

Implementation of Biochar-Supported Fish Smoking Technology as A Green Technology Model for Sustainable Coastal Community Economy

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ABSTRACT

Background: Traditional fish smoking practices in coastal communities still rely heavily on firewood and conventional smoking systems, resulting in excessive smoke emissions, inefficient fuel consumption, and environmental pollution. This community service program introduced biochar-supported fish smoking technology as a green technology innovation to strengthen sustainable coastal community economies.

Contribution: This program contributes an integrative and replicable community empowerment model that combines biochar-based green technology, entrepreneurship strengthening, and digital marketing transformation within cross-country coastal communities.

Methods: The program was implemented in Bintang Meriah Village, Langkat Regency, North Sumatra, Indonesia, and Kuala Kedah, Malaysia, involving 28 participants from fish-smoking SMEs and coastal community groups. Activities were conducted through socialization, training, technology application, and mentoring.

Results: The implementation of biochar-supported fish smoking technology reduced firewood consumption by approximately 26%, decreased smoke emissions by around 30%, and improved production efficiency by approximately 24%. Approximately 68% of participants successfully adopted digital marketing platforms for product promotion and business expansion.

Conclusion: The integration of biochar-supported fish smoking technology and community empowerment successfully improved environmental sustainability, production efficiency, and local economic resilience.

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1. Introduction

Environmental sustainability and economic resilience have become critical issues for rural and coastal communities that depend heavily on natural resources for their livelihoods. One sector that continues to face environmental and economic challenges is the traditional fish smoking industry, which remains widely practiced in many coastal areas of Southeast Asia [1], [2]. Conventional fish smoking systems generally rely on firewood as the primary fuel source and use traditional smoking chambers with limited temperature control. These practices often result in excessive smoke emissions, unstable product quality, and inefficient fuel consumption, contributing to environmental pollution and unsustainable production processes [3]. The coastal communities in Bintang Meriah Village, Langkat Regency, North Sumatra, Indonesia, and Kuala Kedah, Malaysia, rely significantly on fish smoking activities as an important source of household income. However, most fish-smoking small and medium enterprises (SMEs) in these regions still use traditional smoking technology that contributes to environmental degradation due to intensive firewood usage and uncontrolled smoke emissions.

In addition, these small-scale enterprises frequently face challenges related to technology adoption, entrepreneurship capacity, financial management, and product competitiveness in wider markets [4], [5]. Previous traditional fish smoking programs have mainly focused on improving production efficiency and product quality. However, limited community service studies have integrated environmentally friendly biochar technology with entrepreneurship strengthening and digital market transformation in coastal communities. Therefore, this program introduces an integrative approach by combining biochar-supported fish smoking technology, entrepreneurship education, and digital marketing training to support sustainable coastal community economies and environmental conservation [6], [7]. To address these issues, a community service program was conducted by Universitas Muslim Nusantara Al Washliyah in collaboration with Universiti Teknologi MARA Cawangan Kelantan.

This program introduced green technology through the implementation of a biochar-supported fish smoking system integrated with entrepreneurship strengthening and digital marketing education. Biochar produced from agricultural waste such as banana peels was utilized as an alternative fuel capable of producing cleaner combustion and reducing environmental pollution [8]. [9] The program also aimed to improve the business management capacity and market competitiveness of local fish-smoking small and medium enterprises (SMEs). The biochar-supported fish smoking system used in this program is presented in [Figure 1](#).

The focus of this community service activity aligns with the thematic areas of environmental sustainability and community empowerment through the implementation of green technology and circular economy approaches. Recent studies have highlighted that integrating renewable energy innovation, community participation, and sustainable fisheries management can strengthen coastal economic resilience and environmental conservation [10], [11]. In addition, the activity supports the implementation of the Merdeka Belajar Kampus

Merdeka (MBKM) program by involving students directly in community-based learning activities. Through this program, students gain practical experience while contributing to solving really environmental and socio-economic problems faced by local communities [12], [13]. The implementation of this program is expected to improve fish smoking production efficiency, reduce environmental impacts, and strengthen the economic capacity of coastal communities.

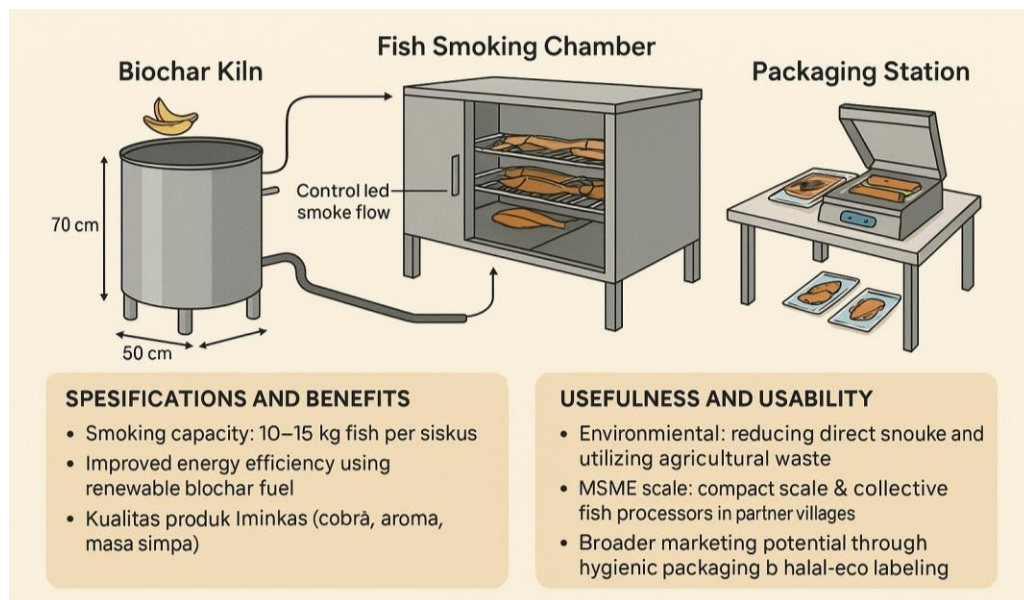


Figure 1. Biochar-Supported fish smoking system

The novelty of this program lies in the integration of biochar-supported fish smoking technology with entrepreneurship strengthening and digital marketing transformation within cross-country coastal communities [14], [15]. Furthermore, the integration of green technology and community empowerment is expected to create a sustainable and replicable model for environmental-based economic development in other coastal regions [16], [17].

2. Method

The implementation methods employed in this community service program consisted of several integrated stages designed to support the adoption of biochar-supported fish smoking technology, entrepreneurship strengthening, and digital marketing transformation within coastal communities.

2.1. Participants and Location

This community service program involved 28 participants from two coastal communities located in Bintang Meriah Village, Langkat Regency, North Sumatra, Indonesia, and Kuala Kedah, Malaysia. The participants consisted of 20 fish-smoking small and medium enterprises (SMEs), 8 representatives from women’s community groups, 6 youth organization members, and 6 local community representatives involved in fisheries and fish processing activities. The participants were selected purposively based on their active involvement in traditional fish

smoking activities and their willingness to participate in the implementation of environmentally friendly technology and entrepreneurship training programs. Most participants had previously relied on conventional fish smoking systems using firewood as the primary fuel source. The community service program was implemented collaboratively by Universitas Muslim Nusantara Al Washliyah and Universiti Teknologi MARA Cawangan Kelantan from January to March 2026. The implementation activities included socialization, training, technology application, mentoring, and evaluation related to biochar-supported fish smoking systems, entrepreneurship strengthening, and digital marketing transformation [18], [19]. In addition to community participants, several university students were also involved in assisting training activities, technology demonstrations, documentation, and community mentoring as part of the Merdeka Belajar Kampus Merdeka (MBKM) program.

2.2. Data Collection Techniques

Several data collection techniques were employed in this community service program, including direct observation, semi-structured interviews, questionnaires, documentation, and pre-test-post-test evaluations. Direct observations were conducted before and after the implementation of the program to identify traditional fish smoking practices, fuel consumption patterns, environmental conditions, and the adoption process of biochar-supported fish smoking technology within coastal communities [20], [21]. Semi-structured interviews were carried out with fish-smoking small and medium enterprises (SMEs), community leaders, women's groups, and youth organization representatives to explore challenges related to traditional fish smoking systems, entrepreneurship capacity, environmental sustainability, and market competitiveness.

The interviews also aimed to identify participant responses toward the implementation of green technology and digital marketing training. Questionnaires were distributed to participants to assess their knowledge, perceptions, and satisfaction regarding biochar technology, entrepreneurship education, and digital marketing transformation [22], [23]. Pre-test and post-test instruments were used to measure participants' knowledge improvement before and after training activities. Documentation activities included photographs, activity records, fuel consumption data, participant attendance lists, and records of technology implementation during the program. These data were used to support evaluation and monitoring processes throughout the implementation of the community service activities.

2.3. Program Implementation

The implementation of this community service program was carried out through several systematic stages to address the environmental and economic challenges faced by traditional fish-smoking communities. The stages include socialization, training, application of technology, supplementation and evaluation, continuity and sustainability, and partner participation. These stages were designed to ensure effective technology transfer and community empowerment through the adoption of green technology.



Figure 2. Implementation

Socialization. The implementation process began with a structured socialization phase to ensure clear understanding, commitment, and readiness from all stakeholders, particularly partner communities in Bintang Meriah Village, Langkat Regency, Indonesia, and Kuala Kedah, Malaysia. This stage included initial community meetings facilitated by both the Indonesian and Malaysian teams to introduce the objectives, benefits, and responsibilities of the program. Stakeholder mapping was also conducted to identify local leaders, women’s groups, youth organizations, and fish-smoking SMEs that would be directly involved in the activities. In addition, this phase aimed to confirm the priority problems faced by the community and gather commitments through cooperation agreements and joint activity planning.



Figure 2. International Socialization and community service activities conducted by Universitas Muslim Nusantara Al Washliyah and Universiti Teknologi MARA Cawangan Kelantan

Figure 2 presents the socialization and international collaborative community service activities conducted by Universitas Muslim Nusantara Al Washliyah and Universiti Teknologi MARA Cawangan Kelantan. The activities involved academic discussions, community engagement sessions, field visits, and collaborative meetings with local partners and coastal communities. These activities aimed to strengthen international collaboration, introduce environmentally friendly fish smoking technology, and support community empowerment through entrepreneurship and sustainable coastal economic development [24], [25].

Training. The training phase focused on improving community capacity in both technological innovation and business management. Training activities were organized into several modules. First, participants were trained in biochar production by utilizing agricultural waste such as banana peels through simple pyrolysis techniques using portable kilns. Participants were also introduced to safety procedures and proper temperature control during the biochar production process.

Second, training was conducted on the operation of biochar-based fish smoking technology. Participants were guided on how to operate the modified smoking chamber, regulate heat and smoke flow, and maintain hygiene standards during fish processing. Third, entrepreneurship and business management training were provided to improve participants' knowledge of cost calculation, pricing strategies, simple bookkeeping, and revenue tracking.

Fourth, digital marketing and packaging innovation training was conducted to introduce participants to the use of smartphones and online platforms such as WhatsApp Business and Facebook Marketplace. Participants were also introduced to branding strategies and eco-friendly packaging to improve product attractiveness and market competitiveness. Training activities were carried out through participatory workshops, video tutorials, augmented reality-based instructional modules, and printed handbooks to facilitate community learning.

Application of Technology. After the training stage, the program continued with the implementation of biochar-supported fish smoking systems within the partner communities. This stage included the deployment of portable biochar kilns and the construction of semi-enclosed fish smoking chambers adapted to local conditions. Six portable biochar kilns were distributed and co-built with community members, with each unit serving one to two households. In addition, four smoking chambers were installed to support fish smoking activities. Trial runs were conducted to evaluate fuel consumption efficiency and smoke quality. Adjustments were made based on community feedback and operational observations.

Supplementation and Evaluation. To support the implementation of the technology, additional materials and tools were provided to community members. These included protective equipment such as gloves, masks, and thermometers, as well as marketing support materials such as product labels and packaging designs. Evaluation activities were conducted to assess the effectiveness of the training and technology adoption. Monitoring was carried out through observation of production processes, documentation of fuel consumption, and discussions with community members regarding the challenges and benefits experienced during the implementation.

Continuity and Sustainability. To ensure the sustainability of the program, several follow-up strategies were implemented. Selected community members were trained to become local facilitators who could continue disseminating knowledge and supporting the adoption of biochar technology within their communities.

In addition, the program encouraged the formation of a community-based group called the "Smoked Fish Eco-Cooperative," which aims to manage shared equipment, develop product branding, and promote fish products through digital platforms. Training materials

and instructional resources were also made accessible through digital platforms to support continuous learning. Partner Participation. Community participation played an essential role in the success of this program. Community members were actively involved in designing and constructing biochar kilns and smoking chambers, participating in training sessions, and providing feedback during the implementation process. The community also contributed as hosts for field activities, demonstration sessions, and knowledge-sharing discussions. Through this participatory approach, the program was able to strengthen collaboration between universities and local communities while encouraging community ownership of the technology introduced.

2.4. Evaluation Instruments

The success of the community service program was evaluated using several instruments, including observation sheets, questionnaires, interview guidelines, and pre-test–post-test evaluation forms. These instruments were used to measure the effectiveness of biochar-supported fish smoking technology implementation, entrepreneurship strengthening, and digital marketing training within coastal communities. Several success indicators were used in this program, including [26], [27]. Technology adoption rate, measured by the number of households and fish-smoking small and medium enterprises (SMEs) implementing biochar-supported fish smoking systems after the training activities. Knowledge score improvement, measured through comparisons between pre-test and post-test results related to biochar technology, entrepreneurship, and digital marketing understanding. Reduction of fuel consumption, measured by comparing firewood usage before and after the implementation of biochar-supported fish smoking technology. Reduction of smoke emissions during fish smoking activities, evaluated through direct observation and participant feedback. Participant satisfaction and participation level during training, mentoring, and technology application activities [28], [29]. The collected data were used to assess the environmental, economic, and educational impacts of the program implementation within the participating coastal communities.

2.5. Analysis Techniques

The data collected in this community service program were analyzed using both quantitative and qualitative approaches. Quantitative data obtained from questionnaires and pre-test–post-test evaluations were analyzed descriptively using percentages and comparative analysis to measure participant knowledge improvement, technology adoption rates, reduction of fuel consumption, and participant satisfaction levels. Qualitative data collected through observations, semi-structured interviews, documentation, and focus group discussions were analyzed using thematic analysis. This analysis aimed to identify participant responses, implementation challenges, environmental impacts, and sustainability opportunities related to the adoption of biochar-supported fish smoking technology within coastal communities [30][28]. The analysis results were used to evaluate the effectiveness of the program implementation and to assess the environmental, economic, and educational impacts of the community service activities.

3. Results and Discussion

The implementation of biochar-supported fish smoking technology produced positive environmental and economic impacts within coastal communities in Bintang Meriah Village, Indonesia, and Kuala Kedah, Malaysia. A total of 28 households and fish-smoking small and medium enterprises (SMEs) successfully adopted the biochar-supported fish smoking system after participating in the training and mentoring activities [31]. The implementation results showed that the use of biochar reduced firewood consumption by approximately 26% compared to conventional fish smoking methods [9]. In addition, smoke emissions during fish smoking activities decreased by around 30%, contributing to improved environmental conditions and cleaner production processes within the surrounding communities, as shown in [Figure 3](#).

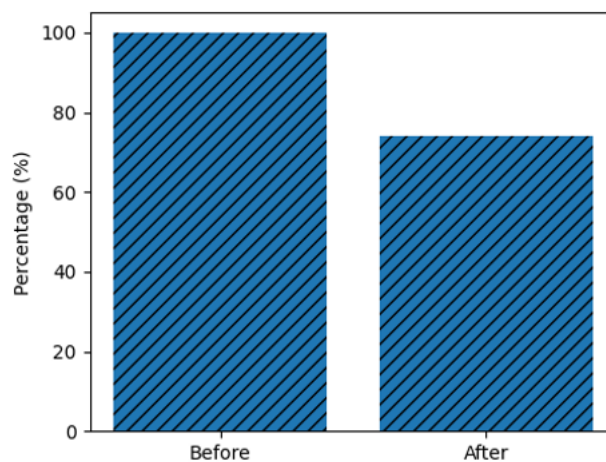


Figure 3. Reduction of firewood consumption before and after Biochar technology implementation

The use of biochar technology also improved production efficiency and product quality. Participants reported more stable heat distribution during the smoking process, resulting in better smoked fish color consistency, aroma, and durability. Monitoring activities indicated that production efficiency increased by approximately 24% after the implementation of biochar-supported fish smoking systems. These findings are consistent with previous Environmental Engineering studies showing that biochar technology improves thermal efficiency and reduces smoke emissions in small-scale food processing industries. Previous studies also reported that biochar utilization contributes to renewable energy development and environmentally sustainable fisheries practices.

3.1. Strengthening Community Capacity through Entrepreneurship Training

Entrepreneurship and digital marketing training activities also produced noticeable improvements in participant knowledge and business management capacity. Based on pre-test and post-test evaluations, participants' knowledge scores increased by approximately 36% after the training activities as shown in [Figure 4](#).

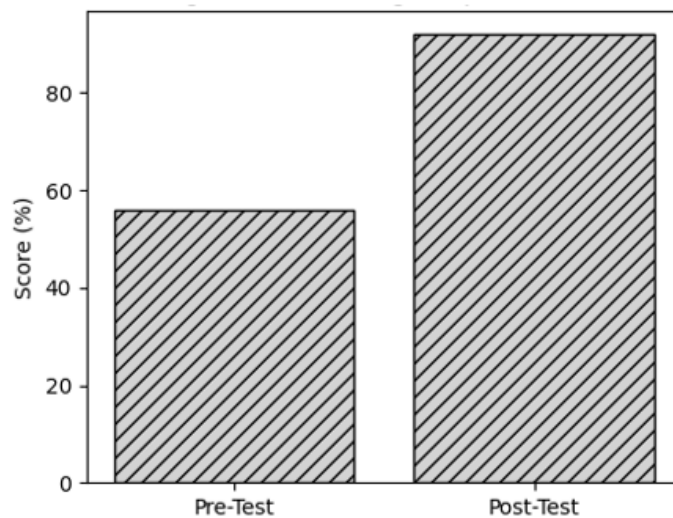


Figure 4. Participants' knowledge improvement based on Pre-test and Post-test results

Participants demonstrated improved understanding of cost calculation, simple bookkeeping, pricing strategies, product branding, and online marketing practices. Approximately 68% of participants successfully utilized digital platforms such as WhatsApp Business and Facebook Marketplace to promote smoked fish products after the training program [26], [32], [33]. In addition, several participants reported increased customer engagement and broader market reach after implementing digital marketing strategies introduced during the training activities [8], [34], [35]. The integration of green technology with entrepreneurship strengthening and digital marketing transformation represents one of the main novelties of this community service program. These findings support previous community empowerment studies emphasizing that digital entrepreneurship and technology adoption can strengthen the competitiveness and sustainability of coastal small and medium enterprises (SMEs).

3.2. Environmental and Economic Impact of Biochar Technology

The environmental and economic impacts of the program were positively perceived by participating coastal communities. The reduction in firewood consumption contributed to lower operational costs and reduced dependency on forest-based fuel resources. In addition, the implementation of biochar-supported fish smoking technology improved product quality, resulting in better smoked fish color consistency, aroma, and product durability. Several participants also reported increased customer interest and broader market reach after applying digital marketing strategies introduced during the training activities. Monitoring results indicated that approximately 72% of participants successfully adopted biochar-supported fish smoking technology in their daily production activities as shown in Figure 5.

Participant satisfaction questionnaires showed that approximately 86% of participants responded positively toward the training, mentoring, and technology implementation activities. Participants stated that the program improved their understanding of

environmentally friendly production systems, entrepreneurship management, and online marketing practices [36], [37]. Overall, the findings demonstrate that the integration of biochar-supported green technology, entrepreneurship strengthening, and community empowerment can create a sustainable and replicable model for environmental-based coastal economic development [18], [38].

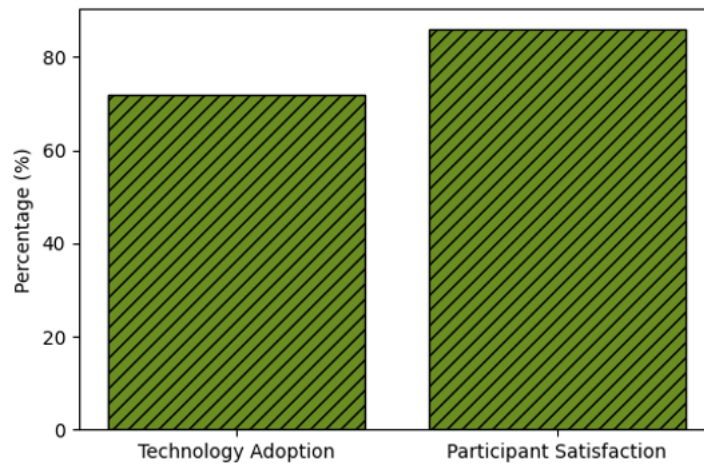


Figure 5. Technology adoption rate and participant satisfaction

4. Conclusion

The implementation of biochar-supported fish smoking technology successfully improved environmental sustainability, production efficiency, and entrepreneurship capacity within coastal communities in Bintang Meriah Village, Indonesia, and Kuala Kedah, Malaysia. The integration of green technology, entrepreneurship strengthening, and digital marketing transformation contributed positively to reducing firewood consumption, improving product quality, and strengthening community economic resilience. Overall, this program demonstrates that community-based green technology can support sustainable coastal economic development and environmental conservation. Future community service programs should focus on expanding commercialization opportunities, strengthening digital market access, and conducting long-term environmental impact assessments to ensure program sustainability.

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References

- [1] C.-T. Pan and S.-J. Hsu, "Effects of a One-day Environmental Education Program on Sixth-Graders' Environmental Literacy at a Nature Center in Eastern Taiwan," *Sustainability*, vol. 12, no. 12, p. 5043, Jun. 2020, <https://doi.org/10.3390/su12125043>
- [2] S. P. Sohi, E. Krull, E. Lopez-Capel, and R. Bol, "A Review of Biochar and Its Use and Function in Soil," 2010, pp. 47–82. [https://doi.org/10.1016/S0065-2113\(10\)05002-9](https://doi.org/10.1016/S0065-2113(10)05002-9)
- [3] A. Yüksel, M. Arıcı, M. Krajčík, M. Civan, and H. Karabay, "Energy consumption, thermal comfort, and indoor air quality in mosques: Impact of Covid-19 measures," *J. Clean. Prod.*, vol. 354, p. 131726, Jun. 2022, <https://doi.org/10.1016/j.jclepro.2022.131726>
- [4] W. Qiao, "Performance of Cu-Ce / M-Al (M = Mg, Ni, Co, Zn) hydrotalcite derived catalysts for hydrogen production from methanol steam reforming," *Int. J. Energy Res.*, vol. 45, no. 9, pp. 12773–12783, Jul. 2021, <https://doi.org/10.1002/er.6610>
- [5] P. Lacy, J. Long, and W. Spindler, *The Circular Economy Handbook*. London: Palgrave Macmillan UK, 2020.
- [6] J. Lehmann and S. Joseph, Eds., *Biochar for Environmental Management*. Routledge, 2015.
- [7] W. D. N. M. S. Tennakoon, M. P. N. Janadari, and I. D. Wattuhewa, "Environmental sustainability practices: A systematic literature review," *Eur. J. Sustain. Dev. Res.*, vol. 8, no. 3, p. em0259, Jul. 2024, <https://doi.org/10.29333/ejosdr/14604>
- [8] B. R. Moharana, B. C. Behera, and K. Muduli, *Digital Technology Enabled Circular Economy*. New York: CRC Press, 2024.
- [9] A. Patro, S. Dwivedi, A. Thakur, P. K. Sahoo, and J. K. Biswas, "Recent approaches and advancement in biochar-based environmental sustainability: Is biochar fulfilling the sustainable development goals?," *iScience*, vol. 27, no. 9, p. 110812, Sep. 2024, <https://doi.org/10.1016/j.isci.2024.110812>
- [10] M. Afshar and S. Mofatteh, "Biochar for a sustainable future: Environmentally friendly production and diverse applications," *Results Eng.*, vol. 23, p. 102433, Sep. 2024, <https://doi.org/10.1016/j.rineng.2024.102433>
- [11] A. B. Duwiewuah, Z. Mutawakil, and E. O. Oyelude, "Eco-friendly banana peel biochar for adsorption of toxic metals from landfill treatment pond leachate," *Int. J. Phytoremediation*, vol. 27, no. 5, pp. 596–605, Apr. 2025, <https://doi.org/10.1080/15226514.2024.2428434>
- [12] S. Suryanto, "The potential contribution of Indonesian fishing vessels in reducing Green House gas emission," *Aquac. Fish.*, vol. 10, no. 3, pp. 372–381, May 2025, <https://doi.org/10.1016/j.aaf.2024.08.002>
- [13] P. Warner, C. Kerry, A. Nuno, N. A. Miller, M. Rickwood, and K. Metcalfe, "A synthesis of research into marine small-scale fishers' operational behaviour," *Mar. Policy*, vol. 179, p. 106740, Sep. 2025, <https://doi.org/10.1016/j.marpol.2025.106740>
- [14] M. Rizwan, "Sustainable manufacture and application of biochar to improve soil properties and remediate soil contaminated with organic impurities: a systematic review," *Front. Environ. Sci.*, vol. 11, Nov. 2023, <https://doi.org/10.3389/fenvs.2023.1277240>

- [15] N. Rai, A. Kachore, J. M. Julka, and S. P. Das, "Biochar-based technologies for sustainable aquaculture: A review of synthesis, properties, and application in water quality improvement and nutrient management," *J. Water Process Eng.*, vol. 71, p. 107338, Mar. 2025, <https://doi.org/10.1016/j.jwpe.2025.107338>
- [16] O. Olagoke-Komolafe and J. Oyeboade, "Circular Economy in Fisheries: Transforming Aquatic Waste into Sustainable Resources for Agricultural and Industrial Use," *Int. J. Multidiscip. Futur. Dev.*, vol. 6, no. 2, pp. 45–58, 2025, <https://doi.org/10.54660/IJMFD.2025.6.2.45-58>
- [17] S. Akbar, R. P. Putra, I. M. N. Saragih, and N. Ranasti, "Circular economy transition through community-based ecopreneurship empowerment model: Reconstructing the environmental care community," *EcoProfit Sustain. Environ. Bus.*, vol. 3, no. 1, pp. 51–70, Jul. 2025, <https://doi.org/10.61511/ecoprofit.v3i1.2025.2152>
- [18] M. M. H. Mozumder and P. Schneider, "Advancing sustainability through the circular economy in small-scale fisheries: A global review of practices, challenges, and policy innovations," *Mar. Policy*, vol. 185, p. 107001, Mar. 2026, <https://doi.org/10.1016/j.marpol.2025.107001>
- [19] S. A. Siddiqui, S. Singh, N. A. Bahmid, and A. Sasidharan, "Applying innovative technological interventions in the preservation and packaging of fresh seafood products to minimize spoilage - A systematic review and meta-analysis," *Heliyon*, vol. 10, no. 8, p. e29066, Apr. 2024, <https://doi.org/10.1016/j.heliyon.2024.e29066>
- [20] A. Hassoun, "Use of industry 4.0 technologies to reduce and valorize seafood waste and by-products: A narrative review on current knowledge," *Curr. Res. Food Sci.*, vol. 6, p. 100505, 2023, <https://doi.org/10.1016/j.crfs.2023.100505>
- [21] A. Salim, H. Saediman, and Y. Yusnaini, "Profitability of Vannamei Shrimp Farming: Traditional vs. Intensive Systems in Kolaka District in Indonesia," *J. Glob. Innov. Agric. Sci.*, pp. 597–606, Apr. 2025, <https://doi.org/10.22194/JGIAS/25.1595>
- [22] D. Sarkity, A. Fernando, Y. Pratama, and B. Irawan, "Global warming's effects on marine and coastal environments: Students' knowledge, attitudes, and environmental behaviour," *J. Environ. Sustain. Educ.*, vol. 3, no. 2, pp. 250–261, Jun. 2025, <https://doi.org/10.62672/joease.v3i2.81>
- [23] I. Hossain, A. K. M. M. Haque, and A. Al Masud, "Mapping urban nature-based solutions and environmental sustainability in South Asia: A social–ecological–technological systems perspective on research trends, governance gaps and policy pathways," *Nature-Based Solut.*, vol. 9, p. 100326, Jun. 2026, <https://doi.org/10.1016/j.nbsj.2026.100326>
- [24] S. B. Kurniawan, "Tackling marine pollution in the blue economy: Synergies between wastewater treatment technologies and governmental policies," *Mar. Pollut. Bull.*, vol. 222, p. 118627, Jan. 2026, <https://doi.org/10.1016/j.marpolbul.2025.118627>
- [25] N. M. Suki, N. M. Suki, A. Sharif, S. Afshan, and K. Jernsittiparsert, "The role of technology innovation and renewable energy in reducing environmental degradation in Malaysia: A step towards sustainable environment," *Renew. Energy*, vol. 182, pp. 245–253, Jan. 2022, <https://doi.org/10.1016/j.renene.2021.10.007>

- [26] J. Paul, I. Alhassan, N. Binsaif, and P. Singh, "Digital entrepreneurship research: A systematic review," *J. Bus. Res.*, vol. 156, p. 113507, Feb. 2023, <https://doi.org/10.1016/j.jbusres.2022.113507>
- [27] Y. Yu, Z. Wang, Q. Chen, and Q. Chen, "Innovative Approaches to Waste Management in Circular Economy: Technological Advancements and Policy Implications," *J. Fintech Bus. Anal.*, vol. 2, no. 1, pp. 11–15, Feb. 2025, <https://doi.org/10.54254/3049-5768/2025.20858>
- [28] M. Al-Emran and C. Griffy-Brown, "The role of technology adoption in sustainable development: Overview, opportunities, challenges, and future research agendas," *Technol. Soc.*, vol. 73, p. 102240, May 2023, <https://doi.org/10.1016/j.techsoc.2023.102240>
- [29] A. F. Rahman, "Community-Based Approaches to Environmental Sustainability: A Social Science Review," *Int. J. Soc. Sci. Appl. Technol.*, vol. 1, no. 1, pp. 12–21, Sep. 2025, <https://doi.org/10.64391/ijssat.v1i1.002>
- [30] S. S. Saraugi, F. Asare, R. Gazo, and W. Routray, "Advances in sustainable production of biochar and biochar-based nanocomposites: A critical review," *J. Clean. Prod.*, vol. 514, p. 145752, Jul. 2025, <https://doi.org/10.1016/j.jclepro.2025.145752>
- [31] M. Keiluweit, P. S. Nico, M. G. Johnson, and M. Kleber, "Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)," *Environ. Sci. Technol.*, vol. 44, no. 4, pp. 1247–1253, Feb. 2010, <https://doi.org/10.1021/es9031419>
- [32] M. Faishal, E. Mohamad, E. Utami, O. Adiyanto, H. M. Asih, and S. A. Kurnia, "Developing Marketing Strategies for MSMEs through SWOT Analysis and the Analytical Hierarchy Process (AHP)," *Appl. Community Transformation and Sustainability*, 2025, [Online]. Available: <https://journal.ygtmi.org/acts/article/view/33>
- [33] O. Adiyanto, F. Maruf, and A. Hopic, "The Predicting The Optimal Compressive Strength of Sustainable Brick Using Response Surface Method (RSM)," *Eng. Access*, 2025, [Online]. Available: <https://ph02.tci-thaijo.org/index.php/mijet/article/view/253919>.
- [34] I. Muis, "The State of Digital Transformation Among Indonesian SMEs: Insights from a Systematic Review," *J. Ilmu Multidisiplin*, vol. 4, no. 3, pp. 1407–1419, Aug. 2025, <https://doi.org/10.38035/jim.v4i3.1227>
- [35] Z. Maulana, M. C. Hidayat, and I. Agustina, "Using digital marketing for small and medium enterprises (SMEs) in Bumdes Remboko Sumberrejo village Sleman regency," *SPEKTA (Jurnal Pengabdian Kepada Masyarakat Teknologi dan Aplikasi)*. 2022, <https://doi.org/10.12928/spekta.v3i1.4563>
- [36] M. P. Shah and P. Kaur, *Biomass Energy for Sustainable Development*. Boca Raton: CRC Press, 2024.
- [37] J. F. Saldarriaga and J. E. López, "Biochar as a Bridge Between Biomass Energy Technologies and Sustainable Agriculture: Opportunities, Challenges, and Future Directions," *Sustainability*, vol. 17, no. 24, p. 11285, Dec. 2025, <https://doi.org/10.3390/su172411285>
- [38] P. Chowdhury, T. Chowdhury, H. Chowdhury, and E. Bontempi, "Food waste to biochar; a potential sustainable solution for Australia: a comprehensive review," *Carbon Res.*, vol. 4, no. 1, p. 41, May 2025, <https://doi.org/10.1007/s44246-025-00207-7>