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DEVELOPING A SUSTAINABLE BUSINESS MODEL FOR BIO-NANO FERTILIZERS TO ENHANCE PEATLAND AGRICULTURE AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

Background: The utilization of bio-nano fertilizers derived from oil palm waste presents an innovative approach to sustainable agriculture, addressing both environmental concerns and soil fertility enhancement. Conventional fertilizers often contribute to soil degradation and pollution, highlighting the need for eco-friendly alternatives.
Purpose: This study aims to develop a sustainable business model for bio-nano fertilizers by integrating economic feasibility, stakeholder perspectives, and nanotechnology applications.
Design/methodology/approach: A qualitative research approach was employed, combining literature reviews and stakeholder interviews with representatives from government, academia, industry, and farming communities. A total of 12 key respondents were interviewed for this study. The Business Model Canvas (BMC) approach and framework were used to analyze key elements, such as mission, value propositions, key activities, key partnerships, key resources, channels, customer segments, customer relationships, cost structures, revenue streams, impact, and measurements.
Findings/results: The results of this study indicate that bio-nano fertilizers made from micro-cellulose and micro-carbon provide potential benefits, such as increasing soil nutrients, controlling nutrient release, and reducing waste. The business model developed emphasizes cooperation strategies, a variety of distribution channels, and revenue streams, including product sales, licensing, and training services. Policy and regulatory support, research investment, and digital marketing integration are important to strengthen and expand the adoption of this bio-nano fertilizer innovation.
Conclusion: Bio-nano fertilizers have a strong potential for commercialization, benefiting both agricultural productivity and environmental sustainability. This study primarily focuses on business modeling and does not address scalability, long-term impacts, or policy interventions, as these require extensive field trials, multi-year assessments, and policy framework development. Future research should explore these aspects to facilitate broader adoption and sustainable implementation.
Originality/value (state of the art): This study presents a novel business model integrating waste utilization, nanotechnology, and agribusiness sustainability, contributing to the discourse on green innovation and circular economy practices in agriculture.

Keywords: bio-nano fertilizers, business model, nanotechnology, sustainable agriculture, oil palm waste

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INTRODUCTION

Indonesia possesses the largest tropical peatland in the world, covering approximately 24.67 million hectares (Miles et al. 2017; KLHK, 2020). These peatlands are primarily distributed in Sumatra (43%), followed by Kalimantan and Papua (Osaki et al. 2016; Ritung et al. 2012; Ritung et al. 2011). Peatlands play a crucial role in global carbon storage, water regulation, and biodiversity conservation. However, there is rapid degradation in these peatland ecosystems. From 2006 to 2016, large-scale peatland conversion accelerated due to the expansion of oil palm plantations (2–2.5 million hectares), industrial tree plantations (3.2 million hectares), and the construction of inappropriate canal networks (KLHK, 2020; Osaki et al. 2016; Dohong et al. 2017; Miettinen et al. 2016). The degradation of peatland not only contributes to reducing soil fertility but also unbalancing hydrological conditions. Furthermore, this degradation will contribute to climate change and sustainable agricultural development challenges in peatland areas (Mishra et al. 2021; Leng et al. 2019).

After the COVID-19 pandemic, the Indonesian government has targeted programs to improve national food security and mitigate the national food supply deficit through food estate development in potential agricultural areas including peatland (KLHK, 2020). The agriculture and food production programs in peatland areas can address national and global food supply chain problems as well as ensure food price stability and reduce malnutrition after the COVID-19 pandemic. In addition, the Indonesian government launched the national Free Nutritious Meal Program to enhance food security and human resource development. The objective of this national program is to ensure the availability of adequate nutrition for children, pregnant women, and vulnerable communities. Therefore, this program needs more sustainable food production, availability, and supply. To support this program's goals, sustainable agriculture needs to be implemented by optimizing low-productive potential land such as peatland areas.

One-third of peatland areas in Indonesia can be utilized for agricultural practices because of its shallow depth for cultivation (Ritung et al. 2011). However, low fertility and nutrients as well as high pH acidity in the soil of peatland areas are the main challenges in implementing agricultural practices (Ridho et al. 2014; Istikorini et al. 2022). The agroforestry systems adoption and integration between agricultural and plantation crops provide a practical solution to improve soil conditions and generate more sustainable income for farmers service (Hartoyo et al. 2015; Hartoyo et al. 2019). Conversely, the conventional monoculture agricultural system has several challenges including biodiversity limitations and lower revenue problems for farmers due to depending on only a single agricultural crop income. Agroforestry systems can play an essential role in supporting national agricultural and food production through soil fertility, farmers' livelihood, income generation, and efficient land use improvement.

Agroforestry systems can be a more sustainable solution than monoculture agriculture systems, especially in peatland areas. Ridho et al. 2014 and Marinus; 2014 found that the integration of agroforestry systems between *Dyera polyphylla (Jelutong)* with coffee, oil palm, rambutan, and pineapple has environmental and economic benefits. Sundawati, et al. 2020 also explored the ecological benefit integration between *Shorea balangeran* with oil palm in agroforestry systems. Such agroforestry systems not only improve sustainable land use but also farmers' income and livelihood. The agroforestry systems approach provides several sources of income for farmers while conserving peatland areas. However, the main challenges of implementing agroforestry systems are the high initial investment required and the long period of maturation before significant economic returns can be achieved. Farmers also experience financial and market access constraints that limit the widespread adoption of these agroforestry practices.

Soil health and fertility have become a crucial aspect of implementing sustainable agricultural practices and agroforestry systems in peatland areas. Reduction of soil nutrients and increasing greenhouse gas emissions are still environmental issues nowadays due to the massive and long-term application of chemical fertilizers in agriculture practices. Some innovations have been researched in nanotechnology for developing more sustainable fertilizers. Compared with chemical fertilizers, the utilization of these bio-nano fertilizers can increase reactivity, surface area, and kinetic dissolution. Chitosan has been researched as one of the potential raw materials for bio-nano fertilizer development (Ohta et al. 2000; Ohta et al. 2004). The

advantages of bio-nano fertilizers based on chitosan materials are efficiently improve soil nutrients and are naturally more biodegraded than other nanomaterials (El Tanahy et al. 2012; Wu and Liu, 2008).

However, the research on socioeconomic and business aspects of bio-nano fertilizers based on chitosan is still quite limited. The previous studies more focus on technical and agricultural aspects without further integration with multidisciplinary aspects. The benefits of bio-nano fertilizers based on chitosan materials therefore can be more beneficial and impactful for wider stakeholders through an interdisciplinary approach. Some aspects of the socioeconomic and business of bio-nano fertilizers that can be studied are cost and benefit analysis, supply chain management, market development, consumer behavior, and business model development. In addition, environmental aspects are currently a major concern due to worsening climate change. Studies on reducing palm oil plantation waste by utilizing it for sustainable agricultural practices are still very limited. The fiber from palm oil waste has a side function of providing micro-cellulose and micro-carbon as reinforcing materials for bio-nano fertilizers development based on chitosan. Micro-cellulose and micro-carbon from palm oil waste fiber can contribute to absorbing contaminants and heavy metals, releasing soil nutrients slowly, and improving water retention (El-Naggar et al. 2018; Farma et al. 2021; Garba et al. 2019; Maulina and Iriansyah, 2018). Furthermore, the excellent absorption function of chitosan-based bio-nano fertilizers can be used to improve soil quality in peatland areas and implement sustainable agricultural practices.

Currently, there is a scientific knowledge gap between nanotechnology discoveries in developing bio-nano fertilizers and the business economic impact on agriculture practice adoption. This business model study provides hypothetical and practical solutions for addressing this scientific knowledge gap. Therefore, the adoption of the business model will contribute to solving environmental issues by reducing palm oil waste and conserving peatland as well as increasing food production. This study will utilize not only agriculture and forestry approaches but also socio-economics approaches in developing sustainability programs for smallholder dairy farms in peatland areas. The expected business model results on bio-nano fertilizers development can contribute to supporting the national food security programs in Indonesia through sustainable agriculture production. Therefore, agricultural stakeholders, local governments, and smallholder farmers can receive benefits by implementing and adopting the innovation of sustainable fertilizers from micro-cellulose and micro-carbon extracted palm oil waste.

The study novelty is one of the innovations in assessing a business model for sustainability by developing bio-nano fertilizers to reduce palm oil waste and increase crop production and soil fertility. Such studies have not been widely researched in practice. Furthermore, the objective of the study is to explore and analyze an innovative business model canvas of bio-nano fertilizers from micro-cellulose and micro-carbon for achieving farm sustainability. By combining the agroforestry approach and nanotechnology innovation, this study's findings might provide some benefits, such as improvement of soil health, peatland management sustainability, and smallholder farmers' livelihood. In addition, the implementation of the research findings will be useful in increasing agricultural crop productivity, reducing carbon emissions in peatland areas, and supporting national food and environmental programs in Indonesia.

METHODS

This study employs a qualitative research approach to analyze the development of bio-nano fertilizers on peatlands using oil palm waste. The research integrates a combination of literature reviews and stakeholder interviews to gather comprehensive data. The stakeholders interviewed include representatives from local governments (Muaro Jambi District, Jambi Province), academics (IPB University and Jambi University), farmers, and industry experts who are directly involved in peatland agriculture and sustainable fertilization practices. A total of 12 key respondents were interviewed for this research. The research was carried out in West Java and Jambi Provinces from November to December 2024.

The qualitative research design was utilized to develop a sustainable business model for bio-nano fertilizers based on chitosan from oil palm waste in order to support agroforestry systems in peatland areas. By combining literature reviews and stakeholder

interviews, this study gathered comprehensive data as baseline business model analysis. The stakeholders who were directly involved in agriculture practices in peatland areas and sustainable fertilizer development were interviewed including Muaro Jambi District and Jambi Province local governments, IPB University and Jambi University researchers, smallholder farmers, and industrial experts. In total, there were 12 key informants for this business model development research. The research was conducted from November to December 2024 in Jambi and West Java Provinces, Indonesia.

The primary data sources for this study are in-depth interviews with key stakeholders, while secondary data are obtained from scientific journals, government reports, and policy documents related to peatland management and nanotechnology applications in agriculture. The literature review focuses on previous studies regarding the use of nanotechnology-based fertilizers, oil palm waste utilization, and sustainable business models for agroforestry on peatlands.

The data collection process involves a structured review of existing literature alongside semi-structured interviews. The literature review helps establish a theoretical foundation and identify research gaps, while interviews provide insights into real-world applications, challenges, and opportunities associated with bio-nano fertilizer development. Interviews are conducted using purposive sampling, selecting stakeholders based on their expertise and relevance to the research topic. The transcript of the stakeholders' interviews was collected and extracted to gather relevant topics of bio-nano fertilizers from chitosan application.

Qualitative data analysis was employed to formulate, develop. visualize, and interpret data as well as the results. Business Model Canvas (BMC) based on Osterwalder and Pigneur's (2010) theoretical concept was used as the main data analysis framework. Value propositions, key resources, key activities, key partnerships, customer segments, channels, customer relationships, cost structure, and revenue streams are identified for the business model development with nine key elements. Two additional key elements (mission and impact measurement) were also added to facilitate social, economic, and environmental aspects for modifying the sustainable business model canvas of bio-nano fertilizers. Formulation eleven key elements of this sustainable business model canvas for chitosan-based bio-nano fertilizers in peatland areas were used literature review and stakeholder interview results.

The hypothesis of this study was stated that chitosan-based bio-nano fertilizer from extracted palm oil waste can improve the conditions of peatland area environment, including soil fertility improvement. Beside that, the innovation of bio-nano fertilizers also will provide economic benefits through increasing income of smallholder farmers and stakeholders. Previous research findings on utilizing chitosan-based bio-nano fertilizers to improve soil fertility and prevent environmental damage were employed to build the research hypothesis. Furthermore, the developed business model from this research will provide insights into the long-term sustainability of agriculture practices in Indonesian peatland areas.

Figure 1 illustrates the framework of this business model research using a systematic approach. Firstly, the research framework starts by exploring through a comprehensive literature review the current condition of bio-nano fertilizer innovations and their implementation in agroforestry and agriculture practices in peatland areas. Scientific journals, government reports, and policy brief documents were then used to investigate the knowledge gaps in bio-nano fertilizer implementation in Indonesian peatland agriculture.

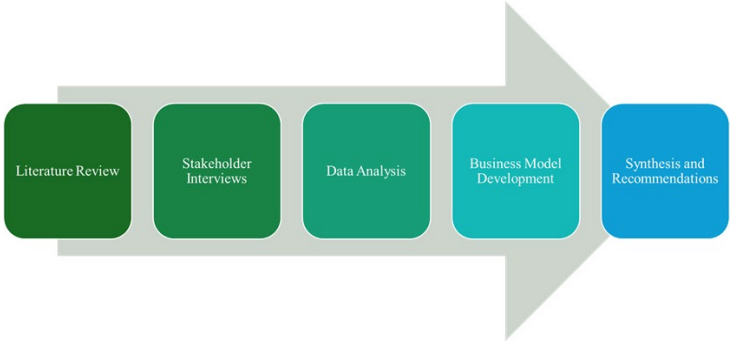

Figure 1. Research framework

Second, the next step is to interview relevant stakeholders such as local government representatives, researchers, smallholder farmers, and industrial experts who are experienced in agriculture development in peatland areas. The interviewed stakeholders provide their empirical insights, local knowledge, and suggestions for developing a sustainable business model of bio-nano fertilizers. In addition, the challenges and opportunities of this innovative business model were also identified based on interview sections.

Third, thematic and qualitative data analyses were conducted to formulate a business model for developing bio-nano fertilizers based on a literature review and interview insights. Fourth, the business model canvas approach was then applied to examine eleven key elements of the modified Osterwalder and Pigneur's (2010) business model, including value propositions, key activities, key partnerships, customer relationships, customer segments, channels, key resources, cost structure, revenue streams, mission, and impact measurements. The identified elements contribute to constructing a sustainable business model canvas of bio-nano fertilizers for peatland agriculture in Indonesia.

Finally, the findings from all research framework steps (literature review, stakeholder interviews, data analysis, and business model development) were utilized for the synthesis step to gather comprehensive insights into formulating a rational and viable business model. In addition, this step contributes to exploring interconnection among all eleven key elements of the business model. This step also provides recommendations for the implementation and adoption of bio-nano fertilizers in peatland agriculture while reducing palm oil waste. The recommendations include practical solutions, policy strategies, and suggestions related to multidisciplinary aspects (social, economic, business, and environmental aspects) in supporting the long-term sustainability of peatland agriculture and food production. Relevant stakeholders can use these recommendations for the wider impact of bio-nano fertilizer innovations.

Furthermore, a comprehensive and well-developed research framework can ensure the rational implementation of the bio-nano fertilizer business model and gather higher potential social, economic, and environmental impact in practices. By combining scientific literature, stakeholder interviews, data analysis, business model development, and research synthesizes and recommendations, this research can fill the knowledge gap related to bio-nano fertilizers technology and socioeconomic implementation for the long-term sustainability of peatland agriculture and agroforestry.

RESULTS

Comparative Analysis with Previous Research Findings

Chitosan has several better characteristics than conventional fertilizer materials, including more biodegradable, biocompatible, and controlled-release characteristics. Chitosan as a composite or host polymer matrix effectively enhances nitrogen control release and has stronger mechanical for fertilizers. Kusumastuti et al. (2019) demonstrated using chitosan combined with polyanion solutions as NPK fertilizer coating materials. These combined materials enhanced the release efficiency of nitrogen and the mechanical resilience of fertilizers. Table 1 summarizes the research findings of chitosan development and utilization as bio-nano fertilizer materials.

This study has elaborated some insights from previous studies to explore value proposition of business model development of bio-nano fertilizers from chitosan. Bio-nano fertilizers made from chitosan have been widely researched and developed, including conventional applications and advanced implementations using nanotechnology.

Based on Wu and Liu (2008), chitosan materials can be served as fertilizer coating and additive contents. Kumar et al. (2020) also found that the benefits of chitosan materials for bio-nano fertilizers development in enhancing soil fertility and the growth of agricultural crops.

Ohta et al. (2000) investigated the effect of chitosan as additive materials with or without nitrogen treatment using conventional nanotechnology on seedling growth of agricultural crops in early stage. Ohta et al. (2024) also explored that chitosan materials can enhance nutrient availability in the soil, serve as soil guard material, and contribute to agricultural crop growth. Kumaraswamy et al. (2018) in their research found that bio-nano fertilizers using chitosan can stimulate and

maintain the growth of agricultural crops. Improvement of agricultural crop growth will be beneficial for accelerating food production in peatland areas.

Based on Jamnongkan and Kaewpirom (2010) and Kusumastuti et al. (2019), chitosan as bio-nano fertilizer material has potential advantage in controlling nutrient release in the soil. In addition, Wu and Liu (2008) has examined the bio-nano fertilizer which coated and compounded by chitosan can contribute to increase water retention, reduce nutrient leaching risk, and improve nutrient release control capacity in the soil. These findings provide insights into this study for developing value proposition of business model of bio-nano fertilizers made from chitosan due to its benefit improving peatland soil conditions. Abdel-Aziz et al. (2016a) and Abdel-Aziz et al. (2016b) have also investigated in their studies that bio-nano fertilizers from chitosan contribute to reduce environmental impacts due to their capability in increasing soil conditions and nutrient absorption efficiently.

Research conducted by Santos et al. (2025) found that chitosan as nano material for bio fertilizers can enhance the ability for keeping the nutrient availability in the soils effectively in long-term periods. Santos et al. (2025) also used the time-domain reflectometry for analyzing the nutrient control release ability of chitosan as bio-nano fertilizers. This chitosan ability will be beneficial for helping bio-nano fertilizer business model development, especially for agricultural practices in peatland areas. These peatland areas are very challenging for plantation in gathering adequate soil nutrients. Kumar et al. (2020) explored the function of chitosan in NPK fertilizers development that could increase the nutrient absorption efficiency of plantations.

Besides many benefits investigated in several literature, bio-nano fertilizers based on chitosan also face some challenges in the implementation. As example, research by Khalifa and Hasaneen (2018) identified potential negative environmental impacts of NPK fertilizer development using nanotechnology. Their findings also suggested conducting further research to prevent and mitigate negative environmental impacts on the environment from fertilizers development using nanotechnology. This business model study might provide the insights for solving this issue by exploring more positive impacts of development bio-nano fertilizers using chitosan as main material. Furthermore, insights on chitosan-based bio-nano fertilizers from previous literature and model business development of this study will contribute to support sustainable agriculture practices in peatland areas.

Table 1. Chitosan-based bio-nano fertilizers research and development findings, technology, and application

Research development	Technology	Application
Effect of chitosan with or without nitrogen treatment on seedling growth (Ohta et al., 2000)	Conventional	Additives or input materials
Chitosan-soil mixture for seedling growth (Ohta et al., 2004)	Conventional	Additives or input materials
Chitosan-coated compound fertilizer for products with controlled release capacity and good water retention (Wu and Liu, 2008)	Conventional	Host or coating
Chitosan-based bio-nano fertilizers controlled release (Jamnongkan and Kaewpirom, 2010, Kusumastuti et al., 2019)	Conventional	Host or coating
Preliminary study of NPK fertilizer into chitosan nanoparticles (Kumar et al. 2020)	Nanotechnology	Host or coating
Time-domain reflectometry (TDR) analysis of chitosan-montmorillonite microspheres and its controlled release in bio-nano fertilizers (Santos et al., 2015)	Conventional	Host or coating
Bio-nano fertilizer based on chitosan (Abdel-Aziz et al., 2016a, Abdel-Aziz et al., 2016b)	Nanotechnology	Host or coating
Chitosan-based nanomaterial engineered for plant growth and protection (Kumaraswamy et al., 2018)	Nanotechnology	Additives or input materials
The negative effect of chitosan-PMAA-NPK bio-nano fertilizer (Khalifa and Hasaneen , 2018)	Nanotechnology	Host or coating

Sustainable Business Model Analysis for Bio-Nano Fertilizers

Figure 2 illustrates the results of sustainable business model development and analysis for bio-nano fertilizers. This business model was investigated based on previous comparative analysis findings and stakeholders' interview as well as their validation. By combining literature review and stakeholders' interview, the bio-nano fertilizer business model might provide comprehensive knowledge and insights into more impactful for practical solution. There are nine key elements identified based on original business model canvas developed by Osterwalder and Pigneur's (2010) which consists of: value propositions, key activities, key partnerships, customer relationships, customer segments, channels, key resources, cost structure, revenue streams. This study has also identified two additional key elements including: mission, and impact measurements for accommodating sustainability aspect of business model for chitosan based bio-nano fertilizers development in Indonesian peatland areas.

<table>
<tr><td colspan="5">Business Model Canvas (BMC) of Bio-nano Fertilizers Based on Chitosan for Supporting Sustainable Agriculture Practices</td></tr>
<tr><td colspan="5">Mission: 1) Improving soil nutrients, 2) Reducing palm oil waste, 3) Increasing food production, and 4) Improving community livelihood</td></tr>
<tr><td rowspan="2">Key Partners
• Academic
• Research center
• Government
• Farmers
• Manufacture
• Traders
• NGO</td><td>Key Activities
• Research development
• Production
• Dissemination
• Partnership
• Marketing
• Training</td><td rowspan="2">Value Propositions
• Bio-nano fertilizers made from chitosan by utilizing oil palm waste in supporting to improve soil nutrient, food production and increase community livelihood.</td><td>Customer Relationships
• Partnership contract
• After sales
• Dedicated personal assistance</td><td rowspan="2">Customer Segments
• Company
• Local government
• Farmers</td></tr>
<tr><td>Key Resources
• Capital
• Production equipment and materials
• Human resources
• Finance</td><td>Channels
• Direct selling
• Contract
• Marketplace
• Offline store</td></tr>
<tr><td colspan="2">Cost Structure
• Operating costs
• Marketing costs
• Production cost
• Research and development costs</td><td colspan="3">Revenue Streams
• Bio-nano fertilizer sales
• Procurement
• Royalty
• Training and services</td></tr>
<tr><td colspan="5">Impact and Measurement:</td></tr>
<tr><td colspan="2">Impact
• Improved soil nutrient
• Reduced palm oil waste
• Increased food production
• Increased community livelihood</td><td colspan="3">Measurement
• Soil nutrient level
• Palm oil waste weight
• Food production
• Community income</td></tr>
</table>

Figure 2. Sustainable business model canvas (BMC) of chitosan-based bio-nano fertilizers

Mission and Impact Measurement

Mission of business model development of this study was inspired by sustainability aspects which consist of environmental, social, and economical aspects. The environmental mission of bio-nano fertilizers business model development was to improve soil nutrients and conditions in peatland areas by utilizing organic waste from oil palm. Based on Varjani et al. (2021), Chojnacka el al (2023), and Chojnacka et al. (2024) which found that organic waste from agricultural sector can be utilized as materials to improve soil nutrients and conditions in the long-term. The social mission of business model for bio-nano fertilizer was to promote food production and availability for community in the local and national levels. Bhupendra et al. (2022) found that fertilizers development form bio or organic waste contribute to higher agricultural production as well as mitigating environmental issues. The economic mission of this business development is increasing smallholder farms' revenue and improving community livelihood. This mission was in line with Chojnacka et al. (2024) emphasized the potential benefit of organic waste utilization for developing bio-fertilizers as implementation of circular economy concept. The impact and measurement that were expected from bio-nano fertilizers development consist of improved soil nutrient (environmental), reduced palm oil waste (environmental and social), increased food production (social), and increased community income and livelihood (social and economical).

Value Proposition

As start-up business, this bio-nano fertilizers made from organic waste (chitosan extracted from palm oil waste) provides more potential benefits as value propositions compared to conventional chemical fertilizers. Several benefits were explained in more detail in the previous section that analyze comparatively from literature finding regarding bio-nano fertilizer benefits for increasing soil fertility, nutrient absorption, and agricultural crop growth (Wu and Liu, 2008; Santos et al. 2025, Kumar et al. 2020). This value proposition also supported by findings from Chojnacka et al. 2020, Kurniawati et al. 2023 that emphasized fertilizers made from organic based can improve soil fertility and nutrient compared to chemical fertilizers. In addition, value proposition of this bio-nano fertilizer business model provides practical solution that more environmental friendly considering its benefit to reduce palm oil waste. Finally, value proposition in economic aspect of this business model was supporting circular economy by converting palm oil waste into economically benefits product such bio-nano fertilizers. Bhagat et al. (2023) and Sharma et al. (2024) highlighted that sustainable agricultural practices can be achieved by implementing circular economy and by combining with ecological benefits.

Key Activities

The key activities from developed business model canvas for bio-nano fertilizers were research and development, production, dissemination, marketing, partnerships, and training. These key activities were identified based on value propositions and the stated mission of business model. Research and development become initial and important activities for ensuring the implementation of bio-nano fertilizers as expected. Studies from Chakraborty et al. (2023) and Aliyari Rad et al. (2023) suggested that bio-nano fertilizer innovation from organic waste has benefit to enhance soil condition and nutrient release. This finding inline with our business model canvas that stated producing bio-nano fertilizers might reduce oil palm waste. After research and development as well as production activities have been done, the innovation need to be disseminated to stakeholders through socialization and promotion agenda. Partnership and marketing activities were also important for ensuring the bio-nano fertilizers product reaches potential customer segments. In addition, the targeted customers should receive adequate knowledge regarding bio-nano fertilizers through training activities before product adoption and application on their agricultural field in peatland areas. Grimm and Luck (2020) found that training activities such advisory support and personal approach can contribute to improve adoption and application of product.

Key Resources and Partnerships

For implementing key activities above, the identification of key resources was very crucial, including capital, production, financial, and human resources. When the business unit of bio-nano fertilizers does not have all key resources, the business unit need to have partnerships with several stakeholders. Several potential key partners from public and private sectors who can support the sustainability of bio-nano fertilizers business model are universities, research centers,

local governments, farmers, manufacturers, traders, and non-governmental organizations (NGOs). Based on Pandey et al (2021), partnerships with public and private sectors can contribute to improve production and marketing activities of innovations that support agriculture sustainability. Furthermore, partnership with farmers group and cooperative can enhance the adoption rates and economic feasibility of sustainable agriculture products (Maghirang et al. 2021, Sia et al. 2025).

Customer Segments and Relationships

The customer segments of bio-nano fertilizers business model include farmers, local governments, and companies or manufactures. More specific characteristics of these customer segments who are finding more sustainable fertilizers while economically and environmentally feasible. Therefore, Stewart et al (2015) and Lalani et al (2016) found that farmers willing to adopt innovative fertilizers when they receive more productions and less costs in implementing agricultural practices. Customer relationship activities were needed to deliver value propositions of bio-nano fertilizers to targeted customer segments. Several customer relationship activities of this business model include partnership contract, after sales services, and personal assistance. Based on Legesse et al (2019), the fertilizer distribution through personal assistance as customer relationship programs can contribute to farmers' customer segment access and long-term adoption.

Distribution Channels

In term of reaching customer segments and delivering value propositions of bio-nano fertilizers, distribution channels were needed to be identified. Distribution channels of bio-nano fertilizers include direct selling to customer segments (farmers, local governments, and companies), contract agreement, selling through marketplaces and offline stores. Combining offline and digital platforms of distribution channels is important to expand targeted customer. Research of Deichmann et al. (2016) investigated that digital platform can contribute to enhance agricultural inputs such fertilizers' distribution and increase market access as well as transparency. Furthermore, based on Zhang et al. (2021) and Bernabei et al. (2022) multi distribution channels can improve farmers' accessibility to agricultural sector inputs. Business model developed for bio-nano fertilizers in this study identified the combination among muti distribution channels (offline and online) for reaching wider customer segments.

Cost Structure and Revenue Streams

For implementing key activities of bio-nano fertilizers business model, there are several costs need to be invested and incurred. These costs include research and development costs, operating costs, production costs, and marketing costs. Costs identification will support the stakeholders in calculating feasibility of the business model through comparing with revenue streams. Research and development costs include all costs for conducting research for improving bio-nano fertilizers products quality. This is in line with research by Sekhon (2014) and Kim et al. (2018) emphasized the need of research and development investments for nanomaterials-based fertilizers to improve sustainable business and long-term economic benefits by enhancing efficiency and reducing production costs. Operating and production costs consist of raw materials, additive materials, packaging, and other variable as well as fixed costs. Finally, marketing costs include the expenses for promotion, distribution channels, and customer relationships costs. Meanwhile, the business model of bio-nano fertilizers also offers several revenue streams such as product sales, procurement contract fee, and royalty from intellectual property rights, as well as training and services. Additionally, training and consultancy services offer supplementary income while reinforcing product awareness and adoption. Similar diversified revenue models have been successfully applied in sustainable agricultural enterprises, increasing financial stability and long-term growth (Barnes et al. 2015, Therond et al. 2017). The diversification of revenue streams enhances financial stability and ensures long-term business viability.

The findings from this study align with previous research on the economic feasibility of bio-nano fertilizers and sustainable agricultural innovations. Earlier studies have emphasized the importance of cost-effective and environmentally friendly fertilizers, but limited research has focused on the utilization of oil palm waste as a raw material for bio-nano fertilizer production. This study addresses that gap by presenting a sustainable business model that integrates waste valorization with nanotechnology-based fertilizer development. These have highlighted the potential of nanotechnology in improving crop yields and soil health. Their research demonstrates that nano-

fertilizers can enhance nutrient efficiency and reduce environmental pollution compared to conventional chemical fertilizers. This study builds upon those findings by incorporating a waste-based production approach, thereby offering a novel contribution to both sustainable agriculture and waste management.

Additionally, controlled-release mechanisms in chitosan-based fertilizers have been shown to improve nutrient availability while reducing environmental impact. The ultimate impact of business model development of bio-nano fertilizers were improved soil nutrient, reduced palm oil waste, increased food production, and increased community livelihood. Therefore, bio-nano fertilizers made from chitosan can contribute to enhance peatland soil conditions and achieve sustainable agricultural practices.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In conclusion, developed bio-nano fertilizers business model might provide the insights into reducing oil palm waste to convert become valuable product in supporting soil fertility and agricultural crop growth in peatland areas in Indonesia. In addition, comparative analysis from previous findings have inspired the development of this bio-nano fertilizers business model. By utilizing business model canvas (BMC) analysis, nine key elements were identified and analyzed, include value propositions, key activities, key partnerships, customer relationships, customer segments, channels, key resources, cost structure, revenue streams. This study has also identified two additional key elements including: mission, and impact measurements for accommodating sustainability aspect of business model for chitosan based bio-nano fertilizers development in Indonesian peatland areas.

The importance remark from developed business model of bio-nano fertilizers were implement multi distribution channels for delivering value propositions to customer segments and implementing customer relationships. This business strategy would create potential long-term benefits for bio-nano fertilizers business models. In addition, partnerships with public and private sectors can contribute to improve production and marketing activities of innovations that support agriculture sustainability. Local government's support plays crucial role in implementing this bio-nano fertilizers through policy and regulation which promoting sustainable agricultural practices in peatland areas.

Recommendations

This study was more focused on business model development of bio-nano fertilizers by utilizing chitosan from oil pail waste. Future research should explore these aspects to facilitate broader adoption and sustainable implementation. Future research should focus on field trials to assess the long-term agronomic, economic, and environmental impacts of bio-nano fertilizers. Additionally, exploring policy interventions tailored to different agricultural contexts will be essential for ensuring sustainability and scalability. By continuously refining production processes, expanding market outreach, and fostering collaborative efforts, bio-nano fertilizers have the potential to become a mainstream solution for sustainable agriculture.

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REFERENCES

Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omer, A. M. (2016a). Foliar application of nano chitosan NPK fertilizer improves the yield of wheat plants grown on two different soils. *Egyptian Journal of Experimental Biology, 14*(1), 63–72.

Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omer, A. M. (2016b). Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Egyptian Journal of Experimental Biology, 14*(1), 1–9. https://doi.org/10.5424/sjar/2016141-8205

Aliyari Rad, S., Nobaharan, K., Pashapoor, N., Pandey, J., Dehghanian, Z., Senapathi, V., Minkina, T., Ren, W., Rajput, V. D., & Asgari Lajayer, B. (2023). Nano-microbial remediation of polluted

soil: A brief insight. *Sustainability, 15*(1), 876. https://doi.org/10.3390/su15010876

Barnes, A. P., Hansson, H., Manevska-Tasevska, G., Shrestha, S. S., & Thomson, S. G. (2015). The influence of diversification on long-term viability of the agricultural sector. *Land Use Policy, 49*, 404–412. https://doi.org/10.1016/j.landusepol.2015.08.023

Bhagat, R., Walia, S. S., Sharma, K., Singh, R., Singh, G., & Hossain, A. (2024). The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: A comprehensive review. *Food and Energy Security, 13*, e534. https://doi.org/10.1002/fes3.534

Bhupendra, K., Yakoob, M., & Shah, M. P. (2022). Agricultural waste management strategies for environmental sustainability. *Environmental Research, 206*, 112285. https://doi.org/10.1016/j.envres.2021.112285

Bernabei, M., Colabianchi, S., & Costantino, F. (2022). Actions and strategies for coronavirus to ensure supply chain resilience: A systemic review. *Sustainability, 14*(20), 13243. https://doi.org/10.3390/su142013243

Chakraborty, R., Mukhopadhyay, A., Paul, S., Sarkar, S., & Mukhopadhyay, R. (2023). Nanocomposite-based smart fertilizers: A boon to agricultural and environmental sustainability. *Science of The Total Environment, 863*, 160859. https://doi.org/10.1016/j.scitotenv.2022.160859

Chojnacka, K. (2023). Valorization of biorefinery residues for sustainable fertilizer production: A comprehensive review. *Biomass Conversion and Biorefinery, 13*, 14359–14388. https://doi.org/10.1007/s13399-023-04639-2

Chojnacka, K., Moustakas, K., & Mikulewicz, M. (2022). Valorization of agri-food waste to fertilizers is a challenge in implementing the circular economy concept in practice. *Environmental Pollution, 312*, 119906. https://doi.org/10.1016/j.envpol.2022.119906

Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology, 295*, 122223. https://doi.org/10.1016/j.biortech.2019.122223

Deichmann, U., Goyal, A., & Mishra, D. (2016). Will digital technologies transform agriculture in developing countries? *Agricultural Economics, 47*(S1), 21–33. https://doi.org/10.1111/agec.12300

Dohong, A., Aziz, A. A., & Dargusch, P. (2017). A review of the drivers of tropical peatland degradation in Southeast Asia. *Land Use Policy, 69*, 349–360. https://doi.org/10.1016/j.landusepol.2017.09.035

El-Naggar, M. E., Radwan, E. K., El-Wakeel, S. T., Kafafy, H., Gad-Allah, T. A., El-Kalliny, A. S., & Shaheen, T. I. (2018). Synthesis, characterization and adsorption properties of microcrystalline cellulose-based nanogel for dyes and heavy metals removal. *International Journal of Biological Macromolecules*, *113,* 248-258. https://doi.org/10.1016/j.ijbiomac.2018.02.126

Farma, R., Lestari, O., Taer, E., Apriwandi, Minarni, & Awitdrus, A. (2021). Removal of Cu, Fe, and Zn from peat water by using activated carbon derived from oil palm leaves. *Advanced Materials Research, 1162*, 65–73. https://doi.org/10.4028/www.scientific.net/AMR.1162.65

Garba, Z. N., Lawan, I., Zhou, W., Zhang, M., Wang, L., & Yuan, Z. (2019). Microcrystalline cellulose (MCC)-based materials as emerging adsorbents for the removal of dyes and heavy metals: A review. *Science of the Total Environment, 717, 135070*. https://doi.org/10.1016/j.scitotenv.2019.135070

Grimm, M., & Luck, N. (2020). Can training enhance adoption, knowledge, and perception of organic farming practices? Evidence from a randomized experiment in Indonesia. *IZA Discussion Papers, 13400*. Institute of Labor Economics (IZA), Bonn. https://hdl.handle.net/10419/223842

Hartoyo, A. P. P., Siregar, I. Z., Supriyanto, Prasetyo, L. B., & Theilade, I. (2015). Biodiversity, carbon stocks and community monitoring in traditional agroforestry practices: Preliminary results from two investigated villages in Berau, East Kalimantan. *Procedia Environmental Sciences, 33*, 376–385. https://doi.org/10.1016/j.proenv.2016.03.088

Hartoyo, A. P. P., Wijayanto, N., Karimatunnisa, T. A., & Ikhfan, A. N. (2019). Keanekaragaman hayati vegetasi pada praktik agroforestri dan kaitannya terhadap fungsi ekosistem di Taman Nasional Meru Betiri, Jawa Timur. *Jurnal Hutan Tropis, 7*(2). https://dx.doi.org/10.20527/jht.v7i2.7305

Istikorini, Y., Nurhafifah, Hartoyo, A. P. P., Solikhin, A., & Octaviani, E. A. (2022). Effect of plant growth-promoting rhizobacteria and bionanomaterial

membrane applications on chemical properties of peat soils. *IOP Conf. Series: Earth and Environmental Science, 959*, 012049. https://doi.org/10.1088/1755-1315/959/1/012049

Jamnongkan, T., & Kaewpirom, S. (2010). Controlled-release fertilizer based on chitosan hydrogel: Phosphorus release kinetics. *Science Journal, 1*(1), 43–50.

Khalifa, N. S., & Hasaneen, M. N. (2018). The effect of chitosan–PMAA–NPK nanofertilizer on Pisum sativum plants. Biotech, 8(4), 1–12.

KLHK [Kementerian Lingkungan Hidup dan Kehutanan]. (2020). Pelaksanaan pemulihan ekosistem gambut di Eks PLG, Provinsi Kalimantan Tengah, untuk mendukung ketahanan pangan (Food Estate) dan pemulihan ekonomi nasional (PEN).

Kim, D.-Y., Kadam, A., Shinde, S., Saratale, R. G., Patra, J., & Ghodake, G. (2018). Recent developments in nanotechnology transforming the agricultural sector: A transition replete with opportunities. *Journal of the Science of Food and Agriculture, 98*, 849–864. https://doi.org/10.1002/jsfa.8749

Kumar, M. A., Telagam, N., Mohankumar, N., Ismail, K., & Rajasekar, T. (2020). Design and implementation of real-time amphibious unmanned aerial vehicle system for sowing seed balls in the agriculture field. International Journal on Emerging Technologies, 11(2), 213–218.

Kumaraswamy, R. V., Kumari, S., Choudhary, R. C., Pal, A., Raliya, R., Biswas, P., & Saharan, V. (2018). Engineered chitosan-based nanomaterials: Bioactivities, mechanisms, and perspectives in plant protection and growth. International Journal of Biological Macromolecules, 113, 494–506. https://doi.org/10.1016/j.ijbiomac.2018.02.042

Kurniawati, A., Toth, G., Ylivainio, K., et al. (2023). Opportunities and challenges of bio-based fertilizers utilization for improving soil health. *Organic Agriculture, 13*, 335–350. https://doi.org/10.1007/s13165-023-00432-7

Kusumastuti, Y., Istiani, A., Rochmadi, & Purnomo, C. W. (2019). Chitosan-based polyion multilayer coating on NPK fertilizer as controlled released fertilizer. Advances in Materials Science and Engineering, 2019, 1–8. https://doi.org/10.1155/2019/2636789

Lalani, B., Dorward, P., Holloway, G., & Wauters, E. (2016). Smallholder farmers' motivations for using conservation agriculture and the roles of yield, labour and soil fertility in decision-making. *Agricultural Systems, 146*, 80–90. https://doi.org/10.1016/j.agsy.2016.04.002

Legesse, E. E., Srivastava, A. K., Kuhn, A., & Gaiser, T. (2019). Household welfare implications of better fertilizer access and lower use inefficiency: Long-term scenarios for Ethiopia. *Sustainability, 11*(14), 3952. https://doi.org/10.3390/su11143952

Maghirang, P. K. B., Quicoy, A. R., & Maghirang, M. A. T. (2021). Cooperative-led green value chain development for selected highland vegetables in Buguias, Benguet. *Journal of Economics, Management, and Agricultural Development, 7*(2), 81–91. https://doi.org/10.22004/ag.econ.333539

Marinus, K. H. (2014). Agroforestry berbasis jelutung rawa: Solusi sosial, ekonomi, dan lingkungan pengelolaan lahan gambut. Balai Penelitian Kehutanan Banjarbaru: FORDA Press.

Maulina, S., & Iriansyah, M. (2018). Characteristics of activated carbon resulted from pyrolysis of the oil palm fronds powder. IOP Conference Series: Materials Science and Engineering, 309, 012072. https://doi.org/10.1088/1757-899X/309/1/012072

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra, and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 6, 67–78. https://doi.org/10.1016/j.gecco.2016.02.002

Miles, L., Ravilious, C., Garcia-Rangel, S., de Lamo, X., Darie, G., & Lewis, S. (2017). Carbon, biodiversity, and land-use in the Central Congo Basin peatlands. Global Change Biology, 18(1), 164–178. https://doi.org/10.1111/gcb.13777

Ohta, K., Atarashi, H., Shimatani, Y., Matsumoto, S., Asao, T., & Hosoki, T. (2000). Effects of chitosan with or without nitrogen treatments on seedling growth in Eustoma grandiflorum (Raf.) Shinn. cv. Kairyou Wakamurasaki. Engei Gakkai Zasshi, 69(1), 63–65.

Ohta, K., Morishita, S., Suda, K., Kobayashi, N., & Hosoki, T. (2004). Effects of chitosan soil mixture treatment in the seedling stage on the growth and flowering of several ornamental plants. Engei Gakkai Zasshi, 73(1), 66–68.

Osaki, M., Nursyamsi, D., Noor, M., Wahyunti, & Segah, H. (2016). Peatland in Indonesia. In M. Osaki & N. Tsuji (Eds.), Tropical peatland ecosystems (pp. 49–58). Springer. https://doi.

org/10.1007/978-4-431-55681-7_4

Osterwalder, A., & Pigneur, Y. (2010). Business model generation: A handbook for visionaries, game changers, and challengers. Wiley.

Pandey, N., de Coninck, H., & Sagar, A. D. (2021). Beyond technology transfer: Innovation cooperation to advance sustainable development in developing countries. *WIREs Energy and Environment, 11*(2). https://doi.org/10.1002/wene.422

Ridho, M. F., Sarifuddin, S., & Lubis, A. (2014). Pemberian ameliorant terhadap status hara, pertumbuhan, dan produksi padi di lahan gambut dataran tinggi. Jurnal Agroteknologi Universitas Sumatera Utara, 2, 102287.

Ritung, S., Wahyunto, K. N., Sukarman, Hikmatullah, Suparto, & Tafakresnanto, C. (2011). Peta lahan gambut Indonesia, skala 1:250.000. Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian, Kementerian Pertanian.

Ritung, S., Wahyunto, & Nugroho, K. (2012). Karakteristik dan sebaran lahan gambut di Sumatera, Kalimantan, dan Papua. Balai Besar Litbang SDLP.

Santos, B. R. dos, Bacalhau, F. B., Pereira, T. dos S., Souza, C. F., & Faez, R. (2015). Chitosan-montmorillonite microspheres: A sustainable fertilizer delivery system. Carbohydrate Polymers, 127, 340–346. https://doi.org/10.1016/j.carbpol.2015.04.061

Sekhon, B. S. (2014). Nanotechnology in agri-food production: An overview. *Nanotechnology, Science and Applications, 7*, 31–53. https://doi.org/10.2147/NSA.S39406

Sharma, P., Bano, A., Singh, S. P., et al. (2024). Sustainable organic waste management and future directions for environmental protection and techno-economic perspectives. *Current Pollution Reports, 10*, 459–477. https://doi.org/10.1007/s40726-024-00317-7

Sia, R., Darma, R., Salman, D., & Riwu, M. (2025). Sustainability assessment of the Arabica coffee agribusiness in North Toraja: Insight from a multidimensional approach. *Sustainability, 17*(5), 2167. https://doi.org/10.3390/su17052167

Stewart, R., Langer, L., Rebelo Da Silva, N., Muchiri, E., Zaranyika, H., Erasmus, Y., Randall, N., Rafferty, S., Korth, M., Madinga, N., & de Wet, T. (2015). The effects of training, innovation, and new technology on African smallholder farmers' economic outcomes and food security: A systematic review. *Campbell Systematic Reviews, 11*(1), 1–224. https://doi.org/10.4073/csr.2015.16

Sundawati, L., Pamoengkas, P., Siregar, I. Z., Mardhatillah, M., Rangkuti, A. B., Hartoyo, A. P. P., & Fadillah, A. (2020). Development of agroforestry oil palm for peatland restoration in Jambi Province: Establishing process and initial results. IOP Conference Series: Earth and Environmental Science, 449, 012031. https://doi.org/10.1088/1755-1315/449/1/012031

Varjani, S., Shah, A. V., Vyas, S., & Srivastava, V. K. (2021). Processes and prospects on valorizing solid waste for the production of valuable products employing bio-routes: A systematic review. *Chemosphere, 282*, 130954. https://doi.org/10.1016/j.chemosphere.2021.130954

Therond, O., Duru, M., Roger-Estrade, J., & Martin, G. (2017). A new analytical framework of farming system and agriculture model diversities: A review. *Agronomy for Sustainable Development, 37*, 21. https://doi.org/10.1007/s13593-017-0429-7

Wu, L., & Liu, M. (2008). Preparation and properties of chitosan-coated NPK compound fertilizer with controlled-release and water-retention. Carbohydrate Polymers, 72(2), 240–247. https://doi.org/10.1016/j.carbpol.2007.08.020

Zhang, L., Wu, L., Huang, L., & Zhang, Y. (2021). Wield the power of omni-channel retailing strategy: A capability and supply chain resilience perspective. *Journal of Strategic Marketing, 1–25*. https://doi.org/10.1080/0965254X.2021.1972440