

## From The Sea to Sustainability: Transforming Seaweed into High-Value Products for the Economic Resilience of Farmers Groups in East Nusa Tenggara

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**ABSTRACT:** Transforming seaweed from a basic commodity into a high-value product has paved a significant path for economic resilience among farmer groups in East Nusa Tenggara, Indonesia. This study aims to (1) examine the potential of seaweed as a primary material in the production anti-corrosive coatings, (2) analyze the economic impact of seaweed product diversification on the income and economic resilience of seaweed farming groups in East Nusa Tenggara, and (3) develop a model for coastal community empowerment based on sustainable product innovation. Employing qualitative methods, including observation, in-depth interviews, documentation and focus group discussions, we investigated the impact of CSR-led training in improving the technical skills, economic opportunities, and environmental awareness of seaweed farming communities. This indicates that product diversification not only increases farmers' incomes but also creates an economic ecosystem that protects them from the volatility of the raw seaweed market. Furthermore, this empowerment encourages sustainable practices that support the preservation of coastal ecosystems. The study highlights the importance of CSR in promoting social innovation, providing insights for policymakers to drive similar initiatives that strengthen economic resilience and Environmental Management in coastal regions.

**KEYWORDS:** anti-corrosion paint innovation, coastal community empowerment, environmental sustainability, seaweed potential, socio-economic impact

### INTRODUCTION

As a large archipelago, Indonesia has natural resources that can be maximized to support a sustainable economy, especially in coastal ecosystems (Mahardianingtyas et al., 2018; Estradivari et al., 2024). These coastal ecosystems are attractive by offering economic opportunities without harming the ecological balance, for example through seaweed cultivation (Song & Gao, 2024; Ayyam et al., 2019; Zhao et al., 2024). Seaweed is one of the multifunctional resources with wide economic and environmental benefits, such as foodstuffs (Blikra et al. 2021), fertilizers (Bahcevandzhev and Pereira 2021), to pharmaceuticals (Cotas et al. 2024). The diverse potential of this seaweed has implications for global demand that continues to increase every year.

Although it has great potential, the development of the seaweed industry in Indonesia faces various challenges, such as fluctuations in market demand, lack of spatial planning, and the weakness of the regulatory framework (Busthanul et al., 2020; Kosicsek et al., 2024). In addition, limited cultivation expertise and low consumer awareness are also major obstacles (Tabrani, Angkasa, and Deviarni 2024). Previous research conducted by Permani et al., (2024) and Sultana et al., (2023), has highlighted the importance of regulations supporting seaweed industrialization and empowering seaweed farmers in efforts to mitigate the impacts of climate change.



Interestingly, in Tablolong Village, West Kupang, Kupang regency, East Nusa Tenggara province, there has been a local community group accompanied by PT Pertamina Patra Niaga Integrated Terminal Tenau successfully produced anti-corrosion paint made from *Eucheuma cottonii* (EC) seaweed extract. This innovation reflects the utilization of seaweed as an environmentally friendly organic corrosion inhibitor, as supported by previous research (Kokilaramani et al., 2021; Wang et al., 2024). Potential organic inhibitors of seaweed extracts have even shown efficiencies of up to 95% in inhibiting corrosion (Rhazzane et al. 2024). In the context of the blue economy, value-added product innovations such as seaweed-based anti-corrosion paint not only support the diversification of farmers' income (Yong et al. 2022), but also contribute to the preservation of the environment (Meybeck et al., 2024; Mirera et al., 2020). This study aims to (1) assess the potential of seaweed as a basic ingredient in the production of anti-corrosion paint, (2) analyze the economic impact of diversification of seaweed products on income and economic resilience of seaweed farmers in East Nusa Tenggara, and (3) develop a model of coastal community empowerment based on sustainable product innovation. The results of this study are expected to be an alternative solution based on local resources in the context of the use of Natural Resources in strengthening the economy and natural sustainability in line with sustainable development goals, especially in coastal areas.

## METHODS

This study uses a qualitative descriptive method (Creswell 2020), within the framework of a case study to understand seaweed utilization-based empowerment initiatives in East Nusa Tenggara (Dawson R. and Algozzine 2021). Data collection in this study using purposive and snowball techniques involved 34 informants from various sectors, such as government, academia, community, and private (Solarino & Aguinis, 2021; Zickar & Keith, 2023), through observation, semi-structured interviews, document analysis, and focused group discussions (FGDs) (Mey 2022). Data analysis was done systematically with steps of transcription, issue mapping, thematic grouping, interpretation, and reporting of results (Taylor, Bogdan, and DeVault 2015). The validity of the data was carried out through member-checking, resulting in deep insights into seaweed-based product innovation (Zairul 2021). This methodological framework supports a comprehensive exploration of the potential and challenges of seaweed-based product innovation, contributing significantly to the academic discourse and practical application of Coastal Community Empowerment.

## RESULT AND DISCUSSION

### 1. Unveiling seaweed's Potential: A Sustainable Solution for Industrial Corrosion Protection

In general, it can be seen that there are several potential organic inhibitors such as pine resin can reduce the corrosion rate by 87%, Gambier by 11%, tobacco by 64%, coffee by 58%, and seaweed by 93.49% (Rochmat et al., 2019; Simatupang DF, 2020). Among some of these potential organic inhibitors, red seaweed (EC) has the greatest potential as a natural corrosion inhibitor, being an environmentally friendly alternative to paints based on harmful and expensive synthetic materials (Gaylarde, Neto, and da Fonseca, 2021; Forero-López et al., 2024). Its content of bioactive compounds, such as tannins, flavonoids, saponins, terpenoids, alkaloids, phenols, and hydroquinones, acts through various mechanisms: tannins form a layer of metal complexes, flavonoids inhibit redox, and saponins create a hydrophobic layer (Biris-Dorhoi et al., 2020; Qi, Li, Bi, and Dam-Johansen, 2024; Azahar et al., 2024). Terpenoids block oxygen, alkaloids form a protective film, phenols prevent corrosive biofilms, while hydroquinone reduces oxidation (Huynh et al. 2024). This combination makes EC superior for environmentally friendly and sustainable Anticorrosive paint applications (Thomas et al. 2022).

In this study, EC extract was taken for tannin content for conventional paint mixtures. Tannins are quite important in forming complex compounds with iron ions into Fe-tannates. This Fe-tannate complex compound will be a water barrier to direct contact with ferrous metals. Tannic acid can accelerate the corrosion process by lowering the pH and forming complexes with iron that adhere to the surface. Tannic acid acts on available iron ions in three ways. First, tannins can form complex compounds with the  $Fe^{2+}$  ion to ferrotannate, which is easily oxidized to ferric tannate in the presence of oxygen. Second, tannins can react directly with  $Fe^{3+}$  ions to form tannic ferries. Third, due to the ability of the reducing properties of tannins,  $Fe_2O_3$  can be reduced to  $Fe^{2+}$  ion ions (Xu, Han, and Wang 2019).

The test results showed that this innovation exceeded PT Pertamina's internal *best practice corrosion rate* standards, with an increase in the corrosion control category from "acceptable" to "excellent corrosion control". The result of this innovation, named *Coattonix*, is able to reduce the use of conventional paints by up to 50% through a combination with seaweed extracts. Since its implementation in January 2023, Coattonix has shown significant ability in reducing corrosion rate from 3.15 MPY to 0.03 MPY. This is due to the



tannin content of 0.0785% in the EC extract, which is not found in conventional paints. This innovation also succeeded in reducing the cost efficiency of Budget use by 15.4%, saving paint material costs by 36.85%, and reducing the need for primary paint by 50%. In addition to the technical and financial benefits, the implementation of *Coattonix* contributes to environmental sustainability by reducing the generation of B3 waste from paint cans by up to 300 kg per year. This finding means further strengthening the argument Ahmed et al., (2024) who argued that seaweed can be used as an additional value in inhibiting the corrosion rate.

The innovation further strengthens the prospects for entering the global market in the industrial infrastructure maintenance sector, in particular in anti-corrosion protection. Corrosion is a major challenge in modern industry, given that most metal-based equipment is susceptible to damage from exposure to corrosive environments (Al-Moubaraki and Obot 2021). In this context, seaweed developed as an organic corrosion inhibitor offers an environmentally friendly and efficient solution, in line with increasing global demand. According to the Allied Market Research Report, the global anti-corrosion protection products market is expected to grow with a compound annual growth rate (CAGR) of 8.6%, and the value of this market is projected to reach 41.2 billion US dollars by 2027 (Voroobyova et al. 2023). This demonstrates the industry's increasing awareness of the need for more sustainable corrosion protection solutions. In addition, studies by Pradeep Kumar & Mohana, (2014) indicate that corrosion inhibitors for neutral air and water environments with high corrosive properties will have the highest demand, given their wide application in various industrial sectors such as oil and gas, transportation, as well as construction. With its efficiency and environmentally friendly properties, seaweed has the potential to become a superior raw material for organic corrosion inhibitors that can compete in the global market. This innovation not only addresses the technical needs of the industrial sector, but also supports the global sustainability agenda by reducing dependence on synthetic chemicals.

## 2. Product Diversification through Seaweed Innovation: Transforming Coastal Livelihoods

Innovation-based product diversification is often successful in increasing revenue in a type of business (Vance et al. 2023). In this seaweed empowerment program, through the innovation of conversion into anti-corrosion paint has had a significant impact on increasing the income of farmers. Before this diversification, the price of raw seaweed in the local market was only about Rp 15,000 per kilogram. However, after being processed into anti-corrosion paint, the product was successfully sold at a price of Rp 50,000 per can. This transformation provided significant added value, with a 3.33-fold increase in revenue. Such changes prove the effectiveness of product diversification in strengthening the economic position of farmers (Gittins et al. 2025), especially in coastal areas prone to market price instability of raw commodities (Langford et al. 2022).

Fluctuations in raw seaweed prices are often influenced by various factors, including changes in export policies and international market dynamics (Permani et al. 2024). This dependence on unstable markets previously created income uncertainty for farmers. However, diversification through the production of anti-corrosion paints allows farmers to access a more stable market with more consistent profit margins. Thus, this diversification becomes an economic risk mitigation strategy while improving the welfare of farmers in a sustainable manner (Antonelli, Coromaldi, and Pallante 2022). The implementation of product diversification in Tablong Village, Kupang Barat District, East Nusa Tenggara, involves intensive assistance from PT Pertamina Patra Niaga Integrated Terminal Tenau. Nona Nori seaweed farmers group received technical training on the process of processing seaweed into anti-corrosion paint. This training not only improves the technical skills of farmers, but also broadens their horizons regarding the concept of added value (Petit et al. 2023). Previously, farmers tended to view seaweed as a raw commodity with low selling value. Through this training, they understand that the processing of raw materials into high-value products can change their business pattern from just a supplier of commodities to a manufacturer of processed products.

The results of this training are reflected in increasing the independence of the local economy. Farmers now have more control over the value chain of their products, from production to distribution. In addition, with better technical capabilities, they can optimize the use of local resources to manufacture more competitive products in the market. This impact shows that capacity building-based interventions have great potential in driving the economic transformation of coastal communities. This product diversification also has a positive impact in the form of creating new jobs at the local level. The established anti-corrosion paint production facilities require labor on various lines, including production, packaging, marketing and distribution processes. These employment opportunities are not only limited to farmers, but also involve their family members who previously did not have direct access to productive economic activities.

These opportunities help increase community involvement in local economic activities. The technical training provided also strengthens the skills of the workforce, enabling them to compete in the wider job market. With this diversification, local communities

have more diverse income alternatives, thus increasing their economic resilience. The additional revenue generated from this sector contributes directly to improving the welfare of peasant households. In addition to its economic impact, the diversification of seaweed-based products also contributes positively to environmental sustainability. Seaweed as a raw material has ecological advantages over synthetic chemicals that are usually used in conventional anti-corrosion paints. Production of seaweed-based paints results in lower carbon emissions and is more environmentally friendly (Zhang et al. 2024), in line with the principles of green economy (Waqas et al. 2024).

Processing seaweed into anti-corrosion paint also supports the preservation of coastal ecosystems, the main habitat for the growth of seaweed. The preservation of this ecosystem is very important because in addition to being a source of raw materials, coastal ecosystems also play a role in protecting coastal areas from erosion and climate change. With this approach, diversification programs not only generate economic benefits, but also strengthen people's awareness of the importance of preserving the environment as an integral part of their economic sustainability. The success of this seaweed product diversification program shows that local resource-based innovation can provide integrated economic, social, and environmental impacts (Fatima et al. 2024). Increased product added value, income stability, and preservation of the ecosystem are the cornerstones of the success of this program. The success in Tablolong Village provides a model that can be replicated in other coastal areas, especially those with similar potential in the development of seaweed-based products. With the right strategy and sustainable assistance, this program has the opportunity to expand its impact to a wider scale, supporting the achievement of the *Sustainable Development Goals*, especially in supporting inclusive economic growth, decent job creation (SDG 8), and conservation and sustainable use of marine ecosystems (SDG 14) (Osuji & Agbakwuru, 2024; Zhao et al., 2024).

### 3. Empowerment Through Sustainable Innovation: A Coastal Community Model

In the context of community empowerment, social innovation is a key element (Herzog and Krehl 2024) to address the complexity of the challenges faced, especially in coastal areas such as Tablolong Village. As global problems, such as climate change and economic vulnerability to natural disasters, increasingly affect people's lives, conventional approaches are often insufficient to create sustainable impacts (ElZein et al. 2024). This is where social innovation becomes relevant, by providing solutions that are not only creative and locally based but also systemic (Arocena & Sutz, 2020; Midgley & Lindhult, 2021). Social innovation-based empowerment programs, such as Nona Nori, serve as catalysts for creating positive change that directly engages communities. In addition to providing practical solutions, the program also enables a more inclusive and adaptive transformation of social values, structures, and relationships (Doten-Snitker et al. 2021). Therefore, social innovation is not only about creating something new, but also redesigning the way society faces and utilizes existing challenges for common progress (Moulaert, MacCallum, and Hillier 2013). The Nona Nori Program is a social innovation based on the management of local resources, namely seaweed, which is developed into an organic anti-corrosion paint. With this approach, the program not only offers solutions to corrosion problems in coastal infrastructure but also utilizes the potential of nature optimally to create added value. The uniqueness of this program lies in its novelty that integrates science and technology with local wisdom (Havas, Schartinger, and Weber 2023), providing a touch of originality that is relevant in the context of the needs of the environment and society. The implementation of this program involves the transfer of knowledge in a structured manner to the community, in accordance with PT Pertamina's core competencies in energy and environmental innovation. Training provided includes seaweed processing techniques into paint, organic formula development, and marketing strategies. This process strengthens the skills of local communities, opens up new opportunities for them to participate in the wider value chain, while instilling insights into sustainability.

The development of Nona Nori is based on the results of The Life Cycle Assessment (LCA) analysis, which ensures that each stage of production has a minimal environmental impact (Bouillass, Blanc, and Perez-Lopez 2021). With a lower carbon footprint than conventional paints, these products offer a much-needed environmentally friendly alternative amid growing global pressure to reduce emissions. This makes the program not only innovative but also responsive to crucial environmental issues (Voegtlin et al. 2022). On the other hand, this program is sensitive to the condition of people who are often affected by natural disasters on the coast. By providing employment options and a stable income through seaweed management, Nona Nori helps reduce the economic vulnerability of communities. The program's organic paint also contributes to protecting infrastructure from further damage from corrosion, which is often compounded by climate extremes.

Another advantage of Nona Nori is that its model can be replicated in other coastal areas that have seaweed potential. Through technical guidance accompanied by training, the program allows other communities to adopt a similar approach, expanding its positive



impact geographically. This replicability also reflects efforts to create greater systemic change in natural resource-based sectors of local economies (Howard, Böhm, and Eatherley 2022). Through this program, a new, more collaborative relationship between seaweed farmers, seaweed processing women, and industry players is created. This cooperation builds a collective mindset oriented towards sustainability, while strengthening productive social networks. In the context of resources, the program demonstrates the ability of optimizing local assets in an innovative and efficient way, providing dual benefits for the community economy and environmental sustainability. Overall, Nona Nori is a model of social innovation that not only creates direct economic impacts but also influences social systems, relationship patterns, and sustainability approaches in society (Gasparin et al. 2021). With the potential for replicability and widespread benefits, this program is an inspiring solution for Community-Based Resource Management.

## CONCLUSION

This study demonstrates the great potential of seaweed as a raw material in the production of anti-corrosion paints, providing an innovative environmentally friendly alternative and relevant to the needs of coastal industries. Through material analysis, seaweed has proven to be able to produce products with high durability while reducing environmental impact, offering sustainable solutions in infrastructure protection. From the economic side, diversification of seaweed-based products significantly increases the income of farmers in East Nusa Tenggara. This model expands added value, opens up new market access, and reduces dependence on traditional business patterns that are prone to price fluctuations. Thus, product diversification has contributed to the economic resilience of coastal communities in the region. This study also managed to develop a model of empowerment based on sustainable product innovation. Through technology transfer, training, and collaboration with stakeholders, the model not only encourages community self-reliance but also creates new relationships that support local economic systems. This Model has the potential to be replicated in other coastal regions with similar characteristics, ensuring a broader impact in supporting sustainable coastal economies and ecosystems.

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