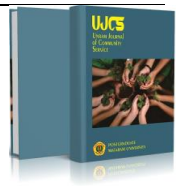
UJCS 7(3) (2026)

Unram Journal of Community Service

https://jurnalpasca.unram.ac.id/index.php/UJCS



Integrated Pyrolysis and Fermentation for Sustainable Agricultural Biomass Waste Utilization and Community-Based Circular Economy Development

Mustika Dewi[1], Anca Awal Sembada[2*], Sabrina Mutiara Gani[3], Eynge Kezia Bungalessy[3], Sutrisno[2], Eka Mulya Alamsyah[2], Pathmi Noerhatini[4]

[1] Microbial Biotechnology Research Group, School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia.
[2] Forestry Technology Research Group, School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia.
[3] Forestry Engineering Program, School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia.
[4] Humanities Research Group, Faculty of Arts and Design, Institut Teknologi Bandung, Bandung, Indonesia.

Article Info
Received : August 15, 2026
Revised: August 28, 2026
Accepted: September 18, 2026
Published: September 30, 2026

Corresponding Author:
Anca Awal Sembada
ancaawals@itb.ac.id

DOI: 10.29303/ujcs.v7i3.1838

© 2026 The Authors. This open access article is distributed under a (CC-BY License)

Abstract: Biomass and organic waste generated from agricultural activities represent an underutilized resource that can be converted into value-added products through appropriate technologies. This community service activity aimed to improve the knowledge and practical skills of farmers and local communities in Cicareuh Village, Sukabumi Regency, West Java, in utilizing oil palm biomass and other organic waste through pyrolysis and fermentation technologies. A participatory approach was applied through lectures, discussions, demonstrations, hands-on practices, and evaluations. Pyrolysis was demonstrated as a thermochemical process under oxygen-limited conditions to produce liquid smoke and charcoal/biochar from biomass waste. Fermentation was introduced as a biological method for processing organic waste into organic fertilizer using effective microorganisms. The integration of these technologies provided participants with practical experience in converting locally available waste into potentially useful agricultural products and promoted the principles of circular economy and resource recovery. The activity increased participants' understanding of waste utilization and provided practical skills for biomass processing. Further activities are recommended to characterize product quality, evaluate the efficacy and safety of liquid smoke, assess organic fertilizer quality, and examine the economic feasibility and sustainability of community-level implementation.

Keywords: Biomass Waste, Pyrolysis, Liquid Smoke, Organic Fertilizer, Circular Economy.

Introduction

Biomass waste is one of the issues that requires attention in the development of sustainable agricultural and plantation systems. Oil palm produces various types of biomass residues, including empty fruit bunches, fronds, trunks, fibers, and shells. These biomass residues contain lignocellulosic components and organic matter, making them suitable for conversion into various value-added products (Nuryawan et al., 2022). Biomass utilization through conversion technologies can reduce environmental burdens while increasing the economic value of local resources. One of the technologies that can be used to process lignocellulosic biomass is pyrolysis. Pyrolysis is a thermal decomposition process of organic materials under oxygen-limited conditions (Hadiyane et al., 2026). This process produces three main fractions: a solid fraction in the form of biochar or charcoal, a gaseous fraction, and a liquid fraction obtained through the condensation of pyrolysis vapors. The liquid fraction is commonly known as liquid smoke or pyroligneous acid.

How to Cite:
Dewi, M., Sembada, A. A., Gani, S. M., Bungalessy, E. K., Sutrisno, Alamsyah, E. M., & Noerhatini, P. Integrated Pyrolysis and Fermentation for Sustainable Agricultural Biomass Waste Utilization and Community-Based Circular Economy Development. *Unram Journal of Community Service*, *7*(3), 255–263. https://doi.org/10.29303/ujcs.v7i3.1838

Liquid smoke contains various organic compounds resulting from the thermal decomposition of biomass, including organic acids, phenolic compounds, carbonyl compounds, and other substances (Tegang et al., 2020). The composition of liquid smoke is influenced by the type of feedstock and the pyrolysis conditions. The presence of these compounds gives liquid smoke various potential applications, including as a preservative, antimicrobial agent, and plant pest-control material.

In the agricultural context, biomass-derived liquid smoke can be developed as a material for controlling plant pests and pathogens. Several components of liquid smoke, particularly phenolic compounds and organic acids, are known to exhibit antimicrobial activity (Brustolin et al., 2024). However, the effectiveness of liquid smoke depends strongly on its composition, concentration, target organism, and application method. Therefore, the term biopesticide in this community empowerment activity is used in the context of introducing the potential of liquid smoke as a biological or biobased pest-control material, whereas claims regarding its effectiveness as a pesticide require further testing. In addition to pyrolysis, fermentation technology is a relatively simple method for processing organic waste into organic fertilizer. The fermentation of organic materials utilizes the activity of microorganisms to accelerate the decomposition process (Mengqi et al., 2023). The use of effective microorganisms can facilitate the breakdown of organic matter, making the material more readily decomposed and suitable for use as fertilizer or a soil amendment.

The production of organic fertilizer at the community level can be carried out using simple equipment, such as plastic drums or composters. Oil palm residues and other organic wastes are first chopped to reduce particle size. The materials are then placed into a composter and supplemented with an inoculum or effective microorganisms. Moisture and aeration conditions need to be controlled throughout the fermentation process to ensure optimal microbial activity. The integration of pyrolysis and fermentation technologies for waste management provides an interesting approach to implementing a circular economy. Biomass that was previously considered waste can be converted into several products, including liquid smoke from the liquid fraction of pyrolysis, charcoal or biochar from the solid fraction, and organic fertilizer through biological processing. Thus, a single resource can be utilized through multiple processing pathways to produce different value-added products.

This concept is relevant to the development of a circular economy because production residues are not immediately discarded but are instead returned to the production system as resources. The utilization of oil palm residues to produce value-added products has been widely investigated as a strategy for reducing waste and improving resource-use efficiency. Cicareuh Village, Sukabumi Regency, was selected as the site for a community service activity aimed at introducing technologies for utilizing oil palm waste to local communities. The activity employed a combination of approaches, including lectures, technology demonstrations, hands-on practice, discussions, and question-and-answer sessions. Based on these conditions, this activity aimed to improve the knowledge and skills of the community in utilizing oil palm waste and other organic residues through two processing technologies: pyrolysis to produce liquid smoke with potential applications as a plant pest-control material, and fermentation to produce organic fertilizer.

Method

Location, Participants, and Implementation Approach

The community service activity was conducted in Cicareuh Village, Sukabumi Regency, West Java, on 23–24 May 2026. The activity involved 30 participants from the local community who participated in a series of training sessions and practical activities focused on the utilization of oil palm biomass and other organic waste. The selection of Cicareuh Village as the activity location was based on the potential availability of biomass and organic residues that could be further utilized as raw materials for value-added products. Rather than treating these materials solely as waste, the activity introduced an approach in which organic residues could be processed and returned to the production system through relatively simple and accessible technologies.

The activity was designed using a participatory training approach that combined theoretical explanations, technology demonstrations, hands-on practice, discussion, and evaluation. This approach was intended to ensure that participants not only received information about biomass waste management but also gained direct experience in applying the technologies introduced. The participatory approach was particularly important because the successful adoption of waste-processing technologies at the community level depends not only on the technical feasibility of the process but also on participants' understanding, practical skills, and confidence in operating the equipment and handling the resulting products.

Stages of the Activity

The implementation of the community service program was conducted through several interconnected stages. The activity began with coordination and preparation, followed by the delivery of introductory materials, technology demonstrations, hands-on

practice, discussion, and participatory evaluation. Prior to the practical sessions, the implementation team prepared the raw materials, equipment, and supporting materials required for pyrolysis and fermentation. The preparation stage also included ensuring that the biomass was suitable for processing and that the equipment could be operated safely during the training.

The second stage involved the delivery of educational materials concerning biomass waste management, the characteristics of lignocellulosic biomass, the basic principles of pyrolysis and fermentation, and the potential utilization of the resulting products. The material was presented in a manner adapted to the participants' backgrounds and was accompanied by examples of potential applications in agricultural activities. The participants were also introduced to the concept of converting waste into value-added products as part of a broader circular-economy approach.

The subsequent stages consisted of demonstrations and hands-on practices. The implementation team first demonstrated the pyrolysis process, followed by direct participant involvement in liquid smoke production. A similar approach was applied to organic fertilizer production, beginning with a demonstration of the fermentation process and continuing with hands-on practice. The activity concluded with discussions, question-and-answer sessions, and participatory evaluation. These sessions provided an opportunity for participants to clarify technical aspects, discuss potential applications, and provide feedback regarding the technologies introduced.

Production of Liquid Smoke through Pyrolysis

The production of liquid smoke was carried out using oil palm biomass that was available at the activity location and considered suitable for thermal conversion. Before being introduced into the pyrolysis reactor, the biomass was prepared to improve the consistency of the process. Preparation involved reducing excess moisture and adjusting the size of the biomass to facilitate more uniform heat transfer during thermal treatment (Hidayat et al., 2025). Appropriate preparation of the feedstock is important because moisture content and particle size can influence the heating rate, thermal decomposition process, and distribution of pyrolysis products (Islam et al., 2026). The prepared biomass was subsequently loaded into the pyrolysis reactor. After loading, the reactor was closed to restrict the supply of oxygen. Heating was then initiated under oxygen-limited conditions. During this stage, the organic components of the biomass underwent thermal decomposition, generating a mixture of gases and vapors. The vapors generated inside the reactor were subsequently directed through a condensation system.

As the pyrolysis vapors passed through the condenser, cooling caused condensable compounds to change from the vapor phase into a liquid fraction (Sun et al., 2024). This condensed liquid was collected as liquid smoke. The overall process therefore involved several sequential stages, beginning with biomass preparation and heating, followed by thermal decomposition, vapor formation, condensation, and collection of the liquid product. A schematic representation of the process is presented in Figure 1. In addition to the liquid fraction, the pyrolysis process also generated a solid residue that remained inside the reactor after thermal treatment. This solid fraction consisted primarily of charcoal or biochar. Although the primary focus of the training was the production of liquid smoke, participants were also introduced to the potential utilization of the solid fraction. Biochar can potentially be applied as a soil amendment or used for other purposes depending on its physicochemical characteristics and the intended application (Kang et al., 2022). Thus, the pyrolysis process can provide more than one potentially useful product from the same biomass feedstock.



Figure 1. Schematic of the pyrolysis system used in the study.

Following the condensation process, the liquid smoke was collected in suitable containers. During the training, participants were introduced to the potential agricultural applications of liquid smoke, particularly its potential as a material for controlling plant pests and pathogens. Liquid smoke contains various compounds generated during the thermal decomposition of biomass, including organic acids, phenolic compounds, carbonyl compounds, and other organic constituents (Syguła et al., 2024). Some of these compounds have been reported to possess biological activities, including antimicrobial properties. Consequently, liquid smoke has attracted interest for potential applications in agricultural

production and crop protection. Nevertheless, the training emphasized that the potential use of liquid smoke as a biopesticide or plant protection material should not be interpreted as evidence of confirmed pesticide efficacy. The biological properties of liquid smoke can vary substantially depending on the feedstock, pyrolysis temperature, residence time, heating conditions, and condensation process. Therefore, before liquid smoke is applied extensively for pest or pathogen control, further characterization and efficacy testing are required. Such assessments may include determination of pH, characterization of the organic compounds present, and laboratory or field-based bioassays against specific target organisms. This consideration is particularly important to ensure that recommendations for agricultural use are supported by appropriate scientific evidence.

The explanation of these aspects was intended to provide participants with a balanced understanding of the technology. The training therefore did not focus solely on the production of liquid smoke but also emphasized the importance of product quality, appropriate application, and further validation. In this way, participants were introduced not only to the practical operation of a pyrolysis system but also to the scientific considerations underlying the potential utilization of its products.

Production of Organic Fertilizer through Fermentation

The second technology introduced during the activity was fermentation for the production of organic fertilizer. This process was selected because fermentation can be implemented using relatively simple equipment and can utilize a variety of organic residues. Oil palm residues and other locally available organic wastes can potentially serve as feedstocks, thereby providing an alternative approach to managing organic materials that might otherwise be discarded. Before fermentation, the organic materials were first sorted and prepared. The materials were chopped into smaller pieces to increase their surface area. Reducing the particle size facilitates contact between the organic substrate and microorganisms and can improve the efficiency of the decomposition process. More uniform and smaller particles can also facilitate mixing and improve the distribution of moisture and microbial inoculum throughout the material.

The prepared organic materials were subsequently placed into a plastic drum or composter (Figure 2). An inoculum or solution containing effective microorganisms was then added according to the formulation used during the training. The addition of microorganisms was intended to initiate and facilitate biological decomposition of the organic substrate (Wei et al., 2022). The materials were mixed or arranged to promote relatively uniform distribution of the inoculum throughout the substrate. The general sequence of organic fertilizer production consisted of material preparation, size reduction, loading into the fermentation container, addition of microbial inoculum, and controlled fermentation.



Figure 2. Composter used in the study for organic fertilizer production system.

During the fermentation process, several physical conditions were monitored, particularly moisture, aeration, temperature, and odor. These parameters provide practical indicators of the progress and condition of the fermentation process. Moisture is important because excessive dryness can restrict microbial activity, whereas excessive moisture may reduce aeration and promote undesirable anaerobic conditions. Aeration is also important for maintaining an appropriate microbial environment, particularly when aerobic microorganisms are used (Fu et al., 2023). Temperature may change as microbial activity increases and organic matter is decomposed, while changes in odor can provide an additional qualitative indication of the condition of the material. The microorganisms utilize organic compounds as sources of carbon and energy, resulting in the gradual decomposition and transformation of the original material. Through this process, the organic substrate becomes increasingly stabilized and can potentially be utilized as an organic fertilizer or soil amendment. However, the maturity and quality of the resulting material depend on the characteristics of the raw materials, microbial community, moisture content, aeration, temperature, and duration of the fermentation process. Proper management of these factors is therefore necessary to obtain a stable and suitable organic product.

During the practical session, participants were encouraged to observe changes in the material and relate these changes to the biological processes occurring during fermentation. This hands-on component was intended to improve participants' understanding of the relationship between the physical conditions of the

fermentation system and microbial decomposition. In addition, the activity demonstrated that organic waste management can be integrated into routine community activities using relatively simple infrastructure.

Training Methods

The training methodology was designed to combine knowledge transfer with direct practical experience. Four complementary approaches were used: lectures and discussions, technology demonstrations, hands-on practice, and participatory evaluation (Hidayat et al., 2026). The combination of these approaches was intended to accommodate different learning processes and to ensure that participants could understand both the theoretical principles and practical procedures involved in biomass waste processing. The first approach consisted of lectures and discussions. The implementation team provided introductory information concerning biomass waste, lignocellulosic materials, pyrolysis, liquid smoke, fermentation, effective microorganisms, and organic fertilizer. The discussion also addressed the potential benefits and limitations of biomass conversion technologies. Particular attention was given to the concept of waste reduction and resource recovery, whereby biomass residues can be viewed as potential resources rather than materials with no further value.

The second approach involved technology demonstrations. The implementation team demonstrated the pyrolysis process step by step, beginning with biomass preparation and reactor loading and continuing through heating, vapor condensation, and liquid smoke collection. The fermentation process was similarly demonstrated, including preparation and size reduction of organic materials, loading of the fermentation container, addition of microbial inoculum, and management of the fermentation conditions. Demonstrations allowed participants to observe the operation of the technologies before conducting the procedures themselves. The third approach was hands-on practice. Participants were directly involved in preparing raw materials, operating or assisting with the processing stages, and observing the products generated. Direct participation was intended to strengthen participants' practical skills and provide experience that could potentially facilitate subsequent adoption of the technologies at the household or community level. Through hands-on activities, participants could also identify practical challenges associated with material preparation, equipment operation, and process control.

The final approach was participatory evaluation. Rather than relying exclusively on formal testing, the evaluation considered participant engagement throughout the activity, their ability to follow the practical procedures, the questions raised during the training, and their responses to the technologies introduced (Rumidatul et al., 2025). Discussions during and after the practical sessions were also used to identify participants' perceptions of the feasibility and potential usefulness of pyrolysis and fermentation technologies in their local context. Overall, the training was designed not merely as a technology demonstration but as an introductory capacity-building activity. By integrating theoretical knowledge, practical demonstrations, direct participation, and discussion, the program sought to strengthen community understanding of biomass waste utilization and to introduce feasible pathways for converting locally available residues into potentially useful agricultural products. The combination of pyrolysis and fermentation also provided participants with an initial understanding of a circular approach to biomass management, in which different organic residues can be processed through complementary pathways to generate multiple value-added products while reducing the amount of waste requiring disposal.

Result and Discussion

Implementation of the Activity

The training activity was conducted over two days and was attended by 30 participants from the local community. The implementation integrated theoretical instruction with hands-on practice, allowing participants to gain an understanding of the underlying technological principles while also obtaining direct experience in biomass and organic waste processing (Figure 3). This combination was intended to bridge the gap between theoretical knowledge and practical application, particularly because waste-processing technologies require not only conceptual understanding but also operational skills and familiarity with the equipment.



Figure 3. Delivery of training materials.

The practical component represented an important part of the community empowerment

process. Participants were involved in several stages of the activities, including preparation of raw materials, observation of equipment operation, processing procedures, and discussion of the resulting products. Documentation of the activity shows that the empowerment process was conducted through a combination of material delivery, technology demonstrations, interactive discussions, and hands-on waste-processing practices. This approach provided participants with opportunities to observe the processes directly and to ask questions regarding the operation, potential applications, and limitations of the technologies introduced. Participants demonstrated considerable interest and enthusiasm toward the technologies presented during the training. One factor contributing to this response was the use of locally available biomass and organic materials as feedstocks. The relatively simple processing principles and equipment also made the technologies easier to understand and potentially adaptable to community-level applications. The activity therefore served not only as a technical training program but also as an introduction to the concept of converting locally available waste materials into potentially useful agricultural products.

Pyrolysis Technology and Liquid Smoke Production

Pyrolysis is a thermochemical conversion technology that can be used to transform biomass into solid, liquid, and gaseous products. The process involves heating organic materials under oxygen-limited conditions, resulting in the thermal decomposition of complex organic components (Thiagarajan et al., 2025). The vapors generated during this process can subsequently be cooled and condensed to obtain a liquid product, commonly referred to as liquid smoke or pyroligneous acid. During the training, participants were introduced to the principle that oil palm residues do not necessarily have to be discarded or subjected to uncontrolled open burning. Instead, biomass residues can be directed into a controlled pyrolysis system, where thermal conversion produces several fractions that may have further applications. This approach provides an alternative strategy for reducing biomass waste while simultaneously recovering resources from materials that would otherwise have limited economic value.

The production of liquid smoke was one of the main focuses of the pyrolysis demonstration (Figure 4). Liquid smoke is of particular interest because it contains a complex mixture of organic compounds formed during the thermal decomposition of biomass. Depending on the feedstock and pyrolysis conditions, these compounds may include acetic acid and other organic acids, phenolic and phenolic-derived compounds, carbonyl compounds, and other volatile and semi-volatile organic constituents. The composition of the resulting liquid smoke can vary considerably depending on factors such as biomass type, moisture content, heating temperature, heating rate, residence time, and condensation conditions (Zhang et al., 2025). The presence of these compounds may contribute to the biological activity of liquid smoke. In particular, phenolic compounds and organic acids have been associated with antimicrobial activity, providing a basis for investigating liquid smoke for potential agricultural applications. Iacomino et al. (2024) reported that wood vinegar or liquid smoke has potential applications in agriculture, although its effectiveness and mode of action depend strongly on its chemical composition and application concentration.



Figure 4. Liquid smoke produced from the pyrolysis system.

The pyrolysis demonstration therefore provided participants with an understanding of biomass conversion from both a technological and resource-utilization perspective. Participants could observe how biomass is transformed through thermal processing and how different product fractions are generated. The activity emphasized that pyrolysis can be viewed not simply as a waste-disposal method but as a resource-recovery technology capable of producing multiple potentially useful products.

Production of Organic Fertilizer through Fermentation

The second technology introduced during the activity was organic waste processing through fermentation. This approach was selected as a relatively simple biological technology that can be applied to oil palm residues and other locally available organic wastes. Unlike pyrolysis, which relies on thermal conversion, fermentation utilizes the activity of microorganisms to facilitate the decomposition and transformation of organic materials. The process began

with the preparation of the organic feedstock. Oil palm residues and/or other organic wastes were first reduced in size through chopping. This step is important because particle size influences the surface area available for microbial colonization and interaction. Reducing the particle size can increase the contact area between the organic substrate and microorganisms, thereby facilitating the decomposition process (Wen et al., 2025). Appropriate particle size can also improve material mixing and help promote more uniform distribution of moisture and microbial inoculum.

After preparation, the chopped organic materials were placed into a plastic drum or composter. An inoculum containing effective microorganisms was then added according to the formulation used during the training. The microorganisms were introduced to facilitate the biological degradation of organic compounds and accelerate the transformation of the raw material into a more stable organic product. The fermentation process is influenced by several environmental and chemical factors, including moisture content, temperature, aeration, pH, carbon-to-nitrogen (C/N) ratio, and microbial activity (Borkertas et al., 2025). Consequently, successful organic fertilizer production cannot be attributed solely to the addition of microbial inoculum. Appropriate management of the fermentation environment is equally important. Excessive moisture, for example, may reduce aeration and create unfavorable conditions, whereas insufficient moisture may restrict microbial activity. Similarly, appropriate aeration and temperature conditions are important for maintaining microbial activity and promoting efficient decomposition.



Figure 5. Organic fertilizer produced during the training was used for plant cultivation.

During the practical session, participants were introduced to these factors through direct observation and discussion (Figure 5). They were encouraged to monitor changes in the material during the fermentation process and to understand the relationship between changes in the physical characteristics of the substrate and microbial decomposition. This practical approach was intended to improve participants' ability to manage the process independently after completion of the training. The use of plastic drums or simple composters provides several practical advantages for community-level implementation. Such systems are relatively easy to operate, require limited space, and can be adapted to household or community-scale waste management. Therefore, fermentation technology has potential for application not only by individual households but also by farmer groups or community organizations that generate organic residues on a regular basis.

Evaluation of the Training Activity

The effectiveness of the training was evaluated using pre- and post-training knowledge tests involving 30 participants (Table 1). The mean knowledge score increased from 60.0 ± 6.1 before the training to 84.7 ± 5.6 after the training, representing a mean increase of 24.7 points or 41.2%. The improvement indicates that the combination of theoretical explanation, technology demonstrations, hands-on practice, and discussion effectively increased participants' understanding of biomass waste utilization, pyrolysis, liquid smoke production, fermentation, and organic fertilizer production.

Table 1. Evaluation Scores.

Participant	Pre-test	Post-test	Improvement
P1	55	80	25
P2	60	85	25
P3	65	85	20
P4	50	75	25
P5	70	90	20
P6	55	80	25
P7	60	85	25
P8	65	90	25
P9	50	75	25
P10	60	80	20
P11	55	85	30
P12	65	90	25
P13	70	95	25
P14	55	80	25
P15	60	80	20
P16	50	80	30
P17	65	90	25
P18	60	85	25
P19	55	80	25
P20	70	90	20
P21	60	75	15
P22	55	90	35
P23	65	90	25
P24	50	75	25
P25	60	90	30
P26	70	100	30
P27	55	70	15
P28	65	85	20
P29	60	90	30
P30	55	80	25

In addition to the knowledge assessment, all 30 participants (100%) participated in the hands-on sessions. Participants were able to follow the basic procedures for preparing biomass, operating the pyrolysis system, collecting liquid smoke, preparing organic materials, and applying microbial inoculum during fermentation. The results suggest that the training successfully improved both participants' theoretical understanding and their initial practical skills in biomass waste utilization.

Conclusion

The community empowerment activity successfully introduced pyrolysis and fermentation technologies as alternative approaches for utilizing oil palm biomass and other organic wastes. Pyrolysis was introduced as a thermochemical conversion process under oxygen-limited conditions that produces a liquid fraction in the form of liquid smoke and a solid fraction in the form of charcoal or biochar. Liquid smoke was introduced to the community as a biomass-derived product with potential applications in the management of plant pests and pathogens. Fermentation was introduced as a relatively simple biological approach for processing oil palm residues and other organic wastes. The process involved reducing the size of the organic materials, placing them in plastic drums or composters, and adding effective microorganisms to facilitate decomposition and produce organic fertilizer.

The integration of pyrolysis and fermentation provides an alternative biomass utilization pathway consistent with circular economy principles. The activity also provided participants with practical experience in converting waste materials into potentially useful agricultural products, thereby increasing their understanding of resource recovery and sustainable waste management. Further development is required to support sustainable implementation of these technologies. Future activities should include characterization and quality assessment of the resulting products, efficacy testing of liquid smoke against specific target organisms, quality evaluation of the organic fertilizer, economic feasibility analysis, and continued institutional and technical assistance. These steps are essential to move the technologies beyond initial training toward sustainable community-level application and the development of value-added products from locally available biomass resources.

Acknowledgments

The authors gratefully acknowledge the Directorate of Community Service and Expertise Services of Institut Teknologi Bandung (DPMK ITB) for providing financial support for this community service activity through the Bottom-Up scheme under Contract No. 1356/IT1.B07.5/TA.01/2026. The authors also extend their appreciation to the Head of Cicareuh Village, as well as the local community and farmers of Cicareuh Village, Sukabumi Regency, for their active participation and support throughout the implementation of the activity.

References

Borkertas, S., Viskelis, J., Viskelis, P., Streimikyte, P., Gasiunaite, U., & Urbonaviciene, D. (2025). Fungal biomass fermentation: valorizing the food industry's waste. *Fermentation*, *11*(6), 351. https://doi.org/10.3390/fermentation11060351

Brustolin, A. P., Soares, J. M., Muraro, K., Schwert, R., Steffens, C., Cansian, R. L., & Valduga, E. (2024). Investigating antimicrobial and antioxidant activity of liquid smoke and physical-chemical stability of bacon subjected to liquid smoke and conventional smoking. *Journal of Food Science*, *89*(11), 7217-7227. https://doi.org/10.1111/1750-3841.17379

Fu, S., Lian, S., Angelidaki, I., & Guo, R. (2023). Micro-aeration: an attractive strategy to facilitate anaerobic digestion. *Trends in Biotechnology*, *41*(5), 714-726. https://doi.org/10.1016/j.tibtech.2022.09.008

Hadiyane, A., Rumidatul, A., Sembada, A. A., Bahtiar, H. F., Darwis, A., Dewi, M., & Imra, I. (2026). Community-based pyrolysis training and technology transfer for sustainable biomass utilization in Metut Village. *Room of Civil Society Development*, *5*(3), 348-360. https://doi.org/10.59110/rcsd.959

Hidayat, Y., Sembada, A. A., & Rumidatul, A. (2025). Pelatihan pembuatan silase probiotik sebagai solusi pakan murah dan berkualitas bagi peternak kambing Desa Jatiroke. *Jompa Abdi: Jurnal Pengabdian Masyarakat*, *4*(4), 110-116. https://doi.org/10.57218/jompaabdi.v4i4.2003

Hidayat, Y., Sembada, A. A., Rumidatul, A., Juhaeti, T., & Ruswandi, D. (2026). Integrated utilization of maize residues and kernels through silage and flour production. *Indonesian Journal of Community Services*, *5*(1), 80-85. https://doi.org/10.47540/ijcs.v5i1.2860

Iacomino, G., Idbella, M., Staropoli, A., Nanni, B., Bertoli, T., Vinale, F., & Bonanomi, G. (2024). Exploring the potential of wood vinegar: Chemical composition and biological effects on crops and pests. *Agronomy*, *14*(1), 114. https://doi.org/10.3390/agronomy14010114

Islam, M. A., Kazol, M. H., Rahman, M., Al Rifat, A., & Amin, N. (2026). A comprehensive review of recent advances in biomass pyrolysis: Feedstock

characteristics, thermal decomposition mechanism, temperature, heating rate, residence time, and particle size on product distribution. *Future Energy*, *5*(2), 47-72. https://doi.org/10.55670/fpll.fuen.5.2.5

Kang, M. W., Yibeltal, M., Kim, Y. H., Oh, S. J., Lee, J. C., Kwon, E. E., & Lee, S. S. (2022). Enhancement of soil physical properties and soil water retention with biochar-based soil amendments. *Science of the Total Environment*, *836*, 155746. https://doi.org/10.1016/j.scitotenv.2022.155746

Mengqi, Z., Shi, A., Ajmal, M., Ye, L., & Awais, M. (2023). Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting. *Biomass Conversion and Biorefinery*, *13*(7), 5445-5468. https://doi.org/10.1007/s13399-021-01438-5

Nuryawan, A., Sutiawan, J., Rahmawaty, Masruchin, N., & Bekhta, P. (2022). Panel products made of oil palm trunk: a review of potency, environmental aspect, and comparison with wood-based composites. *Polymers*, *14*(9), 1758. https://doi.org/10.3390/polym14091758

Rumidatul, A., Hidayat, Y., Hadiyane, A., & Sembada, A. A. (2025). Pelatihan diversifikasi produk olahan jagung menjadi tepung maizena bagi Kelompok Taruna Tani Gunung Geulis. *Room of Civil Society Development*, *4*(6), 938-949. https://doi.org/10.59110/rcsd.774

Sun, K., Wang, Y., Zhang, L., Shao, Y., Li, C., Zhang, S., & Hu, X. (2024). High yield of carbonaceous material from biomass via pyrolysis-condensation. *Chemical Engineering Journal*, *485*, 149823. https://doi.org/10.1016/j.cej.2024.149823

Syguła, E., Ciolkosz, D., & Białowiec, A. (2024). The significance of structural components of lignocellulosic biomass on volatile organic compounds presence on biochar-a review. *Wood Science and Technology*, 58(3), 859-886. https://doi.org/10.1007/s00226-024-01557-y

Tegang, A. S., Mbougueng, P. D., Sachindra, N. M., Nodem, N. F. D., & Ngoune, L. T. (2020). Characterization of volatile compounds of liquid smoke flavourings from some tropical hardwoods. *Scientific African*, *8*, e00443. https://doi.org/10.1016/j.sciaf.2020.e00443

Thiagarajan, C., Yuvarajan, D., Channappagoudra, M., Bhanot, D., Upadhye, V. J., Choudhury, S., & Shukla, K. K. (2025). Advancing sustainable medical waste management: The role of pyrolysis in resource recovery and environmental protection. *Results in Chemistry*, *17*, 102639. https://doi.org/10.1016/j.rechem.2025.102639

Wei, Z., Mohamed, T. A., Zhao, L., Zhu, Z., Zhao, Y., & Wu, J. (2022). Microhabitat drive microbial anabolism to promote carbon sequestration during composting. *Bioresource Technology*, *346*, 126577. https://doi.org/10.1016/j.biortech.2021.126577

Wen, X., Qu, F., Chen, J., Tao, W., Zhou, J., Yang, H., & Wei, Z. (2025). Evaluation of coal gangue resource utilization: a study on the humification process and microbial community dynamics in composting with different particle sizes of coal gangue. *Process Safety and Environmental Protection*, *202*, 107701. https://doi.org/10.1016/j.psep.2025.107701

Zhang, S., Jia, W., & Zhang, R. (2025). Polycyclic aromatic hydrocarbons in smoke condensates: A comprehensive review of formation mechanisms, migration pathways to food, and risk assessment. *Food Reviews International*, *41*(9), 3234-3253. https://doi.org/10.1080/87559129.2025.2550592