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Community-Based Pyrolysis Training and Technology Transfer for Sustainable Biomass Utilization in Metut Village

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ABSTRACT

Metut Village, Mentarang Hulu District, Malinau Regency, North Kalimantan, possesses abundant woody biomass residues that remain largely underutilized despite their potential economic and environmental value. Simultaneously, local communities face challenges related to low soil fertility and limited success in agarwood (Aquilaria spp.) seed germination. This community service program aimed to introduce pyrolysis technology for converting woody biomass into biochar and liquid smoke while strengthening local capacity through training and technology transfer. By converting biomass residues that were previously left unmanaged or openly burned into valuable products, the program directly contributes to more sustainable biomass waste management at the village level. The three-day program involved 25 participants, including farmers, agarwood cultivators, village officials, women engaged in agriculture, and village youth. Activities comprised educational workshops, practical demonstrations, hands-on training, and the donation of a portable pyrolysis unit. Program effectiveness was evaluated through pre-test and post-test assessments and observation of participants' practical performance. Results demonstrated a significant increase in knowledge, with average scores rising from 34.2% before training to 82.7% after training, reflecting a marked enhancement in community capacity to independently manage biomass resources. All participants successfully operated the pyrolysis unit during practical sessions. A demonstration run using 12 kg of dry woody branches yielded approximately 3.2 kg of biochar and 2.1 L of liquid smoke, both promising for improving soil fertility and supporting agarwood cultivation. The donated equipment and operational manual provide a practical, replicable foundation for continued community-led biochar and liquid smoke production, supporting the long-term sustainability of biomass utilization and value-added agricultural applications.

Keywords: Biochar; Biomass Utilization; Liquid Smoke; Pyrolysis Technology; Sustainable Rural Development.

INTRODUCTION

North Kalimantan is one of Indonesia's provinces with extensive tropical forest cover, providing abundant biomass resources and representing a significant source of renewable raw materials. Metut Village, located in Mentarang Hulu District, Malinau Regency, is a remote rural community surrounded by forest ecosystems that generate large quantities of woody biomass residues, particularly tree branches and twigs. Despite their abundance, these biomass resources remain largely unutilized. In most cases, the residues are left to decompose naturally or are disposed of through open burning, practices that provide no economic benefit to local communities while contributing to environmental pollution and greenhouse gas emissions. Most residents in Metut Village rely on shifting cultivation and the management of non-timber forest products (NTFPs) as their primary livelihoods. Among these products, agarwood (*Aquilaria malaccensis*) is one of the most valuable commodities due to its high demand and premium market value in both domestic and international markets (Kamarubahrin, 2025). However, the expansion of agarwood cultivation at the farmer level is constrained by the low germination rate of agarwood seeds, which limits seedling production and plantation establishment (Nath et al., 2023). Furthermore, agricultural lands in many interior regions of Kalimantan are characterized by acidic soils with low fertility, resulting in suboptimal crop productivity and reduced agricultural sustainability.

Pyrolysis technology offers a promising solution to address both challenges simultaneously. Pyrolysis is a thermochemical process that converts organic biomass into valuable products through thermal decomposition under limited or oxygen-free conditions (Hadiyane et al., 2026). Two major products generated from this process are biochar, a carbon-rich solid material, and liquid smoke, a condensate containing phenolic compounds, organic acids, and carbonyl compounds. Previous studies have demonstrated that biochar can improve the physical, chemical, and biological properties of acidic soils, thereby enhancing soil fertility and crop productivity (Kapoor et al., 2022). In addition, liquid smoke has shown potential as a natural biostimulant capable of improving seed germination and early seedling growth (Moyo et al., 2022; Sembada et al., 2024), including in forestry species such as agarwood. Despite the considerable potential of pyrolysis technology, a significant gap exists between scientific knowledge and its practical application in rural communities. In Metut Village, residents have limited awareness of biomass valorization technologies and lack access to appropriate equipment needed for converting biomass waste into value-added products. To date, community-scale pyrolysis technology transfer programs that integrate the production of biochar and liquid smoke with agarwood cultivation remain scarce, particularly in remote interior regions of Kalimantan where infrastructure, technical assistance, and market access are limited. As a result, the abundant biomass resources available in the village remain underutilized, while opportunities to improve agricultural productivity and support agarwood cultivation are largely unexplored. This knowledge gap and technology-access gap represent key barriers to the adoption of sustainable biomass management practices in the community.

The novelty of this community service program lies in its integrated design, which combines theoretical training, live demonstration, hands-on practice, and the direct donation of a portable pyrolysis unit within a single intervention. Beyond technology introduction, the program also establishes a concrete utilization plan in which the resulting biochar is intended for application as a soil amendment in general agricultural practices, while the liquid smoke is directed toward use as a germination stimulant in agarwood seed nurseries. This combination of capacity building, equipment transfer, and a clearly defined application pathway distinguishes the program from prior community service initiatives and represents one of the first attempts to link community-based pyrolysis technology with agarwood-based livelihoods in the interior regions of North Kalimantan.

To address these challenges, this community service program was designed to bridge the gap between research-based innovations and community implementation through an integrated approach combining education, hands-on training, and technology transfer. The program introduces pyrolysis technology to residents through extension activities and practical workshops while simultaneously providing a portable pyrolysis unit to support long-term application. By transforming locally available biomass waste into biochar and liquid smoke, the program promotes sustainable resource utilization, improves agricultural soil management, and supports agarwood seed propagation. Furthermore, the provision of equipment ensures that the acquired knowledge can be translated into continuous practice beyond the duration of the program, thereby enhancing the sustainability and long-term impact of the intervention. Therefore, this community service activity aims to: (1) increase community knowledge regarding pyrolysis technology and the benefits of its products; (2) develop local capacity to independently operate a portable pyrolysis system; (3) introduce the use of biochar as a soil amendment and liquid smoke as a germination stimulant for agarwood seeds; and (4) provide a portable pyrolysis unit to community groups in Metut Village to support sustainable biomass utilization and long-term local production.

METHOD

Study Site and Implementation Period

The community service program was conducted in Metut Village, Mentarang Hulu District, Malinau Regency, North Kalimantan, Indonesia, in April 2026. The activity was carried out over three consecutive days. Educational sessions were conducted in the village hall, while practical demonstrations and hands-on training were performed in an open area adjacent to the village hall to ensure adequate space and ventilation for pyrolysis operations. Metut Village is in a forest-dominated landscape characterized by abundant woody biomass residues originating from natural forest vegetation and agricultural activities. The selection of this location was based on the availability of unused biomass resources, the importance of agarwood cultivation as a local livelihood, and the limited access of local communities to biomass conversion technologies.

Participants

A total of 25 participants were involved in the program. Participants were selected through recommendations from the village head based on their active involvement in agricultural activities, agarwood cultivation, and their willingness to serve as local facilitators for the future implementation and dissemination of pyrolysis technology within the community. The demographic profile of participants is presented in Table 1. The participants represented various community groups, including field and plantation farmers (40%), agarwood cultivators (28%), housewives involved in agricultural activities (20%), village officials (8%), and village youth representatives (4%). This composition was intentionally designed to ensure that the knowledge and skills introduced through the program could reach different sectors of the community and support broader technology adoption.

Table 1. Profile of participants involved in the community service program in Metut Village.

No	Participant Group	Number of Participants	Percentage (%)
1	Field and plantation farmers	10	40
2	Agarwood cultivators	7	28
3	Housewives involved in agricultural activities	5	20
4	Village officials	2	8
5	Village youth representatives	1	4
	Total	25	100

Participants ranged in age from 20 to 55 years and possessed diverse educational backgrounds, ranging from elementary school to senior high school level. Prior to participation, all attendees were informed about the objectives of the activity and voluntarily agreed to participate in the educational, practical, and evaluation sessions. As shown in Table 1, farmers and agarwood cultivators constituted most participants (68%), reflecting the program's primary focus on improving agricultural productivity and supporting agarwood cultivation through the utilization of pyrolysis-derived products, namely biochar and liquid smoke. The inclusion of village officials and youth representatives was intended to strengthen institutional support and facilitate the long-term sustainability of the technology within the village.

Portable Pyrolysis Unit

One portable pyrolysis unit was provided to the community as part of the technology transfer component of the program. The unit was designed to convert locally available woody biomass into biochar and liquid smoke under oxygen-limited conditions. The technical specifications of the donated pyrolysis unit are presented in Table 2, while the overall configuration and main components of the unit are shown in Figure 1. The pyrolysis reactor was constructed from SS-304 stainless steel with a diameter of 45 cm and a height of 75 cm, allowing a feedstock capacity of approximately 15 kg dry biomass per batch. Heating was supplied by an LPG gas stove with an average fuel consumption of approximately 0.5 kg LPG per batch. Volatile compounds generated during pyrolysis were directed through a dual-stage water-cooled spiral condenser to facilitate condensation into liquid smoke.

Figure 1. Portable pyrolysis unit donated to the Metut Village community for biomass conversion. (A) Fully assembled portable pyrolysis system showing the reactor and condensation unit used for the production of biochar and liquid smoke from woody biomass; (B) interior view of the pyrolysis reactor/combustion chamber where biomass feedstock is loaded and thermally decomposed under oxygen-limited conditions; and (C) dual-stage water-cooled spiral condenser used to condense volatile pyrolysis gases into liquid smoke.

Figure 1 illustrates the physical configuration and main components of the portable pyrolysis unit used in the community service program. To provide a clearer technical understanding of the equipment, the detailed specifications of the reactor, heating system, condensation unit, operating conditions, expected product yield, and supporting components are presented in Table 2.

Table 2. Technical specifications of the portable pyrolysis unit donated to the community.

No	Specification	Description
1.	Feedstock capacity	15 kg per batch
2.	Reactor material	SS-304 stainless steel
3.	Reactor dimensions	45 cm diameter, 75 cm height
4.	Heating system	LPG gas stove (approximately 0.5 kg LPG per batch)
5.	Condensation system	Dual-stage water-cooled spiral condenser
6.	Operating temperature	300–500°C (regulated through gas valve)
7.	Processing time	60–90 min per batch
8.	Products generated	Biochar (solid) and grade-3 liquid smoke (liquid)
9.	Estimated biochar yield	25–30% of dry feedstock weight

10.	Estimated liquid smoke yield	2–3 L per batch
11.	Unit weight	Approximately 40 kg (portable)
12.	Supporting components	Reactor unit, condenser, connecting hoses, liquid smoke collection container, and written operational manual

The system operated at temperatures ranging from 300 to 500°C, regulated through the gas valve and monitored using a built-in temperature gauge. Each pyrolysis cycle required approximately 60–90 minutes depending on biomass moisture content and operating temperature (Aboelela et al., 2023). Under normal operating conditions, the unit produced approximately 25–30% biochar yield (dry weight basis) and 2–3 L of grade-3 liquid smoke per batch. The total weight of the unit was approximately 40 kg, enabling easy transportation and operation in remote rural areas. As shown in Table 2, the pyrolysis unit was specifically designed for community-scale biomass conversion, combining portability, relatively low fuel consumption, and the ability to produce two value-added products simultaneously. These characteristics make the technology suitable for adoption in rural areas with limited infrastructure and technical resources. The donated package included the reactor, condenser system, connecting hoses, liquid smoke collection container, and a written operational manual. The provision of both equipment and operational guidelines was intended to facilitate the continued use of the technology by the community after the completion of the community service program.

Community Engagement Approach and Educational Session

The program employed a participatory extension approach based on the principles of Participatory Rural Appraisal (PRA), which emphasizes active involvement of community members throughout the learning and technology adoption process (Krishnendu et al., 2025). The approach combined classroom-based education, live demonstrations, hands-on practical training, and technology transfer to maximize knowledge acquisition and practical skill development (Lai, 2024). This methodology was selected because participatory learning has been shown to improve technology adoption in rural communities by enabling participants to directly observe, practice, and evaluate new technologies under local conditions (Hidayat et al., 2025).

On the first day, participants attended an educational workshop designed to introduce the concepts and applications of biomass pyrolysis technology. Four major topics were covered: (1) availability of local biomass resources and environmental impacts of open biomass burning, (2) fundamental principles of pyrolysis technology and product formation mechanisms, (3) benefits of biochar for improving soil fertility, soil structure, nutrient retention, and agricultural productivity, and (4) potential applications of liquid smoke as a germination stimulant for agarwood seeds. The educational materials were delivered using presentations, visual illustrations, and interactive discussions. Before the educational session commenced, participants completed a pre-test questionnaire to assess their baseline knowledge regarding biomass utilization, pyrolysis technology, biochar, and liquid smoke.

Demonstration, Hands-On Training, Technology Transfer, and Equipment Handover

The second day focused on practical demonstrations and participant training. The demonstration was conducted using locally available dry woody branches collected from surrounding areas. The operational procedure included: (1) preparation and size reduction of dry biomass feedstock, (2) loading approximately 15 kg of biomass into the pyrolysis reactor, (3) ignition of the LPG heating system, (4) adjustment of reactor temperature within the range of 300–500°C, (5) observation of volatile gas production and condensation processes, (6) collection of condensed liquid smoke from the condenser outlet, and (7) cooling and harvesting of the resulting biochar. Following the demonstration, participants were divided into five groups consisting of five individuals per group. Each group independently operated the pyrolysis unit under supervision of the community service team. Particular attention was given to safe operation procedures, temperature control, product collection, and equipment maintenance. Additional demonstrations were conducted to illustrate the practical use of biochar as a soil amendment and the application of liquid smoke as a seed treatment agent for agarwood seed germination.

The third day was dedicated to strengthening community capacity and ensuring long-term sustainability of the technology. An open discussion session was conducted to address questions, clarify technical issues, and review key concepts learned during the previous sessions. A post-test evaluation was then administered to assess participant learning outcomes (Rumidatul et al., 2025). Subsequently, a formal handover ceremony was conducted, during which one portable pyrolysis unit and its operational manual were officially transferred to a designated community group. The handover was witnessed by village officials and all participants. To promote sustainable utilization, participants signed a written commitment to collectively manage and operate the equipment for biomass conversion activities following completion of the program.

Evaluation of Program Effectiveness

Program effectiveness was evaluated through both knowledge assessment and practical skill assessment (Alharbi et al., 2024). Knowledge improvement was measured using pre-test and post-test questionnaires consisting of 25 multiple-choice questions covering all educational topics presented during the program. The questionnaire was developed based on the educational materials delivered during the program and was reviewed by two subject-matter experts in biomass pyrolysis and agricultural extension to confirm content validity; minor wording revisions were made prior to administration to improve clarity for participants with varying educational backgrounds. The 25 questions were distributed across the six educational topics presented in Table 3, comprising four items each for the definition and principles of pyrolysis technology, types and characteristics of biomass feedstocks, pyrolysis products (biochar and liquid smoke), benefits of biochar as a soil amendment, and benefits of liquid smoke for agarwood seed germination, and five items for the operation of the portable pyrolysis unit. The questionnaire evaluated participant understanding of biomass management, pyrolysis principles, biochar applications, liquid smoke utilization, and operational aspects of the pyrolysis unit. Individual scores were calculated as the percentage of correct answers. Knowledge gain was determined by comparing pre-test and post-test scores for each participant and calculating the percentage increase in understanding both by topic and overall (Harerimana et al., 2023).

Descriptive statistics (mean and standard deviation) were calculated for pre-test and post-test scores, and the statistical significance of the knowledge gain was examined using a paired-sample t-test, with statistical significance set at $p < 0.05$. Practical competency was evaluated through direct observation during the hands-on training session. A standardized observation checklist was used to assess participants' ability to: (1) prepare biomass feedstock correctly, (2) load and operate the pyrolysis reactor safely, (3) monitor temperature and condensation processes, (4) harvest biochar and liquid smoke appropriately, and (5) conduct basic equipment maintenance procedures. Each of the five checklist items was scored using a three-point performance scale (0 = unable to perform, 1 = performed with guidance, 2 = performed independently), and observations were conducted simultaneously by two trained facilitators for each group to reduce subjectivity.

It should be noted that knowledge improvement was evaluated using a one-group pre-test post-test design without a comparison or control group. This design does not fully rule out alternative explanations for the observed score increase, such as a testing effect arising from repeated exposure to similar questions or maturation occurring naturally over the three-day program. This design was adopted because of the practical constraints of a single-village, short-duration community service activity, in which the formation of a separate control group was not feasible. Accordingly, the reported knowledge gains should be interpreted as indicative of program effectiveness rather than as definitive causal evidence, and future programs are encouraged to incorporate comparison groups or longer-term follow-up assessments where feasible.

RESULT

All 25 registered participants attended the program throughout the three days, with full participation maintained across the educational session, practical demonstration, hands-on training, and evaluation activities. The educational session conducted on the first day proceeded smoothly and was characterized by active participation and engagement from the attendees. Participants demonstrated considerable interest, particularly when the community service team explained that woody branch residues, which had traditionally been disposed of through open burning or left to decompose, could be converted into value-added products such as biochar and liquid smoke. Numerous questions were raised regarding the characteristics of high-quality biochar, the persistence of biochar in soil, and the appropriate concentration of liquid smoke for agarwood seed treatment. Particularly strong interest was observed among agarwood cultivators, who reported difficulties in obtaining sufficient healthy seedlings because of low seed germination rates.

On the second day, a practical demonstration was conducted. Participants were given the opportunity to observe the complete pyrolysis process using locally sourced woody branches that had been air-dried for approximately two days prior to the activity. The demonstration included feedstock preparation, reactor loading, ignition of the LPG heating system, temperature monitoring, observation of the condensation process, and harvesting of the resulting products. From a single demonstration batch containing approximately 12 kg of dry woody branches, approximately 3.2 kg of biochar and 2.1 L of liquid smoke were produced, corresponding to a biochar yield of approximately 26.7% on a dry-weight basis. The biochar exhibited a deep black coloration indicative of effective carbonization, while the liquid smoke displayed a yellowish-brown appearance and a characteristic smoky odor. The portable pyrolysis unit used during the training and subsequently donated to the community is shown in Figure 2. Following the demonstration, participants were divided into five groups, each consisting of five individuals, and were given the opportunity to operate the equipment under supervision. Observational assessment revealed that all participants successfully completed the operational procedures after receiving guidance. Feedstock preparation and biochar harvesting were the skills most rapidly mastered by participants, whereas temperature monitoring and management of the condensation system required additional explanation and practice. Importantly, no major safety issues occurred during the training session.

Pre-test and post-test assessments revealed substantial improvements across all educational topics. Among all 25 participants, the average score increased from 34.2% (SD = 8.64) before training to 82.7% (SD = 7.68) after training, representing an overall improvement of 48.5 percentage points. A paired-sample t-test confirmed that this increase was statistically significant, $t(24) = 25.716$, $p < 0.001$ (Table 3). The highest post-test score was recorded for the topic concerning the benefits of biochar as a soil amendment (85.6%), whereas the lowest post-test score was obtained for the operation of the portable pyrolysis unit (78.8%). The formal handover of the portable pyrolysis unit was conducted on the third day and attended by village officials and all participants. The equipment was transferred to a designated community group responsible for future operation and maintenance. Participants also received a written operational manual. Community representatives agreed to several commitments related to equipment utilization, maintenance, biochar application, liquid smoke utilization, and dissemination of acquired knowledge (Table 4).

Figure 2. Portable pyrolysis unit donated to the Metut Village community for biomass conversion.

Following the practical demonstration and technology handover, participant learning outcomes were evaluated quantitatively through pre-test and post-test assessments. The evaluation was conducted to determine the extent to which the educational session, practical demonstration, and hands-on training improved participants' understanding of pyrolysis technology, biomass feedstocks, biochar, liquid smoke, and the operation of the portable pyrolysis unit. The results of this assessment are summarized in Table 3.

Table 3. Pre-test and post-test evaluation results of participants.

No.	Educational Topic	Pre-test Mean ± SD (%)	Post-test Mean ± SD (%)	t(24)	p-value
1	Definition and principles of pyrolysis technology	30.4 ± 7.73	80.8 ± 8.34	24.585	<0.001
2	Types and characteristics of biomass feedstocks	36.0 ± 9.67	84.0 ± 8.93	22.535	<0.001
3	Pyrolysis products: biochar and liquid smoke	32.8 ± 9.00	83.2 ± 6.22	26.332	<0.001
4	Operation of the portable pyrolysis unit	28.4 ± 9.00	78.8 ± 8.04	21.520	<0.001
5	Benefits of biochar as a soil amendment	38.4 ± 8.64	85.6 ± 6.20	24.456	<0.001
6	Benefits of liquid smoke for agarwood seed germination	39.2 ± 10.23	83.6 ± 6.64	21.532	<0.001
	Overall (n = 25)	**34.2 ± 8.64**	**82.7 ± 7.68**	**25.716**	**<0.001**

The improvement in participants' knowledge and practical skills indicates that the training successfully strengthened their initial capacity to understand and operate the pyrolysis technology. However, the sustainability of the program depends on how the acquired knowledge, skills, and donated equipment are used after the completion of the training. Therefore, community commitments were established to encourage continuous operation of the pyrolysis unit, regular production of biochar and liquid smoke, application of the products in agricultural and agarwood-related activities, and dissemination of knowledge to other village residents. These commitments are presented in Table 4.

Table 4. Community commitments following the community service program.

No	Specification	Description
1.	Operate the pyrolysis unit at least twice per month on a rotating basis among group members	Regular production of biochar and liquid smoke for agriculture and agarwood nurseries
2.	Maintain and protect the donated equipment	Functional operation for at least three years
3.	Apply produced biochar to agricultural land	Improved soil quality during subsequent growing seasons
4.	Use liquid smoke for agarwood seed soaking prior to sowing	Increased agarwood seed germination rates
5.	Disseminate pyrolysis knowledge to other village residents	At least 10 additional residents trained within six months

DISCUSSION

The positive response observed during the educational session indicates that biomass valorization is highly relevant to the socio-economic conditions of Metut Village. The active participation and numerous questions raised by participants suggest that the technology addressed existing challenges associated with agricultural productivity, waste management, and agarwood cultivation. The particularly strong interest shown by agarwood cultivators, who reported persistent difficulties in obtaining sufficient healthy seedlings, suggests that the prospect of a locally produced germination-enhancing material was perceived as directly relevant to a long-standing production constraint, which likely reinforced community motivation to engage with and adopt the technology. Similar observations were reported by Kangana et al. (2024), who found that community engagement increases substantially when educational interventions directly address locally perceived needs. Likewise, Alabdali et al. (2023) reported that rural communities are more likely to adopt new technologies when the benefits are clearly linked to livelihood improvement.

The biochar yield obtained during the demonstration (26.7%) falls within the typical range reported for woody biomass pyrolysis under moderate-temperature conditions. Previous studies have shown that lignocellulosic feedstocks generally produce biochar yields between 20% and 35%, depending on feedstock characteristics and operating conditions. Similarly, the deep black coloration observed in the resulting biochar is indicative of effective carbonization, consistent with the elevated reactor temperatures recorded during the demonstration. The observed yield therefore demonstrates that the portable pyrolysis unit functioned effectively under field conditions and produced outputs comparable to those reported in controlled experimental studies. The ability of all participants to successfully operate the reactor also highlights the appropriateness of the technology for rural applications. Similar findings were reported by Hadiyane et al. (2025), who concluded that user-friendly portable pyrolysis systems can be effectively adopted by local communities after relatively short training periods.

The substantial increase in participant knowledge demonstrates the effectiveness of combining lectures, demonstrations, and hands-on practice. The relatively low pre-test scores indicate that pyrolysis technology was largely unfamiliar to the community before the intervention. Following the training, all educational topics showed marked improvement. The highest post-test score was associated with the benefits of biochar as a soil amendment. This outcome may reflect the immediate relevance of soil fertility issues to participants' agricultural activities. In contrast, the slightly lower score for reactor operation likely reflects the greater complexity of remembering technical procedures. Nevertheless, practical observations confirmed that all participants were able to operate the equipment correctly. These findings support previous educational research demonstrating that experiential learning approaches enhance knowledge retention and technology adoption more effectively than lecture-based instruction alone (Liu et al., 2024).

The potential benefits of biochar and liquid smoke provide strong justification for continued technology adoption. Biochar has been widely reported to improve acidic tropical soils by increasing pH, enhancing cation exchange capacity, improving water-holding capacity, and stimulating beneficial microbial activity (Santos et al., 2022; Zubairu et al., 2023). These characteristics are particularly relevant to agricultural conditions in inland Kalimantan. For agarwood cultivation, liquid smoke represents a promising biostimulant for seed germination. The presence of phenolic compounds, organic acids, and carbonyl compounds may enhance metabolic activation and water uptake during germination (Yuniati et al., 2026). Previous studies have similarly reported improvements in seed germination and seedling vigor following treatment with biomass-derived liquid smoke (Khatoon et al., 2025). Given the high economic value of agarwood species in North Kalimantan, even modest improvements in seedling production could generate significant economic benefits for local communities.

The long-term success of community-based technology transfer depends not only on knowledge acquisition but also on sustained implementation. The formal handover of the pyrolysis unit, provision of operational manuals, and development of community commitments are therefore important indicators of sustainability. O'Hara et al. (2023) emphasized that continued utilization is a critical determinant of impact in community technology-transfer programs. Furthermore, Kalaluka (2022) highlighted the importance of community participation in post-project planning as a mechanism for strengthening ownership and long-term adoption. The planned follow-up monitoring activities will provide opportunities to evaluate implementation progress and address potential operational challenges.

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To ensure the sustainability of the technology transfer, follow-up monitoring should be conducted using clear and measurable indicators. These indicators may include the frequency of pyrolysis unit operation per month, the quantity of biochar produced, the volume of liquid smoke generated, the area of agricultural land treated with biochar, the number of agarwood seeds treated with liquid smoke, and the number of additional community members trained by the initial participants. Monitoring should also assess equipment condition, fuel availability, maintenance practices, and the consistency of group-based management. By using these indicators, the community service team and village stakeholders can evaluate whether the donated pyrolysis unit continues to be used effectively and whether the program generates sustained benefits for biomass waste management, agricultural productivity, and agarwood seedling development in Metut Village.

CONCLUSION

This community service program successfully introduced pyrolysis technology in Metut Village, North Kalimantan, engaging 25 participants from farming, agarwood cultivation, and village administration backgrounds through educational sessions, demonstrations, hands-on training, and the donation of a portable pyrolysis unit. Participant knowledge increased substantially, with average scores rising from 34.2% to 82.7%, and all participants were able to operate the unit independently, producing biochar and liquid smoke from locally available woody biomass. The handover of the equipment, accompanied by an operational manual and community commitments for continued use, provides a practical foundation for the community-led, sustainable utilization of local biomass resources in support of agriculture and agarwood cultivation.

It should be noted, however, that this evaluation reflects only the program's immediate outcomes; long-term monitoring of equipment utilization, the impact of biochar application on soil quality, and the effectiveness of liquid smoke for agarwood seed germination has not yet been conducted and remains an important direction for follow-up activities, alongside wider dissemination of the technology to neighboring communities. Overall, the program demonstrates that community-based pyrolysis technology transfer is an effective approach for strengthening local capacity, supporting sustainable biomass management, and generating value-added products from forest biomass residues in remote rural areas.

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