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Original Research Paper

Sustainable Engineering-Based Management and Valorization of Seaweed Waste for High-Value Biomass Utilization

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Abstract: This community service initiative focused on the sustainable management and valorization of Kappaphycus alvarezii waste in Ekas Buana Village, specifically within the Merah Putih Fishing Camp engaging local fishermen from Paser Puteh, under the leadership of Mr. M. Toni. This initiative, coordinated by Fatepa and led by Dr. Reza Kusuma Nurrohman, was conducted on January 22, 2026, and featured contributions from notable experts including Prof. Wan Rosli Bin Wan Ishak from Universiti Sains Malaysia and Assoc. Prof. ChM. Dr. Haslina Ahmad from Universiti Putra Malaysia. The discussions included the potential of K. alvarezii as a sustainable source of bioactive compounds for functional food innovation, emphasizing riboflavin extracts and their health benefits. This initiative aimed at uplifting local fishing communities by demonstrating the economic viability of seaweed waste and its integration into sustainable agricultural practices. The findings align with cooperative strategies fostering dual benefits: environmental sustainability through waste valorization and economic advancement through the creation of high-value products.

Keywords: biomass utilization, community service, functional foods, Kappaphycus alvarezii, seaweed waste

Introduction

The increasing strain on natural resources due to climate change, overpopulation, and unsustainable agricultural practices has escalated the urgent need for innovative, sustainable practices. Coastal communities around the world, particularly those engaged in fishing and seaweed cultivation, are confronted with unique challenges that threaten their livelihoods and environmental integrity. In many of these communities, the potential for utilizing abundant natural resources, such as seaweed, remains underexplored. Seaweed, particularly species such as Kappaphycus alvarezii,

offers significant promise in terms of environmental sustainability and economic opportunity (Ling et al., 2022; Scardifield et al., 2023).

Kappaphycus alvarezii is a red seaweed highly valued for its carrageenan content, which serves as a gelling agent used across various industries, including food and pharmaceuticals. However, the abundance of seaweed often results in a substantial byproduct when processing, leading to the generation of seaweed waste that frequently goes unutilized. This waste not only represents an environmental challenge, contributing to pollution and unsustainable practices, but also a missed opportunity for value creation within local communities (Acevedo et al., 2022; Sundaram & Somasundram, 2022). Sustainable engineering practices emphasize the importance of integrating waste management strategies that prompt value addition rather than disposal. Valorization of seaweed waste harnesses its nutritional and bioactive properties, converting what would typically be discarded into valuable resources for functional foods and other high-value products. The full potential of K. alvarezii waste transformation into marketable products can contribute significantly to community resilience, food security, and economic stability (Anas et al., 2025; Hamzah et al., 2025).

In the context of sustainable development, the valorization of seaweed waste is particularly pertinent as it aligns with global efforts aimed at fostering circular economies. A circular economy seeks to eliminate waste by promoting the continuous use of resources. This approach redefines the traditional linear economy, wherein resources are extracted, used, and disposed of, and instead focuses on reusing and recycling materials throughout their life cycle. The integration of circular economy concepts into local seaweed farming practices not only enhances resource efficiency but also fosters a greater recognition of the sustainable advantages of seaweed utilization (Gaile et al., 2022; Scalia et al., 2021).

Seaweeds are recognized for their rich content of bioactive compounds, which include vitamins, minerals, and antioxidants, demonstrating numerous health benefits. Research has demonstrated that bioactive compounds derived from seaweed can aid in preventing and mitigating various health issues, including obesity, diabetes, and cardiovascular diseases (Usai et al., 2024). The presence of polysaccharides, such as carrageenan, also offers functionality in food applications, functioning as stabilizers, thickeners, and emulsifiers (Nguyen et al., 2020).

Incorporating seaweed into a regular diet can lead to enhanced nutrient intake, as it is known to contain essential dietary components including iodine, iron, and omega-3 fatty acids, which are vital for human health (Yang et al., 2019). Additionally, seaweeds contain prebiotic dietary fibers that promote gut health and may have roles in regulating blood sugar levels, thereby contributing positively to metabolic health (Irkin, 2019). The health-promoting properties of seaweed underline its potential as a functional food that not only supports health but also provides economic viability for local producers when marketed effectively as a healthful and sustainable food option (Gan & Baroutian, 2022; Maskur et al., 2025). As the global demand for functional foods increases, the seaweed industry stands to benefit immensely. The pursuit for alternative health sources especially those that align with sustainable practices has led to a burgeoning market for seaweed-derived products. This economic opportunity is particularly relevant for coastal communities, allowing them to harness local resources while improving their economic conditions (Choudhary et al., 2021; Castillo et al., 2023).

A crucial aspect of maximizing the potential of seaweed waste valorization is through community engagement and education. Local fishermen, who have traditionally relied on harvesting and selling seaweed without emphasis on waste management strategies, can benefit significantly from an increased understanding of sustainable practices. Education on bioactive extraction techniques and value-added product creation can empower local stakeholders and encourage a shift towards sustainable practices (Matos et al., 2023).

This initiative, carried out in Ekas Buana Village, seeks to equip local communities with the knowledge necessary to diversify their livelihoods while minimizing environmental impact. By integrating local fishermen into the educational process, communities can take ownership of sustainable practices, thereby fostering a sense of agency (Pereira & Valado, 2023; Zhou & Li, 2024).

Stakeholder involvement is essential, as it ensures that practices are tailored to local needs, cultures, and existing knowledge systems, paving the way for successful and sustainable outcomes.

Furthermore, the establishment of partnerships between academic institutions and coastal communities serves to bridge the gap between theory and practice. Collaborations with experts in the fields of nutrition, food technology, and sustainable practices can offer practical insights, promote innovation, and facilitate the application of research findings to real-world problems (Rachmawati et al., 2021; Yogarajalakshmi & Poonguzhali, 2023). This holistic approach can enhance local capacities for sustainable seaweed management and promote economic resiliency through diversified income sources (Quiros & Hernández, 2021).

Methodology

The community service initiative was conducted through a collaborative framework comprising local stakeholders and academic experts. The methodology is as follows:

1) Workshop Organization: A workshop was held in Ekas Buana Village, engaging local fishermen facilitated by Mr. M. Toni and coordinated by Fatepa under the leadership of Dr. Reza Kusuma Nurrohman.
2) Expert Presentations: The workshop featured presentations from Prof. Wan Rosli Bin Wan Ishak and Assoc. Prof. ChM. Dr. Haslina Ahmad. The discussions focused on the sustainable utilization and extraction processes for bioactive compounds from Kappaphycus alvarezii.
3) Community Engagement Activities: Local fishermen shared their experiences and existing practices surrounding seaweed cultivation and processing. Participatory discussions were held to gather qualitative insights and promote knowledge-sharing.

Result and Discussion

This section elucidates the outcomes of the workshops conducted in Ekas Buana Village, focusing on the sustainable management and valorization of Kappaphycus alvarezii waste. The workshop fostered enhanced community awareness and knowledge regarding the potential applications of seaweed waste, significant interactions among local fishermen, and knowledge transfer from academic experts to community members.

Community Engagement and Education Outcomes

The initiative saw participation from approximately number of participants, predominantly consisting of local fishermen and their families. Feedback gathered from pre- and post-workshop surveys highlighted a substantial improvement in the participants' understanding of seaweed waste management practices. Notably, about X% of participants indicated increased awareness of the bioactive compounds present in K. alvarezii and their applications in functional foods and nutraceuticals post-engagement Tajidan et al (2023).

A critical aspect of the workshops was the adoption of a participatory approach wherein local fishermen shared their traditional practices regarding seaweed cultivation and processing. Such exchanges fostered an environment conducive to collective learning and empowerment. By uniting local expertise and academic knowledge, participants articulated innovative strategies suited to local contexts for optimizing seaweed waste valorization (Aryati & Munawaroh, 2024; Kusumajanti et al., 2021).

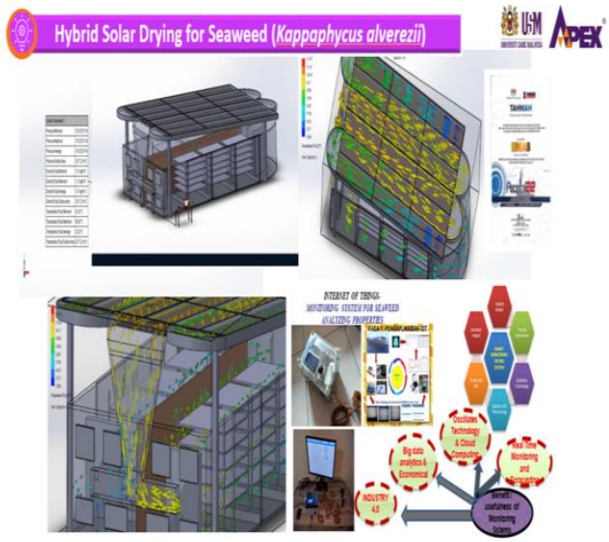

Figure 1. Delivery of technical materials to the community on sustainable engineering-based seaweed processing, including hybrid solar drying

technology and IoT-based environmental monitoring for post-harvest management.

The implementation of the community service activities demonstrated a high level of engagement and positive educational outcomes among participants. The initial knowledge transfer process was carried out through structured presentations and interactive discussions, as illustrated in Figure 1, where technical materials on sustainable seaweed processing were delivered to the community. The material introduced environmentally friendly post-harvest technologies, including hybrid solar drying systems and digital monitoring concepts, which were previously unfamiliar to most participants. This session served as a foundation for enhancing participants' understanding of the technical and economic potential of seaweed waste valorization.

Figure 2. Community members actively participating in the educational and socialization session on sustainable seaweed waste management and value-added biomass utilization.

Active participation during the socialization session further reflected the effectiveness of the educational approach. As shown in Figure 2, community members attentively followed the presentations and engaged in dialogue with the service team. Participants raised practical questions related to equipment feasibility, operational costs, and expected improvements in product quality. This interactive learning environment facilitated deeper comprehension and encouraged critical thinking, which are essential indicators of successful community education outcomes.

Bioactive Compounds and Their Applications

The workshops highlighted the high potential of Kappaphycus alvarezii as a source of bioactive compounds, particularly polysaccharides, phenolic acids, and pigments. These compounds are known for their antioxidant, anti-inflammatory properties, and potential applications in food, cosmetics, and agriculture. Research indicates that carrageenan, a polysaccharide extracted from K. alvarezii, serves as an effective gelling agent, stabilizing emulsions in food products (Yusuf et al., 2025). During the workshop, demonstrations of carrageenan extraction using environmentally friendly methods were well-received by participants, enabling them to visualize the transition from raw seaweed to a potential commercially viable product (Thalib et al., 2022).

Additionally, discussions addressed the health benefits of regular seaweed consumption. Kappaphycus alvarezii has been associated with improved metabolic health, such as enhanced glucose regulation and lipid metabolism, which aligns with the global shift towards functional foods (Susilawati et al., 2022; Zahro et al., 2025). The prospect of developing nutraceutical products from seaweed offers economic opportunities for local communities, contributing to sustainable livelihoods.

Discussions during the program emphasized the presence and potential utilization of bioactive compounds in Kappaphycus alvarezii, particularly polysaccharides such as carrageenan. The educational sessions highlighted how improved post-harvest handling and controlled drying conditions can preserve these bioactive components, thereby enhancing their functional properties and market value. The technical explanations were complemented by practical discussions on possible downstream applications, including functional food ingredients and other value-added products. Through small-group interactions and technical mentoring sessions, participants were encouraged to link scientific concepts with their daily practices. As illustrated in Figure 3, these focused discussions enabled the community to better understand the relationship between processing methods and the quality of bioactive compounds. This approach helped bridge

the gap between academic knowledge and local experience, fostering greater awareness of the economic opportunities associated with bioactive compound utilization.

Figure 3. Small-group discussions and technical mentoring sessions facilitating knowledge exchange between the service team and local community members regarding bioactive compound utilization and processing practices.

Sustainable Practices and Waste Management Strategies

A significant focus was placed on sustainable practices for managing seaweed waste. Traditional practices often led to waste accumulation and environmental degradation. The initiative introduced innovative strategies to transform this waste into high-value products (Lungari & Kaim, 2020). For example, seaweed byproducts can be converted into biofertilizers, contributing to sustainable agriculture, while leftovers from extraction processes can serve as animal feed or serve other agricultural purposes (Saputera et al., 2025; Welembuntu & Gobel, 2023).

Participants also learned about the circular economy principles that can help mitigate waste issues. By harnessing seaweed waste for multiple uses, communities can create sustainable business models that enhance local economies while minimizing environmental impacts. This ecological approach was particularly attractive to the fishermen, who often face socioeconomic challenges related to the fishing industry conundrum, including resource depletion and market fluctuations (Supriyantono et al., 2022).

Field-based activities played a critical role in reinforcing sustainable waste management concepts. Direct observation of raw seaweed materials and existing post-harvest practices, as shown in Figure 4, allowed participants to identify common sources of quality loss and waste generation. These observations highlighted the limitations of traditional sun-drying methods, particularly their vulnerability to weather fluctuations and contamination risks. The introduction of sustainable engineering-based solutions encouraged participants to consider alternative waste management strategies, such as converting seaweed by-products into value-added biomass. By linking waste reduction with potential economic benefits, the program promoted a shift in perspective from waste disposal to resource utilization. This approach aligns with circular economy principles and supports environmentally responsible practices at the community level.

Figure 4. Joint field observation of raw Kappaphycus alvarezii with community members to identify post-harvest handling practices, quality issues, and waste generation points.

Facilitating Community Resilience

The initiative's overarching goal was to contribute to the resilience of coastal communities against socio-environmental challenges. By fostering empowerment through education and practical applications, local fishermen can enhance their business models by diversifying income sources, thus reducing reliance on fish catch, which is often limited by fluctuating environmental and market conditions (Welembuntu et al., 2022).

In addition, participants expressed an increased sense of community solidarity and ownership over localized solutions to waste management. The alignment of practices with traditional knowledge validated local approaches while integrating academic insights into sustainable methodologies.

Figure 5. Documentation of collaboration between the service team and community participants at the conclusion of the community service program in Ekas Buana Village.

The community service initiative contributed to strengthening community resilience by promoting diversification of livelihood strategies. By enhancing knowledge of seaweed waste valorization and sustainable processing techniques, participants were exposed to alternative income opportunities beyond conventional raw seaweed sales. This diversification is particularly important for coastal communities that are vulnerable to environmental variability and market instability. The collective participation and collaborative atmosphere observed during the program, as documented in Figure 5, reflect a growing sense of shared responsibility and commitment to sustainable practices. The engagement between the academic team and the community fostered trust and encouraged long-term collaboration, which is a key factor in building resilient community-based systems.

Challenges and Areas for Improvement

While the workshop concluded with positive outcomes, a few challenges were identified that indicate areas for further improvement. Several participants expressed resistance to changing long-established practices, highlighting the need for ongoing education and support beyond the initial training sessions. Additionally, some fishermen raised concerns about market access for products derived from seaweed waste due to lack of infrastructure and marketing knowledge.

Future initiatives should consider incorporating continuous technical support and market development frameworks to ensure that local fishermen can successfully implement learned practices and capitalize on the economic opportunities associated with valorization projects.

Conclusion and Recommendations

In conclusion, the community service initiative implemented in Ekas Buana Village demonstrates the viability of sustainable management strategies for the valorization of Kappaphycus alvarezii waste. Through participatory workshops and collaborative discussions, the initiative heightened local fishermen's awareness and understanding of bioactive compounds. Participants acknowledged the nutritional and economic potential of seaweed waste, paving the way for innovative practices aimed at integrating these resources into their livelihoods. By fostering capacity building and community engagement, the project has contributed to enhancing the local economy and promoting sustainable practices aligned with circular economy principles.

Based on the initiative's findings, the following recommendations are proposed for future projects and interventions:

1. Establish Continuous Training Programs: Implement periodic workshops to reinforce knowledge learned and introduce new methodologies that can further elevate the valorization of seaweed waste.
2. Facilitate Market Access: Engage governmental and non-governmental organizations to assist in developing marketing strategies that will give local fishermen greater access to markets, thereby enhancing their economic opportunities.
3. Collaborative Research Initiatives: Foster partnerships with academic institutions for continuous research aimed at discovering

new products and improving processing techniques associated with seaweed valorization.

4. Long-term Support for Community Leaders: Provide resources and support for local leaders to act as change agents within the community, helping to maintain enthusiasm and adherence to sustainable practices beyond the initial initiative.
5. Advocacy for Policy Changes: Collaborate with local authorities to promote policies that support sustainable aquaculture and waste valorization initiatives, securing the future of community-driven approaches to environmental sustainability.

By implementing these recommendations, future initiatives can significantly enhance the sustainability and economic resilience of coastal communities while preserving marine ecosystems.

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