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Biomass Valorization for Sustainable Tropical Pest Management: Outcomes of an International Academic Engagement Program

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ABSTRACT

Sustainable pest management remains a critical challenge in tropical agricultural systems, where year-round pest and disease pressure often leads to heavy reliance on synthetic pesticides. Such dependence poses environmental and health risks, necessitating alternative, eco-friendly strategies. This study reports the outcomes of an international academic engagement program aimed at disseminating biomass-based pest management approaches, particularly the valorization of oil palm empty fruit bunch (EFB) into biochar and wood vinegar, as sustainable inputs for tropical agriculture. The program was conducted through academic presentations, laboratory visits, and structured discussions involving Indonesian and Japanese institutions. To evaluate its impact, a Likert-scale questionnaire was administered to participants (n = 24). The overall evaluation yielded a very high mean score (4.69/5.00), with the highest-rated indicator being opportunities for international collaboration (4.83), followed by topic relevance (4.75) and improvement in participants' understanding (4.70). The findings demonstrate that biomass valorization strategies not only offer promising sustainable alternatives to synthetic pesticides but also serve as an effective platform for international knowledge exchange and collaborative research networking. This study highlights the strategic role of international academic engagement in bridging tropical agricultural innovation with global sustainability discourse.

1. INTRODUCTION

Tropical agricultural systems are characterized by continuous cropping cycles, high humidity, and favorable temperatures, which collectively promote the rapid development of pests and plant diseases. As a result, farmers in tropical regions tend to rely heavily on synthetic pesticides to maintain crop productivity. While effective in the short term, this dependency has led to increasing environmental and health concerns (Sharma et al., 2020; Purnama et al., 2023;2025a).

The widespread use of synthetic pesticides has been associated with soil degradation, contamination of water resources, and negative impacts on non-target organisms, including beneficial insects and soil microbiota. Moreover, pesticide residues in food products raise concerns regarding long-term human health risks, particularly in developing countries with limited regulatory control (Sharma et al., 2019). These issues highlight the urgent need for sustainable pest management strategies that reduce reliance on chemical inputs while maintaining agricultural productivity.

In this context, biomass valorization has emerged as a promising approach within the circular bioeconomy framework. Agricultural residues can be converted into value-added products such as biochar and wood vinegar through thermochemical processes, offering environmentally friendly alternatives for agricultural applications. Biochar, in particular, has been extensively studied for its role in improving soil fertility, enhancing nutrient retention, and contributing to climate change mitigation (Lehmann et al., 2021).

Recent studies have demonstrated that biochar application can significantly improve soil physicochemical properties, increase carbon sequestration, and promote plant growth, thereby enhancing crop resilience under

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stress conditions (Suri et al., 2025; Wijitkosum et al., 2025). Meanwhile, wood vinegar, a by-product of biomass pyrolysis, contains bioactive compounds such as phenols and organic acids that exhibit antimicrobial and pesticidal properties, making it a potential biopesticide in sustainable agriculture systems (Anggrayni et al., 2025; Purnama et al., 2026).

Despite these advantages, the adoption of biomass-based pest management remains limited, particularly due to gaps in knowledge dissemination, technological standardization, and cross-regional collaboration. International academic engagement can play a strategic role in addressing these challenges by facilitating knowledge exchange, promoting interdisciplinary collaboration, and strengthening global research networks (de Wit & Altbach, 2021).

Therefore, this study aims to evaluate the outcomes of an international academic engagement program focused on biomass valorization for sustainable tropical pest management. The program emphasizes the use of biochar and wood vinegar derived from oil palm empty fruit bunches (EFB) and explores their potential for sustainable agricultural applications. By analyzing participant responses and engagement outcomes, this study provides insights into the effectiveness of international knowledge exchange in advancing sustainable agricultural practices and fostering collaborative research initiatives.

2. LITERATURE REVIEW

2.1 Sustainable Pest Management in Tropical Agriculture

Tropical agriculture is highly vulnerable to persistent pest and disease pressure because warm temperatures and high humidity support continuous pest reproduction and pathogen development. Under such conditions, synthetic pesticides are often used intensively to protect yields. However, the long-term consequences of excessive pesticide use include contamination of soil, water, and food systems, as well as risks to human health and ecological integrity (Ahmad et al., 2024). Recent reviews also emphasize that sustainable pest management should reduce chemical dependence while maintaining crop productivity and ecosystem health. In this context, integrated pest management (IPM) remains a key conceptual foundation because it combines biological, cultural, mechanical, and targeted chemical measures in a more sustainable framework (Zhou et al., 2024).

2.2 Biomass Valorization as a Circular Bioeconomy Strategy

Biomass valorization refers to the conversion of agricultural residues into higher-value products that can be reused in production systems rather than discarded as waste. In agricultural sustainability discourse, this concept is closely linked to the circular bioeconomy, which seeks to minimize waste, recycle biological resources, and create environmentally beneficial inputs. In oil palm systems, empty fruit bunches and other processing residues represent abundant biomass streams that can be thermochemically converted into products such as biochar and wood vinegar. The theoretical relevance of biomass valorization in this study lies in its dual function: first, as a waste-to-resource strategy, and second, as a pathway for developing low-impact pest management inputs suitable for tropical agriculture (Akley et al., 2023; Purnama et al., 2025b;2026).

2.3 Biochar as a Soil-Health-Oriented Agricultural Input

Biochar is a carbon-rich product generated through biomass pyrolysis and is widely recognized for its capacity to improve soil-related functions. The literature shows that biochar can contribute to climate change mitigation while also affecting soil processes linked to plant performance, including nutrient dynamics, water relations, and microbial interactions. In agricultural contexts, its theoretical importance extends beyond soil amendment alone. By improving the growing environment, biochar may indirectly enhance plant vigor and resilience, which can reduce susceptibility to biotic stress. Thus, in this study, biochar is conceptualized not only as a residue-derived material but also as a functional component of sustainable pest and disease management through soil-mediated mechanisms (Lehmann et al., 2021).

2.4 Wood Vinegar as a Bioactive Pyrolysis By-Product

Wood vinegar, also referred to as pyroligneous acid or wood distillate in some literature, is a liquid by-product of pyrolysis that contains organic acids, phenolic compounds, and other bioactive constituents. Recent studies have shown that wood vinegar can promote soil health and crop productivity and is increasingly recommended as a biocontrol or biostimulant input in agriculture. Additional evidence also indicates that wood

vinegar has antimicrobial potential, supporting its relevance as a candidate material for alternative pest and disease management strategies. The theoretical significance of wood vinegar in this study lies in its multifunctionality: it is not merely a waste-derived liquid, but a bioactive material that may contribute to disease suppression, crop health improvement, and reduced reliance on synthetic pesticides (Akley et al., 2023; Anggrayni et al., 2025; Purnama et al., 2026).

2.5 International Academic Engagement and Knowledge Exchange

The diffusion of sustainable agricultural innovation depends not only on the technology itself but also on how knowledge is exchanged, interpreted, and adapted across institutions and regions. In higher education, internationalization has increasingly been framed as a strategic agenda that supports cross-border knowledge exchange, institutional collaboration, and broader global engagement. At the same time, recent higher-education scholarship highlights that knowledge sharing among academics is a distinct and still-developing field, but one that is essential for improving institutional learning and collaborative productivity. Within this framework, international academic engagement can be understood as a mechanism for transferring scientific knowledge, building networks, and creating pathways for future collaborative research. In the present study, this theoretical perspective is important because the program was designed not only to present biomass-based pest management ideas, but also to stimulate international collaboration and shared scientific understanding (de Wit & Altbach, 2021; Fan & Beh, 2024).

2.6 Conceptual Position of the Present Study

Based on the literature above, this study is positioned at the intersection of three conceptual domains: sustainable pest management, biomass valorization, and international academic engagement. Sustainable pest management provides the agricultural rationale; biomass valorization provides the technological and environmental rationale; and international academic engagement provides the institutional and knowledge-transfer rationale. The article therefore evaluates not only whether the topic was perceived as scientifically relevant, but also whether the engagement model was effective in increasing understanding and opening opportunities for international collaboration. This integrated framework supports the interpretation of the questionnaire outcomes reported in the study (Akley et al., 2023; Zhou et al., 2024; Fan & Beh, 2024; Yaro & Hughey, 2025).

3. METHOD

3.1 Study Design

This study employed a descriptive quantitative approach to evaluate the outcomes of an international academic engagement program focusing on biomass valorization for sustainable tropical pest management. The program was conducted in October 2025 at the Tokyo University of Agriculture and Tokyo University of Agriculture, Japan, involving academic presentations, laboratory visits, and structured discussions between Indonesian and Japanese participants.

A post-activity evaluation design was applied to assess participants' perceptions regarding topic relevance, knowledge improvement, academic delivery, and collaboration opportunities. This approach is widely used in educational and program evaluation studies to measure participant responses following knowledge transfer activities (Creswell & Creswell, 2021).

3.2 Participants

The participants consisted of 24 individuals, including undergraduate and graduate students, academic staff, and researchers from both institutions. Participants were selected using a total sampling approach, as all attendees of the program were invited to complete the evaluation questionnaire. This sampling approach is appropriate for small-scale program evaluations where the objective is to capture the full range of participant responses rather than to generalize findings to a broader population (Etikan et al., 2016).

3.3 Instrument Design

Data were collected using a structured questionnaire developed based on the objectives of the program. The instrument employed a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), which is widely used to assess participants' perceptions, attitudes, and learning outcomes in educational and program

evaluation studies. The questionnaire was designed to capture four key dimensions, namely topic relevance, knowledge and understanding, academic delivery, and collaboration and future engagement. These constructs were selected to reflect both the scientific content of the program and its broader impact on participants' learning and networking experiences. The development of the instrument was guided by commonly used indicators in educational evaluation research to ensure clarity, reliability, and ease of interpretation. Likert-scale instruments have been extensively applied in similar contexts due to their effectiveness in quantifying subjective perceptions and facilitating comparative analysis across multiple indicators (Joshi et al., 2015; Taherdoost, 2019).

3.4 Data Collection Procedure

The questionnaire was distributed immediately after the completion of the program to ensure that participant responses reflected their direct experience. Participants completed the questionnaire voluntarily, and responses were collected anonymously to reduce response bias. This procedure follows standard practices in program evaluation, where immediate post-event assessment is recommended to capture accurate participant perceptions (Dillman et al., 2014).

3.5 Data Analysis

The collected data were analyzed using descriptive statistical methods to summarize participant responses and evaluate the overall effectiveness of the program. The primary analytical measure used was the mean score, calculated by dividing the total score of all responses by the number of participants. This approach allows for a straightforward interpretation of participant perceptions across different evaluation indicators. In addition, the mean scores were categorized into predefined levels to facilitate interpretation, ranging from very low to very high. This categorization provides a clearer understanding of the extent to which the program met its intended objectives. Descriptive analysis is considered appropriate in this context because the study aims to assess participant perceptions rather than to establish causal relationships or test hypotheses. Such an approach is widely adopted in program evaluation and educational research to provide an overall assessment of effectiveness and participant satisfaction (Creswell & Creswell, 2021). Descriptive analysis is appropriate for evaluating program effectiveness when the primary objective is to summarize participant perceptions rather than to test causal relationships (Creswell & Creswell, 2021).

3.6 Ethical Considerations

Participation in the study was voluntary, and respondents were informed about the purpose of the evaluation. No personal identifying information was collected, ensuring confidentiality and anonymity of responses. The study adhered to general ethical principles in educational research involving human participants (American Educational Research Association, 2018).

4. RESULT AND DISCUSSION

4.1 Overall Evaluation of the Program

The overall evaluation of the international academic engagement program indicated a very high level of participant satisfaction, with a mean score of 4.69 out of 5.00. This result suggests that the program was highly effective in achieving its objectives, particularly in delivering relevant knowledge and fostering meaningful academic interaction. Table 1 summarizes the evaluation results across all indicators. As shown in Table 1, the highest-rated indicator was international collaboration opportunity (4.83), followed by topic relevance (4.75) and knowledge improvement (4.70).

Table 1. Summary of Evaluation Results

No	Indicator	Mean Score	Category
1	Topic Relevance	4.75	Very High
2	Knowledge Improvement	4.70	Very High
3	Academic Delivery	4.63	Very High
4	Interactive Discussion	4.58	Very High
5	Potential of Biomass-Based Pest Control	4.68	Very High

6	International Collaboration Opportunity	4.83	Very High
	Overall Mean	4.69	Very High

High evaluation scores in educational and outreach programs generally reflect the alignment between program content and participant expectations, as well as the effectiveness of knowledge delivery mechanisms (Creswell & Creswell, 2021). In this study, the strong overall score indicates that the integration of biomass-based pest management within an international academic setting was well received by participants from diverse academic backgrounds.

4.2 Topic Relevance and Knowledge Enhancement

The indicator of topic relevance received a high mean score of 4.75, demonstrating that participants perceived the subject of sustainable tropical pest management as highly relevant to current agricultural challenges. This finding is consistent with global concerns regarding the environmental and health impacts of synthetic pesticide use, which have driven the search for alternative pest management strategies (Sharma et al., 2020; Purnama et al., 2026).

Similarly, the indicator related to improvement in participants' understanding achieved a mean score of 4.70, indicating that the program effectively enhanced knowledge regarding biomass-based pest management approaches. The use of biochar and wood vinegar derived from oil palm residues was perceived as a novel and applicable solution within the context of tropical agriculture.

The effectiveness of knowledge transfer observed in this study aligns with previous findings that interactive academic engagement activities, such as seminars and collaborative discussions, can significantly improve participants' comprehension of complex scientific concepts (Knight, 2012). Furthermore, the contextualization of the topic within tropical agricultural systems likely contributed to its perceived relevance and applicability.

4.3 Collaboration Opportunities and International Engagement

The highest-rated indicator in this study was opportunities for international collaboration, with a mean score of 4.83. This highlights the strategic importance of academic engagement programs in facilitating cross-institutional partnerships and strengthening global research networks. International collaboration has been widely recognized as a key driver of scientific innovation, particularly in addressing complex and interdisciplinary challenges such as sustainable agriculture (de Wit & Altbach, 2021). The strong response in this category suggests that participants not only valued the knowledge shared during the program but also recognized its potential for future joint research initiatives.

The program provided a platform for interaction between researchers from different countries, enabling the exchange of perspectives and the identification of potential collaborative research themes. This aligns with the concept of internationalization in higher education, which emphasizes the role of academic mobility and knowledge exchange in enhancing research capacity and global engagement (Knight, 2012).

4.4 Integration of Biomass Valorization and Sustainable Pest Management

The positive evaluation of the program also reflects the growing interest in biomass valorization as a sustainable solution in agriculture. The utilization of oil palm residues, such as empty fruit bunches (EFB), for producing biochar and wood vinegar represents an innovative approach that integrates waste management with pest control strategies.

Previous studies have demonstrated that biochar can improve soil properties and indirectly enhance plant resistance to stress, while wood vinegar contains bioactive compounds with antimicrobial and pesticidal properties (Lehmann et al., 2021; Akley et al., 2023). The integration of these materials into pest management practices supports the transition toward more sustainable and circular agricultural systems.

The high level of participant agreement indicates that biomass-based pest management is not only scientifically relevant but also perceived as practically applicable. This is particularly important in tropical regions, where agricultural residues are abundant and can be efficiently converted into value-added products.

4.5 Implications for International Academic Engagement

The findings of this study highlight the dual role of international academic engagement as both a knowledge dissemination platform and a collaboration catalyst. The high scores across all indicators suggest that such programs can effectively bridge the gap between local agricultural innovations and global scientific discourse.

Moreover, the integration of sustainability-oriented topics, such as biomass valorization, into international academic activities can enhance their impact by addressing globally relevant challenges. This approach supports the broader agenda of sustainable development and aligns with efforts to promote environmentally responsible agricultural practices.

However, it is important to note that the study is based on a relatively small sample size and relies on self-reported perceptions. Future studies may incorporate longitudinal assessments or collaborative research outputs to further evaluate the long-term impact of such engagement programs.

5. CONCLUSIONS

This study demonstrates that the international academic engagement program on biomass valorization for sustainable tropical pest management was highly effective in enhancing participant understanding and fostering collaborative potential. The overall evaluation score of 4.69 indicates a very high level of participant satisfaction, with particularly strong responses in international collaboration opportunities, topic relevance, and knowledge improvement. These findings confirm that biomass-based approaches, such as the use of biochar and wood vinegar derived from oil palm residues, are not only scientifically relevant but also well perceived as practical and sustainable alternatives to synthetic pesticides in tropical agriculture. Beyond knowledge dissemination, the program successfully functioned as a platform for international academic networking, highlighting the strategic role of cross-border engagement in advancing sustainable agricultural innovation. However, the study is limited by its reliance on perception-based data and a relatively small sample size. Future work should focus on long-term collaborative research outcomes and field-based validation of biomass-derived pest management strategies to strengthen their applicability and scalability.

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