio's Biblioshiny software to conduct bibliometric analysis. The integration of text mining with a clustering approach enables the creation of connections between various bibliometric needs, providing advanced visualization and interactive functions that make it easier to access and explore bibliometric data networks. These features offer a significant advantage over other programs (van Eck & Waltman 2010). The clustering algorithm operates with adjustable y parameters to fit specific requirements, while the density and colour of clusters can also be visualized within the software (Leydesdorff & Rafols 2012).

Ex-Post Facto

The ex-post facto method is a research type that examines cause-and-effect relationships from events that have already occurred without manipulating variables. The qualitative approach employed in This study aims to gain deeper insights by collecting and analyzing descriptive data (Ary *et al.*2010). The research sample consists of statistical data on palm oil from Indonesia published by the Indonesian Central Bureau of Statistics (BPS). The data encompasses various aspects of palm oil production, distribution, and export in Indonesia, which are processed and analyzed to support the research objectives. The use of secondary data, such as statistics from BPS, provides a comprehensive and reliable overview of the palm oil industry in Indonesia, enabling researchers to draw conclusions based on verified and accountable data.

RESULT AND DISCUSSION

Analysis of Global Trends in the Circular Economy within the Palm Oil Industry

The bibliometric analysis spans 2017 to 2024, reflecting the dynamics of growth and collaboration in the research field.

Table 1 Completeness of bibliographic metadata

MD	Description	MD	Missing %	Status
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
AB	Abstract	3	0.21	Good
C1	Affiliation	4	0.28	Good
DI	DOI	13	0.90	Good
RP	Corresponding Author	54	3.75	Good
DE	Keywords	133	9.24	Good
ID	Keywords Plus	156	10.84	Acceptable
CR	Cited References	1439	100.00	Completely missing
WC	Science Categories	1439	100.00	Completely missing

MD: Metadata; MS: Missing Count

The contributions to these publi-cations were made by 553 authors, with 7 producing individual works. Collabo-ration in research is also notably high, with an average of 5.34 authors contributing to each document. Furthermore, 49.17% of these publications involved international collaboration, highlighting the involve-ment of researchers from various countries in enriching the research.

Evolution of Publications and Globally Most Cited Articles

A total of 436 keywords were employed by the authors in these publications, illustrating the diversity and breadth of topics covered. The average age of the documents analyzed is 2.03 years, indicating that most publications are relatively recent and relevant to current research contexts. Each document received an average of 20.26 citations, suggesting a substantial impact of these studies. One of the initial steps in identifying research trends is observing the annual increase in publications, as shown in Figure 2.

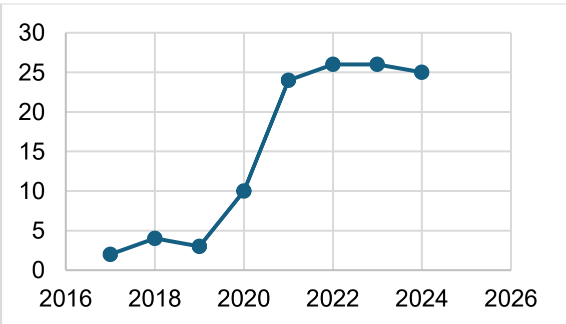

Figure 2 Publication Evolution

Figure 2 illustrates a rapidly evolving research trend over the past few years. The trend developed slowly from 2017 to 2019, with minimal fluctuations. However, the field under investigation only began to gain substantial attention during This period, attracting interest from scientists and researchers. Although growth is evident, the chart suggests that The topic remains in its early stages of development or exploration. A sharp increase occurred in 2019, particularly during the 2019 to 2021 period. Its surge reflects a growing interest in the subject. In 2021 and 2022, the trend peaked, with the number of studies and publications in the field reaching its highest point. Its rapid growth can be attributed to the rising interest in critical issues such as green technology, digital transformation, and sustainability challenges. These topics have not only become trends but have also garnered global attention among scientists and researchers.

The trend begins to stabilize or slightly decline in 2023 through 2024, as the data collection cut-off was in October, leaving room for further growth by December. However, another analysis of The phenomenon suggests that after reaching the peak of innovation and discoveries, the research focus may shift towards developing and applying existing theories or technologies. Its stabilization may also indicate that the research topic has reached a certain level of maturity, leading to a decline in the intensity of new research. Despite This, research in the field continues to be less intensive than at its previous peak. Several studies have focused on how performance metrics evolve. These studies often involve analyzing vital factors, such as growth rates, changing trends, and relationships between performance indicators. Table 2 presents data related to several key metrics from 2017 to 2024. Each column in the It table provides critical information about how different variables have changed, offering insights into the dynamics and trends during the It period.

The evolution of MTCA from 2017 to 2024 reveals significant variation. In 2018, MTCA peaked at 92.50, indicating a substantial increase compared to the previous year. However, after 2018, there was a gradual decline, with MTCA reaching its lowest point in 2024 at 1.08. This suggests the influence of external factors contributing to the consistent decrease in performance. The number of published documents (N), reflecting the number of cases, frequencies, or specific categories, increased significantly each year. From only 2 in 2017, it rose to 26 in 2022 and

2023, maintaining a high level of 25 in 2024. The MTYC variable followed a similar pattern to MTCA, peaking in 2018 (13.21) and gradually declining until 2024 (1.08). The correlation between the two metrics suggests a close relationship. Although the number of documents (N) increased, the decrease in MTCA and MTYC may indicate a decline in effectiveness, productivity, or overall performance. CY, which appears to be related to a specific category, also decreased from 8 in 2017 to 1 in 2024. It indicates a significant shift in the category or classification being analyzed, consistent with the downward trend across other metrics.

Table 2 Average citations per year

Year	MTCA	N	MTCY	CY
2017	17.50	2	2.19	8
2018	92.50	4	13.21	7
2019	59.33	3	9.89	6
2020	62.50	10	12.50	5
2021	24.04	24	6.01	4
2022	14.08	26	4.69	3
2023	9.73	26	4.86	2
2024	1.08	25	1.08	1

MTCA: MeanTCperArt;
MTCY: MeanTCperYear; CY:CitableYears

Citation Source Analysis and Local Impact

Several performance indicators are used to evaluate academic publications and journals. The h-index, g-index, and m-index are metrics used to assess the impact and quality of an author's work or a journal. Each indicator provides a different perspective on the significance and citation frequency of a single work or a body of work. The h-index measures published articles' productivity and citation impact; the higher the value, the more articles with high citations. The g-index assigns more weight to highly cited articles compared to the h-index. The m-index normalizes the h-index based on the time since the first publication, providing a more balanced view of productivity over time. TC (Total Citations) reflects the total number of citations a journal or article receives within a certain period. NP (Number of Publications) indicates the total number of articles published. PY_start denotes the starting year of publications in the analyzed dataset. Various academic journals are pivotal in sustainability, energy, and environmental technology. Table 3 highlights that the Journal of Cleaner Production has the highest h-index (6), indicating that at least six articles from It jouTheal have received at least six citations. It demonstrates the journal's strong reputation in terms of quality and scientific impact. The journal also boasts a TC of 155, with six articles published since 2020, reflecting its consistent performance over a relatively short period. Sustainability (Switzerland), although it has a slightly lower h-index and g-index (5), shows a higher total citation count (227). It indicates that despite having fewer articles and a lower citation rate per article, the journal has a broader overall impact within the scientific community. Meanwhile, the Journal of Oil Palm Research and Renewable and Sustainable Energy Reviews exhibit relatively high h-index and g-index scores, accompanied by significant total citations. The Journal of Oil Palm Research, despite having a lower h-index (4), holds an impressive total citation of 370, implying that several of its articles are highly cited, lending substantial weight to its impact index. It underscores the journal's importance in the context of palm oil and renewable energy research, even though its productivity is relatively limited, with only five articles published since 2018.

Interestingly, journals such as biomass conversion, biorefinery, and fuel have lower total citations. Still, their m-index values suggest that their articles are relatively recent and show early signs of significant academic impact because the m-index, which normalizes the h-index over time, assigns higher values to journals that have demonstrated high productivity over a short period. biomass conversion and biorefinery, which began in 2022, is already showing of increasing productivity.

Collaboration Analysis: Countries and Authors

The distribution of country contributions to scientific publications is detailed in Table 4, which provides insights into articles published by various countries, along with key metrics related to collaboration and the level of each country's contribution. Several vital variables are used here, including Atk (the number of articles published by that country), Atk % (the percentage of articles contributed to the total publications), SCP (Single Country Publication), which refers to the number of articles published by researchers from a single country without international collaboration, MCP (Multiple Country Publication), which represents the number of articles involving international collaboration where researchers from other countries contributed, and MCP % (the percentage of articles involving international partnership relative to the total articles published by that country).

Malaysia has the highest contribution of articles (43), accounting for 35.8% of the total publications. Interestingly, more than half of Malaysia's articles (51.2%) were published through international collaborations, indicating that Malaysia is heavily engaged in global research partnerships. In contrast, with 11 articles (9.2% of the total), Indonesia also demonstrates a reasonably high rate of international collaboration, with 45.5% of its articles resulting from joint efforts with other countries. It highlights how Indonesia is becoming increasingly active in participating in international research networks, although its total number of articles remains lower than that of Malaysia.

Table 3 Source local impact

Source	h_index	g_index	m_index	TC	NP	PY_start
Journal Of Cleaner Production	6	6	1,2	155	6	2020
Sustainability (Switzerland)	5	5	1	227	5	2020
Journal Of Oil Palm Research	4	5	0,571	370	5	2018
Renewable And Sustainable Energy Reviews	3	3	0,429	310	3	2018
Science Of The Total Environment	3	3	0,75	155	3	2021
Biomass Conversion And Biorefinery	2	3	0,667	29	3	2022
Bioresource Technology	2	2	0,5	72	2	2021
Chemical Engineering Transactions	2	3	0,5	13	3	2021
Fuel	2	2	0,667	26	2	2022
Acs Sustainable Chemistry And Engineering	1	1	0,143	31	1	2018

Table 4 Country of correspondence of author

Country	**Atk**	**Atk %**	**SCP**	**MCP**	**MCP %**
Malaysia	43	35.8	21	22	51.2
Indonesia	11	9.2	6	5	45.5
China	6	5.0	0	6	100.0
Thailand	6	5.0	5	1	16.7
Brazil	5	4.2	3	2	40.0
Hungary	3	2.5	0	3	100.0
Italy	3	2.5	2	1	33.3
United Kingdom	3	2.5	2	1	33.3
Colombia	2	1.7	0	2	100.0
Ecuador	2	1.7	1	1	50.0

China and Hungary display an intriguing pattern, with 100% of their articles published through international collaboration. China has six articles, all published through collaborations with other nations, suggesting a firm reliance on international partnerships in its publications. The same applies to Hungary, although its total article count is lower (3 articles). Conversely, Thailand exhibits a different trend, where 5 6 articles were published independently without international collaboration (83.3% SCP). It suggests that Thailand tends to conduct more internal research and is less dependent on cross-country collaborations. Other countries, such as Brazil, Italy, the United Kingdom, Colombia, and Ecuador, display diverse international collaborations and independent publications. Brazil balances SCP and MCP, with 60% of its articles published independently and 40% through cooperation. Italy and the United Kingdom also exhibit similar patterns, slightly preferring independent publications over international collaboration.

It is crucial to observe how distribution influences scientific networks across different regions to understand essential factors in the context of research distribution or global collaboration. The map in Figure 3 provides a visual representation of the countries involved in international research networks, shown through colour distribution based on their level of engagement. Countries with darker shades generally have higher involvement in collaboration, article contributions, or impact in scientific publications.

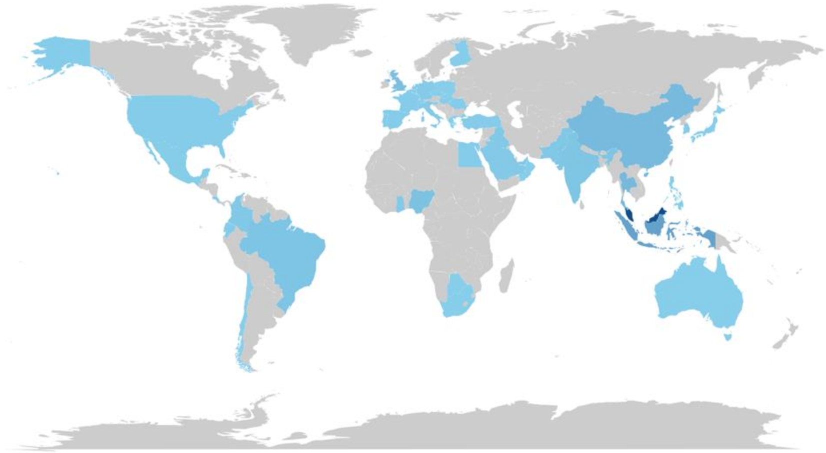

Figure 3 Country participation in research

The world map illustrates the distribution of countries involved in international scientific research or collaboration. Several Southeast Asian countries, such as Malaysia, stand out with darker shades, indicating a high level of engagement in global partnerships. It aligns with earlier data, showing that Malaysia has significant contributions to scientific publications and international collaborations, as reflected by the high MCP (Multiple Country Publications) in various studies. In addition to Malaysia, other Asian countries such as Indonesia, Thailand, and China are depicted on it, although with varying intensities of colour. Reflects the differing levels of contribution and collaboration among these countries. China, which exclusively participates in international collaborations, as shown in the previous table, is highlighted on the map, underscoring its crucial role in global research networks despite its limited independent contributions.

Beyond Asia, the map also displays the involvement of countries in South America, such as Brazil and Colombia, as well as several European countries like Italy and the United Kingdom. These regions exhibit diverse participation in scientific research networks, with some countries, like Brazil and Italy, striking a balance between independent publications and international collaborations. Countries in Africa and Oceania are also represented, although their engagement is more limited than those in Asia and Europe. The map illustrates that while these regions are involved in global research networks, their contributions are smaller regarding the number of articles or scientific collaborations compared to more dominant countries on the map.

Darker shades indicate countries with significant roles in international scientific networks, whereas lighter shades represent smaller contributions or more limited involvement. The image highlights the importance of international cooperation in research, where countries with high levels of collaboration tend to achieve a more significant impact within the global academic community.

Development of Research Issues on Circular Economy in the Palm Oil Industry

The word cloud illustrates various keywords or topics frequently discussed in a specific context, with the majority closely related to research or discourse on palm oil, circular economy, and sustainable development. The word cloud displays words in varying sizes, where the size of each word reflects its frequency or significance within the context being analyzed. Its visual representation helps to highlight the most prominent topics in the research field, providing insight into the critical areas of focus in the study of circular economy within the palm oil industry.

Figure 4 Word cloud

The word "palm oil" appears in the largest font, signifying that the primary topic of discussion revolves around the palm oil industry. The term likely encompasses various aspects of palm oil, from production and processing to environmental impacts. These have become a central focus in the global discourse on sustainability and the green economy. Other prominent words, such as "circular economy" and "sustainable development," also stand out, indicating that discussions or research on palm oil are frequently associated with the concepts of circular economy and sustainable development. It suggests that research on palm oil is not solely focused on its production but also explores how the industry can support more environmentally friendly and sustainable economic systems. In the It context, palm oil is a critical sector that can be integrated into green economic strategies, particularly in regions that rely heavily on Its commodity.

Other significant topics include "biomass," "effluents," and "anaerobic digestion," all of which pertain to waste management and the use of green technologies in palm oil production processes. It indicates that a significant aspect of the discussion centres on how palm oil industry waste, such as residues and effluents, can be processed and repurposed through bioenergy technologies or anaerobic digestion processes, aligning with the circular economy concept. Terms such as "biogas," "biodiesel," and "bioenergy" are also featured in the word cloud, highlighting that renewable energy is another crucial topic in the discussion. It reflects how palm oil by-products such as biogas or biodiesel can generate energy, contributing to green energy development strategies.

Additionally, the words "recycling" and "waste management" emphasize the importance of waste management in the context of the palm oil industry. Effective waste management reduces environmental impacts and enhances resource efficiency through recycling and reusing materials generated from production processes. The word cloud presents a holistic view of the palm oil industry's discourse, focusing on how the It sector can contribute to circular economy goals and sustainable development. Topics such as waste management, bioenergy, and green technological innovation are critical in mitigating its industry's environmental impact and establishing a more sustainable system. The concepts of palm oil, circular economy, and sustainable development can be further analyzed through a more in-depth approach using a concept map visualization. Its visualization illustrates how various topics interconnect within the context of research related to palm oil, environmental management, and renewable energy. In Figure 5, each node represents a topic or concept, while the lines connecting them indicate relationships or linkages between these concepts. Topics more frequently discussed or central to the discourse are displayed in larger fonts, with different colours grouping themes or categories of topics.

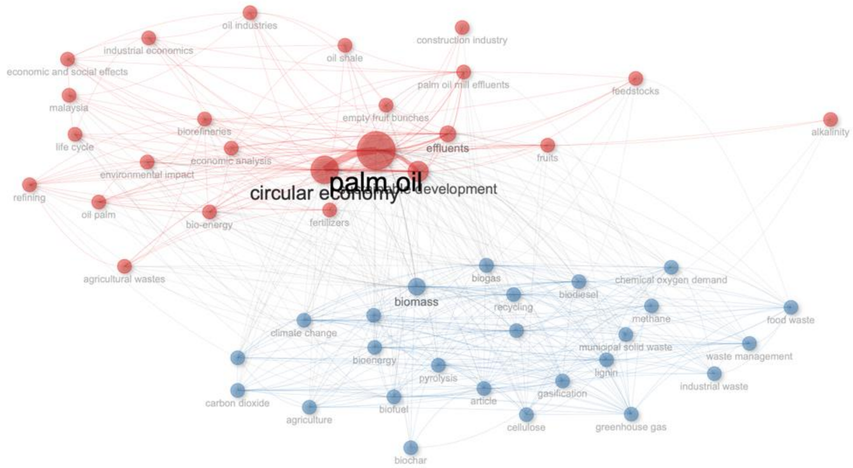

Figure 5 The trend of topics correlates with co-occurrence in research

Palm oil remains at the centre of Its visualization, depicted in a larger size, indicating that Its topic is the core of many discussions. Circular economy and sustainable development are also strongly linked to palm oil, as evidenced by the thick lines connecting them. It reflects that discussions about palm oil cannot be separated from how the industry contributes to achieving circular economy and sustainable development goals.

At the top of the image, a cluster of topics more related to economics and industry (coloured red), such as economic and social impact, oil industry, and economic analysis, are shown to be closely connected with palm oil. It highlights that the financial aspects of the palm oil industry, including its impact on various industrial sectors and society, are vital components in research about palm oil. Issues like industrial waste, effluents, and palm fruit waste also appear, underscoring the importance of waste management within The industry.

At the bottom of the image is a cluster of concepts related to renewable energy and green technologies (coloured blue). Concepts like biomass, biogas, and biodiesel are strongly associated with palm oil and the circular economy. It illustrates that waste from the palm oil industry can be harnessed for renewable energy production, aligning with circular economy principles. Other concepts, such as waste management and recycling, are closely related to biomass, reflecting the importance of recycling and reusing waste in creating a more sustainable production system.

Moreover, a strong link exists between climate change and the bioenergy sector, lignin, and greenhouse gas emissions. This indicates that producing renewable energy from palm oil and other biomass materials is part of the broader effort to mitigate climate change. Waste management and reducing greenhouse gas emissions are critical aspects of the discourse surrounding palm oil and its impact on the global environment.

Its visualization provides deep insights into how palm oil sits at the centre of many discussions on waste management, circular economy, and renewable energy. The interconnect-tedness of these topics highlights the complexity facing the palm oil industry, where success in achieving circular economy and sustainability goals requires an integrated approach that spans multiple sectors, from economics to environmental management.

The Potential of Circular Economy in Indonesia's Palm Oil Industry

Crude Palm Oil (CPO) production in Indonesia has significantly increased over the past two decades, as illustrated in Figure 6, with production volumes rising from 8.39 million tons in 2001 to over 45.7 million tons in 2021. This trend has positioned Indonesia as one of the largest palm oil producers in the world. However, alongside the increase in production, challenges have emerged regarding managing waste generated by the palm oil industry, such as Empty Fruit Bunches, Palm Oil Mill Effluent (POME), and palm shells. Implementing a circular economy can transform waste into valuable resources while mitigating harmful environmental impacts (Duan *et al.* 2022).

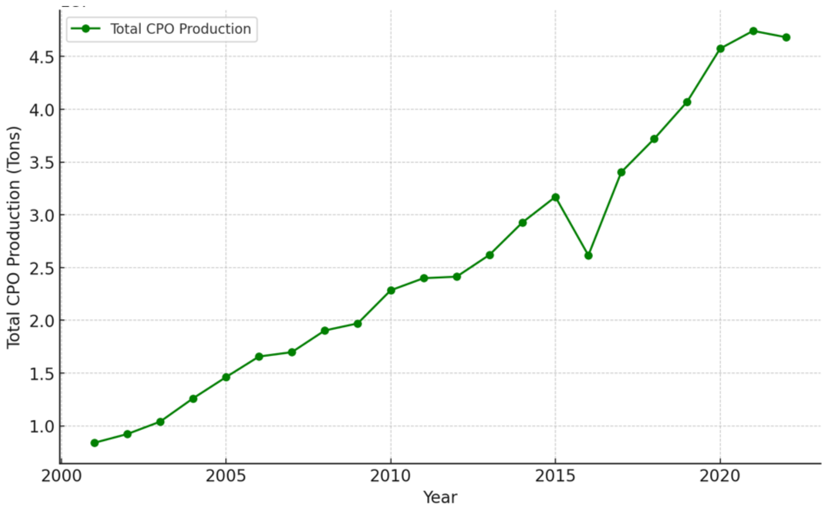

Figure 6 Total production of CPO in Indonesia 2001-2022

The potential of the circular economy in palm oil waste management includes the utilization of Empty Fruit Bunches (EFB) as fuel and fertilizer, the production of biogas from Palm Oil Mill Effluent (POME), and the development of value-added byproducts. EFB is one of the primary waste products in the CPO production process. EFB can be harnessed as biomass fuel to generate electricity or heat through processes like pyrolysis or gasification (Khoo 2011). Additionally, EFB can be processed into organic fertilizer through composting, reducing reliance on chemical fertilizers and enhancing soil fertility. Furthermore, POME, the liquid waste from palm oil mills, is an organic waste with a high potential for biogas production through anaerobic digestion. In the context of the circular economy, POME management can significantly reduce greenhouse gas emissions from the palm oil industry (Chin *et al.* 2013). Beyond bioenergy, palm oil byproducts like lignocellulosic residues can be used as raw materials or bio-materials for the chemical industry. It reduces waste and opens opportunities for product diversification within the palm oil industry (Goh *et al.* 2010).

Implementing a circular economy in the palm oil industry offers economic benefits and reduces environmental impact. Technologies such as pyrolysis for EFB, anaerobic digestion for POME, and using bioenergy from palm shells can reduce factory energy costs while generating additional revenue from the sale of renewable energy (Nasution *et al.*2018). Globally, the circular economy has proven to be an effective strategy for reducing waste and improving resource efficiency (Khoo, 2009). In Indonesia, applying the circular economy to the palm oil industry can help transition the industry toward a more sustainable system while contributing to achieving greenhouse gas emission targets outlined in the Paris Agreement (2015). The potential of the circular economy in Indonesia can also be analyzed based on export and import data for Crude Palm Oil (CPO) and palm kernels from 2001 to 2022, as shown in Figure 7. Indonesia has demonstrated remarkable growth in palm oil export volumes to international markets. In 2001, CPO exports were recorded at around 4.9 million tons, and they surged to a peak in 2020 with a volume of 35.9 million tons. Despite a slight decline in 2022, export volumes remained highly significant at approximately 24.9 million tons. These figures underscore Indonesia’s crucial role as one of the world's primary CPO suppliers.

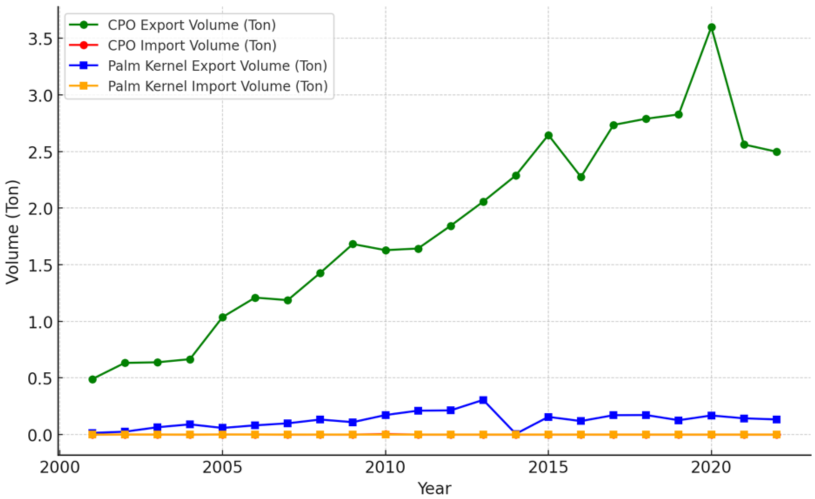

Figure 7 Export and Import Volumes of CPO and Palm Kernel 2001-2022

The volume of CPO imports to Indonesia is relatively small, especially compared to exports. The peak of imports occurred in 2010, with approximately 46,720 tons, but overall, the import volume remains minimal each year. It indicates that most of Indonesia's CPO production is allocated for export, with little reliance on imports to meet domestic demand. The data is significant in the circular economy because the large production volume offers opportunities to utilize the waste generated from the production process before palm oil products are exported. The circular economy in the palm oil industry aims to optimize resource use by reusing waste and byproducts from the production process. Managing palm oil waste, such as Empty Fruit Bunches (EFB) and Palm Oil Mill Effluent (POME), can serve as renewable energy sources and raw materials for other value-added products.

The EFB waste produced during palm oil production can be processed into bioenergy through pyrolysis or gasification. Khoo (2009) states that EFB holds great potential as a feedstock for renewable energy production. Its waste can be converted into electricity, used as fuel for other industries, or processed into organic fertilizer through composting. Such potential can be harnessed domestically before palm oil products are exported, adding value to the products and reducing their environmental footprint. In addition to EFB, the liquid effluent from palm oil processing, known as POME, can also be processed into biogas through anaerobic digestion. The biogas produced from POME can replace fossil fuels and help reduce greenhouse gas emissions associated with palm oil production. Processing POME domestically reduces waste disposal and provides a sustainable source of green energy.

Other palm oil byproducts, such as shells and fibres, can be processed into raw materials for bioenergy or bio-based products. Shuit *et al.* (2009) identified that these byproducts can produce biodiesel and bioethanol, sustainable fuels in high demand in international markets. By processing Its waste before exporting the products, Indonesia can increase the value of palm oil while reducing environmental impacts. With high export volumes, the opportunity to utilize palm oil waste before exporting becomes increasingly essential. Chin *et al.* (2013) emphasized that waste processing before export can enhance the overall sustainability of the palm oil industry. Implementing circular economy technologies, such as energy production from biomass waste and processing liquid waste into renewable energy, can have positive environmental impacts and strengthen Indonesia's position in the international market as a sustainable palm oil producer.

The export and import data of CPO and Palm Kernel highlight Indonesia's critical role in the global palm oil market. Large export volumes create opportunities for Indonesia to leverage the circular economy better, mainly by processing waste before export. Utilizing palm oil waste, such as EFB and POME, for bioenergy and other byproducts can increase the value of exported products while reducing the environmental impact of the palm oil industry. With improved waste management, Indonesia can continue to develop a sustainable and environmentally friendly industrial model aligned with the circular economy's goals.

Opportunities for a Green Economy in the Indonesian Palm Oil Industry

The palm oil industry in Indonesia is one of the most vital economic sectors, both in terms of its contribution to the national GDP and capacity for job creation. However, the industry is frequently associated with environmental issues such as deforestation, greenhouse gas emissions, and biodiversity loss. Therefore, to achieve long-term sustainability, integrating a green economy approach incorporating circular economy principles is crucial. In this context, green economy refers to efforts to minimize the environmental impact of palm oil production while creating added value from the waste generated.

The Potential of Circular Economy in the Palm Oil Industry

A key concept within the green economy is the circular economy, which aims to reduce, reuse, and recycle resources to create a more efficient and environmentally friendly production system. Waste from the palm oil industry, such as Empty Fruit Bunches (EFB) and Palm Oil Mill Effluent (POME), holds significant potential for use in bioenergy production and organic fertilizers. These wastes can be further processed into renewable energy through pyrolysis or anaerobic digestion.

Provinces with large palm oil plantation areas, such as North Sumatra, Riau, and West Kalimantan, statistically have substantial potential to adopt a circular economy approach. The large volume of CPO production in these provinces indicates that the waste generated will also be significant, making its management key to reducing environmental impact and increasing economic value. Khoo (2009) also noted that EFB can be used as biomass fuel, which is highly needed in the renewable energy industry, and can reduce reliance on fossil fuels.

Opportunities and Potential Waste Management in Smallholder Plantations

Smallholder plantations in Indonesia play a significant role in the palm oil industry, though they often face limited resources and technology for effective waste management. In this context, adopting circular economy principles can provide excellent opportunities for improving productivity and sustainability. Data shows that smallholder plantations, such as those in North Sumatra and Riau, contribute substantially to CPO production, although productivity per hectare could be improved. Waste generated from smallholder plantations, such as EFB and POME, can be processed into more valuable products like bioenergy or organic fertilizers.

Chin *et al.* (2013) highlighted that the main challenge in smallholder plantations is the lack of access to technology and infrastructure to utilize waste efficiently. Therefore, collaboration between the government and industry is essential to provide appropriate technologies and training to small farmers to adopt circular economy principles more effectively. One of the significant opportunities arising from the green economy approach in the palm oil industry is the potential for bioenergy production. Palm oil waste, such as EFB and POME, can be converted into renewable energy through biogas technology or biomass combustion. POME has significant potential to be processed into biogas, which can be used to generate electricity and reduce greenhouse gas emissions.

Developing bioenergy from palm oil waste can also support the Indonesian government's target of reducing dependency on fossil fuels and increasing the share of renewable energy in the national energy mix. Given the enormous volume of waste generated from CPO production in crucial provinces like Riau and West Kalimantan, the opportunity to develop bioenergy infrastructure in these regions is substantial.

The green economy potential in the palm oil sector requires the implementation of sustainable technologies that can efficiently process waste and produce value-added products. It necessitates investment in waste recycling technologies and the development of bioenergy processing facilities across central palm oil-producing provinces. Policies that encourage companies to adopt sustainable practices must be strengthened. It is crucial to emphasize waste recycling and utilization throughout the entire lifecycle of palm oil production to reduce environmental impacts and increase resource efficiency (Chin *et al.* 2013).

The palm oil industry in Indonesia has great potential to become more sustainable by adopting green economy principles. Utilizing palm oil waste, such as EFB and POME, within the framework of a circular economy can help reduce environmental impacts, improve resource efficiency, and create added value through new products such as bioenergy and organic fertilizers. The government and industry must collaborate to ensure the necessary technology and infrastructure are available,

CONCLUSION

The research on the circular economy in the palm oil industry has grown significantly, with a 43.45% increase in publications from 2017 to 2024. This shows rising global interest in green technologies, digital transformation, and sustainability. Almost 50% of these studies involve international collaborations, with Malaysia leading the way, contributing over 35% of the total publications, followed by Indonesia. Although the number of publications has stabilized, the circular economy is moving from early research stages to more practical applications. Key research topics include managing palm oil waste like Empty Fruit Bunches (EFB) and Palm Oil Mill Effluent (POME) and developing renewable energy sources such as biogas and biodiesel. This highlights the significant potential for palm oil waste to support the circular economy, reduce greenhouse gas emissions, and help fight climate change.

In Indonesia, the circular economy in the palm oil industry could bring significant environmental and economic benefits. The country's high Crude Palm Oil (CPO) production generates a lot of waste, which can be turned into bioenergy, organic fertilizer, and other valuable products. Technologies like pyrolysis for EFB and anaerobic digestion for POME can reduce greenhouse gas emissions and reliance on fossil fuels. These efforts can also help Indonesia meet its climate goals under the Paris Agreement. Small farmers play an essential role but need better access to technology and infrastructure. Government support and industry collaboration are crucial to helping them adopt these methods, promoting sustainability and green economic growth.

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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.

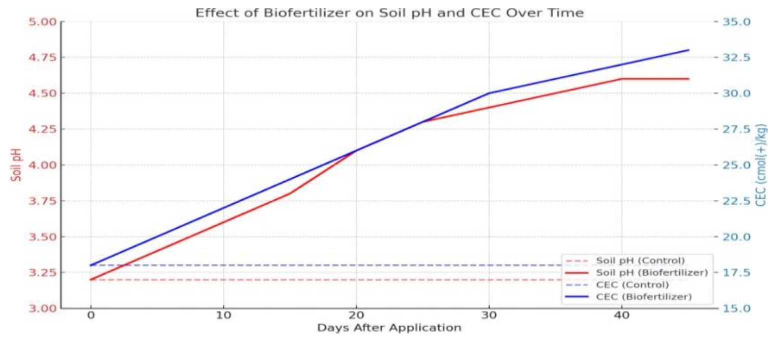

Figure 1 Changes in soil pH and cation exchange capacity (CEC) over a 45-day period after application of the biosilica-based slow-release fertilizer, compared to control (no fertilizer). The formulation significantly increased soil pH from 3.2 to 4.6 and improve CEC from 18 to 33 cmol(+)/kg, demonstrating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

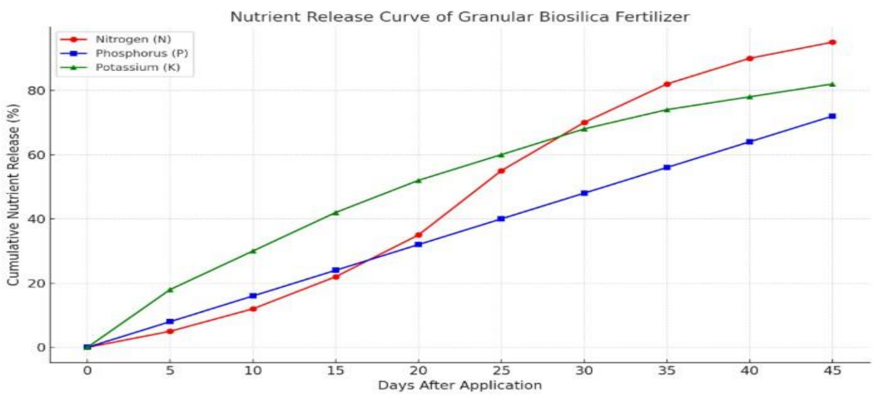

Figure 2 Cumulative nutrient release profile of slow-release biosilica granular fertilizer over a 45-day period under simulated peat soil conditions. The demonstrates a controlled-release pattern for nitrogen (N), phosphorus (P), and potassium (K), aligning with the nutrient uptake dynamics of oil palm 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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Effect of Organic and Biological Fungicides on the Development of *Ganoderma* Fruiting Bodies

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ABSTRACT

Ganoderma sp. are major pathogens of oil palm (Elaeis guineensis), causing basal stem rot and severe yield losses. This study investigated the efficacy of an allicin-based organic fungicide and a Trichoderma-based biofungicide on the growth of *Ganoderma* mycelium in vitro and on fruiting body development in vivo. The in vitro experiment used PDA media amended with different concentrations (0–40%) of an emulsified concentrate (EC) organic fungicide, while the in vivo test evaluated treatments on naturally occurring *Ganoderma* fruiting bodies growing on dead breadfruit trunks. The organic fungicide was applied twice (three-day intervals), followed by one biofungicide application. The EC formulation completely inhibited mycelial growth at concentrations ≥2% (0.67% active ingredient). In field trials, fruiting body enlargement ceased within three weeks after treatment, while untreated controls continued to expand. At 3.5 months post-treatment, *Ganoderma* could no longer be isolated from treated fruiting bodies, whereas viable mycelia persisted in controls. Combined application of organic and biofungicides resulted in tissue browning, compact texture, and death of the fungus. These findings indicate that allicin-based organic fungicides, especially when followed by Trichoderma treatment, can effectively suppress *Ganoderma* fruiting body growth and viability. Further trials on living oil palm tissues are recommended to confirm field applicability.

Keywords: allicin, biofungicide, fruiting body inhibition, *Ganoderma sp.*, organic fungicide, *Trichoderma*

INTRODUCTION

Ganoderma is a major pathogen of oil palm that causes significant losses in oil palm plantations. This fungus can also infect other economically valuable plants such as rubber, eucalyptus, and acacia (Mohammed *et al.* 2014). *Ganoderma* boninense is characterized by large, perennial, rough basidiocarps (fruiting bodies), which are sometimes stalked. The fruiting body typically has a fan or hoof shape on the tree trunk, producing double-walled spores that are yellowish to brownish. In addition to being a soil-borne pathogen, this fungus is also a facultative parasite that can live as a saprobe on decaying stumps and roots, especially on suitable host plants (oil palm). Several control strategies against *Ganoderma* have been developed through improvements in technical, chemical, and biological methods. Environmentally friendly control of *Ganoderma* has become a choice for

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farmers in line with food safety requirements that have become a consumer lifestyle today. Organic fungicides are increasingly being used to control various plant pathogens. Organic fungicides with the active ingredient allicin have been shown to effectively kill several pathogens (Sarfraz *et al.* 2020), such as damping-off disease in tomatoes. Research by An *et al.* (2022) showed that the addition of *Trichoderma reesei* to compost applied near the fruiting bodies of *Ganoderma* growing from trees was able to suppress the growth of *Ganoderma sp.* fruiting bodies, with an average surface area of 18.77 cm². Meanwhile, the fruiting bodies of *Ganoderma* with compost treatment alone developed better, with an average surface area of 65.19 cm², and the average surface area of the control *Ganoderma* fruiting bodies was 62.12 cm². This indicates that the addition of *T. reesei* has a significant effect on inhibiting the growth of *Ganoderma sp.* fruiting bodies. This study aims to test the effectiveness of organic fungicides with the active ingredient allicin and biological fungicides against the development of *Ganoderma* fruiting bodies.

MATERIALS AND METHODS

The *Ganoderma* isolates used in the *in vitro* test were obtained from oil palm plantations in Rejosari and Bekri, Lampung Province. The *Ganoderma* cultures were rejuvenated on potato dextrose agar (PDA) medium and incubated for 14 days at room temperature.

The organic fungicide was made from spices, with allicin as the active ingredient, derived from local Indonesian garlic. The garlic and water (1:2, v/v) were blended and filtered to obtain the filtrate. The filtrate was then formulated as an Emulsified Concentrate (EC) organic fungicide by adding 10% clove oil and surfactants at 10% and 2.5%, respectively. The biological fungicide was made from Trichoderma obtained from oil palm plantations in Medan, North Sumatra, and rejuvenated on PDA medium for 5 days. The *Trichoderma sp.* isolate from one Petri dish was blended in 100 mL of water to obtain a mycelial suspension with a density of 10^6 CFU per mL.

Test of EC Organic Fungicide Against *Ganoderma in vitro*

This test was conducted in two stages. In the first stage, agar poisoning was carried out by adding a certain amount of EC organic fungicide (according to treatment) to sterile PDA medium that was still liquid at around 60 °C, then pouring it into sterile Petri dishes. The EC concentrations used consisted of five levels: 0, 10, 20, 30, and 40%, each replicated twice. *Ganoderma* mycelial colonies were then inoculated in the center of the PDA medium in the Petri dish. The effectiveness of the EC fungicide was measured by the inhibition of *Ganoderma* mycelial growth after 5 days of incubation on PDA medium in a dark room.

The second stage aimed to more precisely determine the effective concentration of the EC organic fungicide tested. This test was carried out in the same way as the first stage, except that the EC concentrations tested in this stage consisted of 12 levels: 0, 0.5, 1.0, 1.4, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, and 15.0%, each replicated twice. These corresponded to 0; 0.17; 0.33; 0.47; 0.67; 1; 1.33; 1.67; 2; 2.67; 3.33; and 5% active ingredient source (AIS).

Test of EC Organic Fungicide and Biological Fungicide Against Ganoderma *in vivo*

This test used two *Ganoderma sp.* fruiting bodies that grew naturally on dead breadfruit tree trunks. The fruiting body used as the control was located on the upper position, while the treated one was below it. The EC organic fungicide at a 20% concentration was evenly applied with a brush over the entire surface of the Ganoderma fruiting body on days 0, 50, 51, and 52. Then, from days 56 to 58, the *Trichoderma* biological fungicide was applied in the same way. Both the EC fungicide and the biofungicide were applied to the underside of the fruiting body (which contains many pores) and the upper surface. The control fruiting body received neither EC nor biofungicide treatment.

On day 65, nutrient agar medium in a Petri dish was placed under the *Ganoderma* fruiting body for one minute, then incubated for 3 to 7 days. The microorganisms that grew on the nutrient agar medium were observed on day 7. On day 104, the *Ganoderma* fruiting body was cut at the base, and a 1 cm² piece was cultured on PDA medium to observe the viability of *Ganoderma*. The growth of *Ganoderma sp.* on breadfruit wood was continuously monitored until day 192.

RESULTS AND DISCUSSION

The *in vitro* test of organic fungicide effectiveness using the emulsified concentrate (EC) formulation showed that at a 10% concentration, after 5 days of incubation, the *Ganoderma sp.* mycelium did not grow. In contrast, the *Ganoderma sp.* mycelium grown on PDA medium alone (control) reached a diameter of 3.5 cm on the 5th day and continued growing until the 14th day. The hyphal structure, which was initially white and hyaline, began to thicken—especially noticeable starting from the 10th day of incubation (Table 1). On the medium without organic fungicide, *Ganoderma sp.* mycelium was able to grow up to a diameter of 9 cm (Table 1). The subsequent stage of *in vitro* testing showed that at low doses of organic fungicide, namely 0.5% (on the 10th day) to 1% EC (on the 14th day), mycelial growth inhibition occurred. At a concentration of 1.4% EC, the *Ganoderma sp.* mycelium from Bekri began to thicken starting from day 7. At this concentration, changes in the mycelial texture were observed—becoming thicker, denser, compact, hardened, and slightly darker in color. At a higher concentration, namely 2% EC or 0.67% active ingredient source (AIS), *Ganoderma sp.* mycelium did not grow at all during 14 days of incubation. The results were similar for *Ganoderma sp.* isolates from both Rejosari (Table 2) and Bekri (Table 3). However, the *Ganoderma sp.* from Rejosari appeared more sensitive than that from Bekri, as indicated by the wider mycelial growth of *Ganoderma sp.* Rejosari (3.5 cm) compared to *Ganoderma sp.* Bekri (2 cm). By the fifth day of incubation, both had reduced to 0.2 cm.

Figure 1 (left) shows *Ganoderma sp.* mycelial growth on PDA medium without treatment (control), while the middle image shows *Ganoderma sp.* growth on PDA medium treated with 10% organic fungicide after 14 days of incubation. To determine the effect of organic fungicide application on *Ganoderma* viability, the treated cultures were transferred to fresh PDA medium without organic fungicide. The right image shows that *Ganoderma sp.* was unable to regrow on the new PDA plate. These results indicate that, based on the *in vitro* test, the application of organic fungicide can kill *Ganoderma sp.*

Table 1 Diameter (cm) of *Ganoderma* Rejosari in the *in vitro* efficacy test of emulsified concentrated organic fungicide up to 14 days of incubation

Dose, %EC (v/v)	5 days	7 days	10 days	14 days
40	0	0	0	0
30	0	0	0	0
20	0	0	0	0
10	0	0	0	0
0	3,5	7	9,0	9,0

Table 2 Diameter (cm) of *Ganoderma* Rejosari in the *in vitro* efficacy test of crude organic fungicide extract up to 14 days of incubation

Dose (b/v)		**Incubation (days)**			
% EC	**%SAI**	**5**	**7**	**10**	**14**
15	5	0	0	0	0
10	3,33	0	0	0	0
8	2,67	0	0	0	0
6	2	0	0	0	0
5	1,67	0	0	0	0
4	1,33	0	0	0	0
3	1	0	0	0	0
2	0,67	0	0	0	0
1	0,47	0	0	0	thicken
1	0,33	0	0	0	0,2
0,5	0,17	0,2	thicken	0,2	4
0	0	3,5	7	7	7

EC: Emulsified concentrate
SBA : Source of active ingredient

Table 3 Diameter (cm) of *Ganoderma* Bekri in the *in vitro* efficacy test of crude garlic extract up to 14 days of incubation

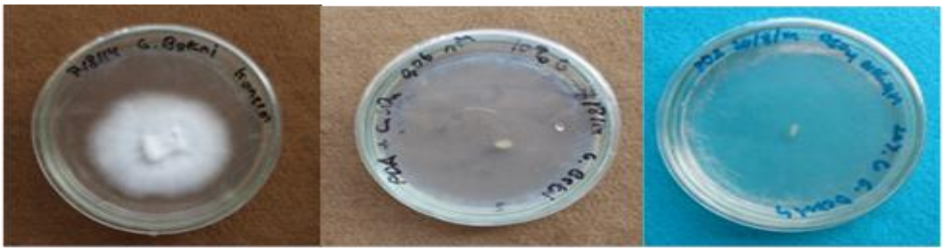
Dose (b/v)		**Incubation (days)**			
% EC333	**%SAI**	**5**	**7**	**10**	**14**
15	5	0	0	0	0
10	3,33	0	0	0	0
8	2,67	0	0	0	0
6	2	0	0	0	0
5	1,67	0	0	0	0
4	1,33	0	0	0	0
3	1	0	0	0	0
2	0,67	0	0	0	0
1	0,47	0	thicken	thicken	thicken
1	0,33	0	0	0	0
0,5	0,17	0,2	2	3	9
0	0	2	7	7	7

EC: Emulsified concentrated
SAI: Source of active ingredient

In the *in vivo* test of the organic fungicide, on day zero, the size of the control fruiting body was smaller than that of the treated fruiting body. Observations showed that visually, there was no apparent effect of the organic fungicide on the development of the fruiting body in terms of color, structure, or size. However, after three weeks, growth inhibition was observed in the treated *Ganoderma sp.* fruiting body, resulting in both the control and treated fruiting bodies being of similar size. This result indicates that it takes approximately three weeks for the organic fungicide to inhibit the growth of *Ganoderma sp.* fruiting bodies. The inhibition appeared to persist, and one month after the first stage of organic fungicide application, the size of the control fruiting body was significantly larger than that of the treated one. These findings show that the organic fungicide strongly inhibits the growth of *Ganoderma sp.* fruiting bodies. This condition continued until day 49 (July 29) (Figure 1). The treatment was continued with a second application of organic fungicide for three consecutive days. This application occurred 50 days after the first application. The organic fungicide was applied to both the top (cap) and bottom (lamella) of the plant. It was observed that the organic fungicide was absorbed into the tissue of the *Ganoderma sp.* fruiting body, although some of it might have evaporated (Figure 3). The control fruiting body continued to grow, increasing in size, whereas the fruiting body treated with the organic fungicide did not grow. There was a change in the texture of the treated fruiting body it became compact, dense, and dark in color. The edge of the treated fruiting body turned slightly brown, while the control fruiting body remained bright white (Figure 4).

At 56 days after the first organic fungicide treatment, the fruiting body was treated with *Trichoderma sp.* by applying it to both the upper (cap) and lower (lamella) parts of the fruiting body. Visual observation showed that the treated fruiting body became darker brown with a more compact texture, while the control fruiting body continued to enlarge and its edges remained bright white (Figure 5). The control fruiting body continued to grow until day 60, while the fruiting body treated with the first stage of organic fungicide did not. Observation of color also showed changes, where the treated fruiting body appeared browner with a denser texture (Figure 6). On the 65th day after the first application of organic fungicide, bacterial growth was observed from the fruiting bodies. Incubation results showed bacterial growth in the control fruiting body, but no bacterial growth from the treated one (Figure 7). These results suggest that the application of the organic fungicide likely killed *Ganoderma sp.* as well as the bacteria growing on the fruiting body.

Observations were continued up to 101 days after the first application of organic fungicide. Growth inhibition of the treated fruiting body was still evident, while the control fruiting body continued to grow. Both color and texture still showed similar results as in previous observations (Figure 8). At 104 days, the fruiting bodies were broken apart, and *Ganoderma sp.* isolation was conducted using PDA medium. The incubation results showed that *Ganoderma sp.* could be isolated from the control fruiting body. In contrast, *Ganoderma sp.* did not grow from the treated fruiting body. However, *Trichoderma sp.* was successfully isolated from the treated fruiting body. An antagonism test between the isolated *Trichoderma sp.* and *Ganoderma sp.* (from the control) showed balanced growth between the two organisms (Figure 9). Observation of the fruiting body development continued at the site where they originally grew. The results showed that 26 days after the fruiting body was broken, new primordia (young fruiting bodies) developed at the control site, while no fruiting body growth occurred at the treated site (Figure 10). The fruiting bodies at the control site continued to develop until 87 days after the fruiting body breakage. The growth rate of the control fruiting bodies ranged from 0.04 cm to 0.2 cm, although between days 79 and 87 of incubation, a decline in growth rate occurred, with an average rate of 0.03 cm per day (Figure 10).



(a) (b) (c)

Figure 1 *Ganoderma* colonies grown on ADK medium (a) and *Ganoderma* grown on ADK medium + 10% organic fungicide formula (EC) (b) and retesting of *Ganoderma* treated with organic fungicide on new ADK medium (c).

(a) (b) (c)

Figure 2 Development of *Ganoderma* fruit bodies of control (top) and those treated with organic fungicide (bottom) a. on day 19, b. day 0, and c. day 49 after the first stage of FO application

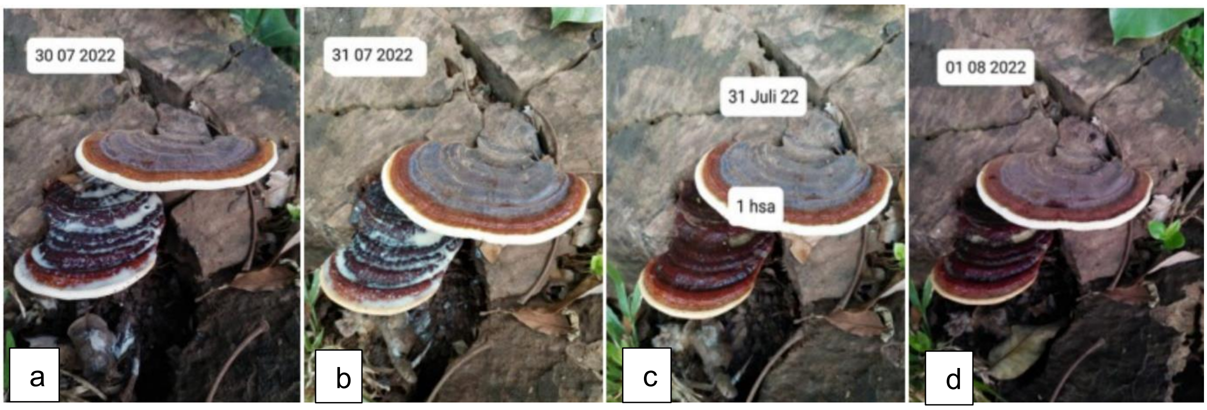


Figure 3 Development of *Ganoderma* fruit bodies of control (top) and those treated with organic fungicide (bottom) stage II consecutively for 3 days. a. On the 50^{th} day, b. on the 51^{st} day, c. on the 51^{st} day (3 hours after FO application), d. on the 52^{nd} day after FO application stage 1

(a) (b) (c)

Figure 4 Development of control (top) and treated (bottom) *Ganoderma* fruit bodies. a. on day 53^{rd}, b. day 54^{th}, and c. 55^{th} day after FO application stage 1

Figure 5 Administration of *Trichoderma sp.* on treated *Ganoderma* fruit bodies (bottom) for 3 consecutive days. The fruit body of the treatment appears browner with a harder or more compact structure. a.On the 54th day seen from above, b. day 54th seen from below, c. day 55th seen from below, d. day 55th seen from above and e. 56th day after FO application stage 1.

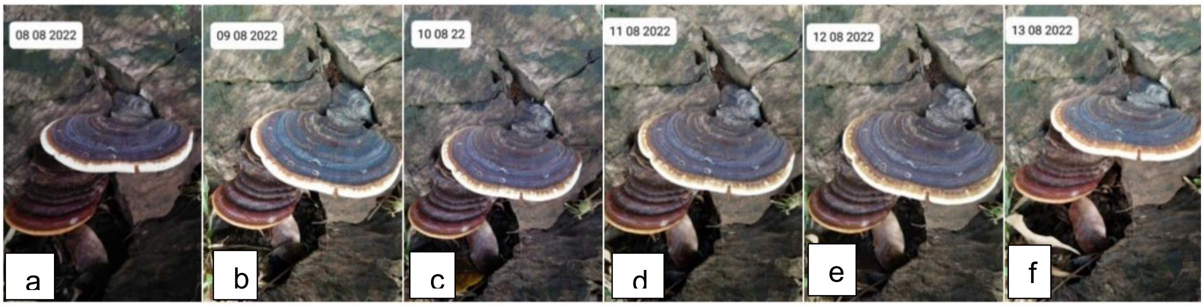


Figure 6 Development of *Ganoderma* fruit bodies of control (top) and treatment (bottom) from incubation a. On day 57th, b. day 58th, c. day 59th, d. day 60th, e. day 61st, and f. day 62nd days after application of organic fungicide stage 1.

(a) (b) (c)

Figure 7 *Ganoderma* fruiting bodies 63 days after application of organic fungicide I (a), bacterial colonies from control (top) and treatment (bottom) *Ganoderma* fruiting bodies. 3-day incubation (b) and 1-week incubation (c).

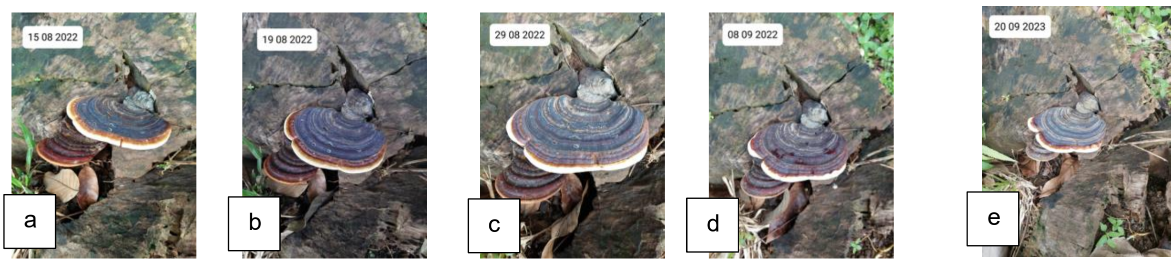


Figure 8 Development of control (top) and treated (bottom) *Ganoderma* fruiting bodies a. on day 64th, b. day 69th c. day 79th, d. day 89th, and e. 100th day after FO application stage 1

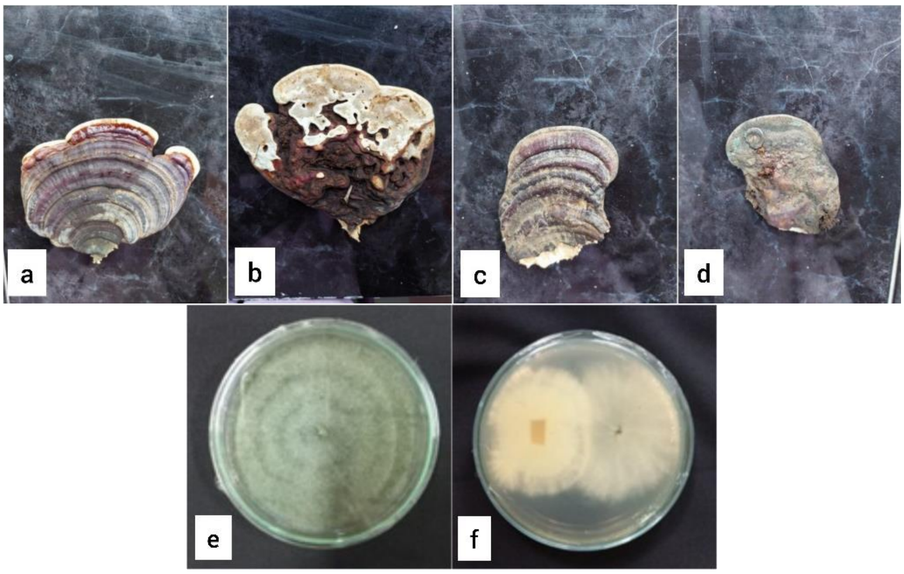


Figure 9 Control fruit body upper part (a), lower part (b), treatment fruit body upper part (c) lower part (d) Trichoderma isolated from treatment *Ganoderma* fruit body (e) and *Ganoderma* vs Trichoderma antagonist test (f).

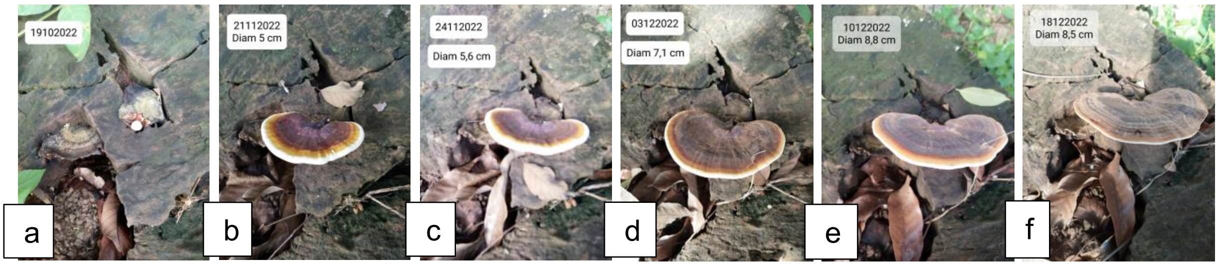


Figure 10 Development of *Ganoderma* sp fruiting bodies after breaking, *Ganoderma* control fruiting bodies (top) and treatment (bottom) a. On the 26th day, b. 33rd day, c. 36th day, d. 45th day, e. 52nd day, and f. 60th day after breaking.

Observations from the *in vitro* test showed that the organic fungicide affected the growth of *Ganoderma sp.* mycelium. It is suspected that the active compound contained in the organic fungicide, namely allicin (Widiastuti *et al.* 2016), inhibited the development of *Ganoderma sp.* mycelium. However, since this test used a crude allicin extract solution, further testing using pure allicin is needed to confirm this assumption. This experiment also showed that the dosage of crude allicin extract solution influenced the response of *Ganoderma sp.* mycelium. The results indicated that a concentration of 1.4% EC of the crude allicin extract solution inhibited the mycelial growth of *Ganoderma sp.* isolates from both Rejosari and Bekri. These findings are consistent with Sarfraz *et al.* (2020), who reported that allicin is capable of controlling pathogens. Observations also showed that it took 19 days (approximately 3 weeks) for the organic fungicide to inhibit the growth of *Ganoderma sp.* fruiting bodies. Further testing with the second stage of organic fungicide application showed continued effects—the mycelial growth remained suppressed, and the fruiting body texture became hard and compact. Similar results were observed in the thickening of mycelium. The development of fruiting bodies treated with *Trichoderma sp.* also showed changes in color, although such changes in color and texture had already occurred after the second stage of organic fungicide application. Research by Elkhateeb and Daba (2022) demonstrated that *Trichoderma Ganodermatigerum* can infect *Ganoderma sp.*, thereby inhibiting both its growth and sporulation. In the test observing microbial growth from the underside of the fruiting body, no bacterial growth was detected. This result indicates that the tested organic fungicide was also capable of killing or inhibiting bacterial growth that coexisted with *Ganoderma sp.* in the lower (lamella) part of the fruiting body.

The viability test comparing fruiting bodies treated with organic and biological fungicides showed that *Ganoderma sp.* could not be isolated from the treated fruiting bodies, while it could be isolated from the control. This confirms that the fruiting bodies treated with the organic fungicide and *Trichoderma sp.* biofungicide had died, or that the combination of organic and biological fungicides successfully killed the *Ganoderma sp.* fruiting bodies. Previous studies by Sarfraz *et al.* (2020) and Yen and Ali (2022) also showed that both allicin and *Trichoderma sp.* can inhibit or kill *Ganoderma sp.*

Observations conducted 26 days after the breaking of the fruiting bodies revealed that at the treated *Ganoderma sp.* sites, no new fruiting body growth occurred, whereas at the control sites, new fruiting bodies reappeared. This result indicates that viable *Ganoderma sp.* tissues still existed within the wood of the breadfruit tree and that *Ganoderma sp.* had infected the wood deeply into its internal tissue. For comparison, in *Coprinopsis cinerea* (*C. cinerea*), the formation of natural fruiting bodies from the hyphal knot stage to autolysis takes about 48 days (Muraguchi *et al.* 2015).

Observation results also showed that the growth rate of *Ganoderma sp.* fruiting bodies varied. Under unfavorable conditions, growth slowed down, while under optimal conditions, growth accelerated. In fact, under unfavorable conditions, fruiting body growth could be inhibited, as observed during the incubation period between days 79 and 87. Pilz and Molina (2002) stated that fruiting body growth is influenced by light, humidity, and ambient temperature. Warm temperatures stimulate fruiting body development more than cool temperatures. Research by Bijalwan *et al.* (2020) reported that for *G. lucidum* cultivated on poplar wood in Sherpur Village, Himalaya, India, *G. lucidum* fruiting bodies were harvested at 64–66 days, 100–101 days, and 135–136 days for the first, second, and third harvests after log installation, respectively. In another village, Manjgaun, fruiting bodies were harvested at 69–71 days, 107–108 days, and 144–145 days for the respective harvests. The temperature in Sherpur Village was higher than that in Manjgaun Village.

CONCLUSIONS

The allicin-based organic fungicide effectively inhibited *Ganoderma* mycelial growth in vitro at concentrations above 2% EC and suppressed fruiting body development in vivo within three weeks of application. Combined treatment with Trichoderma biofungicide enhanced these effects, resulting in complete mortality of *Ganoderma* fruiting bodies after 3.5 months. The treated tissues turned brown, compact, and non-viable. This eco-friendly approach shows potential for integrated management of basal stem rot in oil palm, pending validation on living plants.

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INTERNATIONAL JOURNAL of OIL PALM

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a. at 1 hour until 5 hour, and

b. 4 hour until 16 hour. Blanko = PKM treated with buffer phosphate pH 7, enzyme = PKM treated with recombinant manCK7.

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