Sustainable Marine Structures
https://journals.nasspublishing.com/sms

ARTICLE

Coastal Community Empowerment Based on Local Wisdom and Technological Innovation for Climate Change Adaptation, Erosion Control, and Sustainable Ecotourism Development

R. Ery Ridwan [1], Muhammad Aditya Julianto [1], Putri Nauli Marpaung [1], Annisa Ratri Utami [1], Taufik Ismail [2], Sintia Wahyu Wijayanti [1], Sri Tanjung Subroto [3], Dike Farizan F. [3], Khakam Ma'ruf [4], Rizal Justian Setiawan [5,6]*

[1] *PT Pertamina Hulu Energi Offshore North West Java, South Jakarta, DKI Jakarta 12520, Indonesia*

[2] *Graduate School, Faculty of Economics and Management, IPB University, Bogor 16680, Indonesia*

[3] *Betterly Indonesia, South Jakarta, DKI Jakarta 12740, Indonesia*

[4] *Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Sleman, DI Yogyakarta 55281, Indonesia*

[5] *Asia and China Studies, College of Law and Politics, National Chung Hsing University, Taichung 40227, Taiwan*

[6] *Industrial Engineering and Management, College of Engineering, Yuan Ze University, Taoyuan 32003, Taiwan*

ABSTRACT

This study evaluates the effectiveness of integrating local wisdom with the use of *Alat Pemecah, Peredam Ombak, dan Sedimen Traps (APPOSTRAPS)* or Breakers, Wave Dampers, and Sediment Traps in empowering coastal communities in Karawang, Indonesia, as a strategic response to climate change, coastal erosion, and sustainable ecotourism development. The research aims to assess the combined impact of *APPOSTRAPS* technology and the *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir (JAM PASIR)* or Protecting Nature Through Coastal Community Empowerment program in reducing coastal abrasion, restoring mangrove

*CORRESPONDING AUTHOR:
R. Ery Ridwan, PT Pertamina Hulu Energi Offshore North West Java, South Jakarta, DKI Jakarta 12520, Indonesia; Email: ery.ridwan@pertamina.com

ARTICLE INFO
Received: 4 September 2025 | Revised: 25 September 2025 | Accepted: 30 September 2025 | Published Online: 11 October 2025
DOI: https://doi.org/10.36956/sms.v7i4.2701

CITATION
Ridwan, R.E., Julianto, M.A., Marpaung, P.N., et al., 2025. Coastal Community Empowerment Based on Local Wisdom and Technological Innovation for Climate Change Adaptation, Erosion Control, and Sustainable Ecotourism Development. Sustainable Marine Structures. 7(4): 9–35. DOI: https://doi.org/10.36956/sms.v7i4.2701

ecosystems, and fostering sustainable livelihoods. A mixed methods approach was applied, combining quantitative analysis of coastline changes using *Geographic Information System (GIS)* with *Landsat* and *Sentinel-2 imagery* (2022–2024), field surveys using differential GPS (±2 m accuracy), and qualitative methods including 150 interviews, 18 months of participant observation, and community documentation. Results show a coastline extension of about 400 m (±15 m), increased ecotourism revenue from IDR 11.25 million per month in 2019 to IDR 90 million in 2024, women's participation rising from 12% to 68%, and livelihood diversification reaching 110% of the target with 98 families involved. *APPOSTRAPS*, a patented breakwater and sediment trap made from repurposed tires, combined with the *JAM PASIR* program covering mangrove-based ecotourism, MSMEs for fishermen's wives, waste management, and the *Masyarakat Sadar Lingkungan and Bencana (MASDARLINA)* or Environmentally and Disaster Aware Society system, effectively mitigates erosion and supports economic growth. The study concludes that integrating indigenous knowledge and technology strengthens community resilience and provides a replicable model for sustainable coastal adaptation.

Keywords: *APPOSTRAPS*; Coastal Empowerment; Climate Adaptation; Sustainable Ecotourism; Local Wisdom

1. Introduction

Global climate change has emerged as a significant threat to the sustainability of coastal ecosystems worldwide, including those in Indonesia [1–3]. The impacts of climate change, such as rising sea levels, increased wave intensity [4,5], and changes in extreme weather patterns, have resulted in progressively severe coastal abrasion [6,7]. Indonesia, as an archipelagic nation with the second-longest coastline in the world, faces considerable challenges in managing coastal areas that are highly vulnerable to erosion [8,9]. The northern coastal region of Java Island, particularly Karawang Regency, is among the most severely affected by this phenomenon [10,11]. Coastal communities that rely on marine resources for their livelihoods experience substantial economic and social losses due to the reduction of productive land and the threat posed to residential areas by abrasion. These conditions require the implementation of innovative solutions that integrate modern technological approaches with the traditional knowledge of local coastal communities to develop sustainable and effective adaptation strategies. Globally, a variety of interventions have been implemented to address coastal challenges, including Living Shorelines in the United States, which integrate natural and artificial infrastructure [12]; the Building with Nature program in the Netherlands, which combines nature-based solutions with engineering techniques [13]; and Community-Based Mangrove Restoration in Bangladesh, which emphasizes the active participation of local communities [14]. In contrast, the Indonesian context necessitates specific adaptations due to the unique oceanographic conditions of the Java Sea, the substrate characteristics, and the socio-economic structures of coastal communities.

Coastal erosion has become a widespread phenomenon across Indonesia's extensive coastline, exhibiting varying degrees of severity and impacts on local communities [15,16]. The issue is characterized by progressive shoreline retreat, loss of productive land, and threats to coastal settlements. Affected communities often face a range of interconnected challenges, including displacement, disruption of traditional livelihoods, and damage to coastal infrastructure [17–19]. The complexity of coastal erosion extends beyond physical land loss, encompassing broader socio-economic consequences, particularly for communities whose economic activities are closely tied to marine and coastal resources. These impacts call for intervention strategies that integrate both immediate protective measures and long-term sustainable development approaches [20,21].

Despite facing severe abrasion challenges, the coastal areas of Karawang Regency in Republic of Indonesia, particularly Sukajaya Village, possess significant economic potential in the marine and fisheries sector. Pasir Putih Hamlet in Sukajaya Village is recognized as the largest crab-producing area in West Java, with approximately 80% of men of productive age engaged in crab fishing activities [22,23]. The productivity of the crab fishery reaches 96 tons per month, or approximately

4.8 tons per day, indicating considerable economic potential. However, this potential has not been fully realized due to several constraints, including the limited diversification of processed fishery products [24]. The wives of fishermen, who represent a socio-economically vulnerable group, currently lack access to productive economic activities that could contribute to enhancing household welfare. Furthermore, the issue of coastal waste management, particularly the prevalence of plastic waste, presents an additional challenge to efforts aimed at ensuring the sustainability of the coastal environment [25].

Effective coastal community empowerment requires an approach that integrates local wisdom with modern technological innovations to develop sustainable and contextually appropriate solutions [26,27]. The local wisdom of the Karawang coastal community, which has evolved over generations, such as knowledge of weather patterns, environmentally friendly fishing practices, and the tradition of cooperation in responding to natural disasters, needs to be revitalized and synergized with contemporary technological advancements. This empowerment framework must also incorporate active community participation at all stages of the program, including planning, implementation, monitoring, and evaluation [28,29]. A participatory approach is essential to ensure that empowerment initiatives are not merely charitable or short-term interventions, but rather sustainable efforts that generate long-term impact. Moreover, effective empowerment should include the identification and development of local champions or community leaders who can serve as catalysts for change within the community [30].

The community empowerment initiatives described in this research were implemented by PT Pertamina Hulu Energi Offshore North West Java (PHE ONWJ), a subsidiary of PT Pertamina Hulu Energi. The first program introduced the *APPOSTRAPS* technology innovation, which comprises *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps developed from the repurposing of used tire waste as an innovative solution to coastal abrasion. It applies to the structural model of a fixed offshore platform adapted to nearshore conditions, utilizing a tripod piling installation system. *APPOSTRAPS* not only functions as an effective wave breaker but also enhances the natural sedimentation process, contributing to the formation of new land in coastal areas. The advantages include the use of readily available tire waste materials, relatively low implementation costs, and a reduction in air pollution associated with tire burning. This innovation has received formal recognition from the Indonesian Ministry of Law and Human Rights, with a patent certificate IDS000007668 issued on March 8, 2024, thereby affirming the novelty and validity of the innovation [31].

Furthermore, the second innovation program, *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*), represents one of the flagship initiatives undertaken by PT Pertamina Hulu Energi Offshore North West Java (PHE ONWJ) in Karawang Regency to address the complex challenges confronting coastal communities. This program is built upon the *"New Land, New Hope"* concept, which integrates abrasion management via *APPOSTRAPS* technology, mangrove ecotourism development, the empowerment of fishermen's wives through micro, small, and medium enterprises (MSMEs) support, and coastal waste management into a cohesive, mutually reinforcing system. This approach facilitates sustainable social transformation by enabling the use of sediment accumulated through *APPOSTRAPS* technology as a foundation for new economic activities within coastal communities. The *JAM PASIR* program also incorporates the *Masyarakat Sadar Lingkungan* and *Bencana* or Environmentally and Disaster Aware Society *(MASDARLINA)* system, designed to enhance community awareness of and preparedness for climate change and natural disaster risks. The program's demonstrable economic, social, environmental, and well-being outcomes establish it as a replicable model for other coastal regions in Indonesia.

The novelty of integrating local wisdom with *APPOSTRAPS* technology is reflected in three key aspects. First, offshore platform technology is adapted to nearshore conditions by incorporating traditional community knowledge of currents and sedimentation patterns. Second, a participatory approach is applied by engaging traditional leaders and community representatives in both the design and implementation processes. Third, a synergy is established between customary conservation practices and modern innovations to generate context-specific and sustainable solutions.

Although various abrasion control technologies have been developed previously, including conventional concrete and stone breakwaters, as well as hybrid green-grey infrastructure approaches, there is a significant gap in the development of economical, environmentally friendly, and easily replicable solutions for resource-constrained coastal communities. This research specifically addresses this gap by developing *APPOSTRAPS* technology that utilizes waste tires as the primary material, in contrast to conventional approaches that require high investment costs and greater environmental impacts. The unique contribution of this research lies in the development and implementation of *APPOSTRAPS* technology that has never been tested before in Indonesian coastal areas, as well as its holistic integration with a comprehensive community empowerment program. The novelties added in this case include empirical validation of the effectiveness of waste tire-based technology under the specific oceanographic conditions of the Java Sea, development of a community empowerment model integrated with climate change adaptation technology, and demonstration of the solution's scalability for replication in other coastal areas in Indonesia.

The selection of Sukajaya Village as the study location was guided by several criteria. It has the highest abrasion rate in Karawang Regency, with an average shoreline retreat of 10 m per year between 1989 and 2018. The village also hosts a concentration of vulnerable populations, with 3,365 residents at risk of losing their homes. Additionally, it possesses significant marine economic potential as the largest crab producer in West Java, with a yield of 96 tons per month. The community demonstrates strong local knowledge in coastal resource management, and the substrate conditions are well-suited for the installation of tripod pile technology.

2. Literature Review

Indonesia's coastal areas encounter multifaceted challenges resulting from climate change, environmental degradation, and socio-economic pressures, thereby requiring a sustainable approach to community empowerment [32]. This literature review examines a range of coastal community empowerment strategies that integrate local wisdom, climate change adaptation, disaster risk reduction, and sustainable ecotourism development as comprehensive solutions to address the multidimensional issues faced by coastal regions.

Local wisdom practices play a vital role in the sustainable empowerment of coastal communities. A relevant study conducted in Lawang Agung Village, North Musi Rawas Regency, identified local communities as possessing conservation traditions rooted in local wisdom, such as "nakul" and "bekarang iwak," which have been passed down through generations. However, the rise of modernization and the spread of individualistic values have contributed to the erosion of mutual cooperation and social cohesion within these communities. This study highlights the need for empowerment strategies that are grounded in a comprehensive understanding of local wisdom, the identification of community assets, the implementation of participatory programs, and the establishment of continuous evaluation mechanisms. The integration of modern technology with traditional knowledge, the enhancement of community educational capacity, and the internalization of spiritual values are essential for optimizing environmental conservation efforts and reinforcing a collective commitment to maintaining the balance of coastal ecosystems [33].

Climate change adaptation through local community empowerment has proven to be an effective approach in addressing coastal erosion. A related study conducted at Bungin Beach, Bekasi, highlights the strategic role of the *Kelompok Sadar Wisata* or Tourism Awareness Group (Pokdarwis) in implementing climate change adaptation initiatives during the COVID-19 pandemic. Pokdarwis engaged in mangrove planting and monitoring activities, which served both as a form of bioengineering for abrasion control and as a mechanism for promoting local economic recovery. An analysis of shoreline changes between 2017 and 2021 revealed complex dynamics, including land loss due to abrasion amounting to −1.93 km^2. This community-based approach demonstrates the effectiveness of active participation by coastal communities in environmental conservation and disaster risk management, reinforcing its viability as a sustainable strategy for climate change adaptation [34].

Community institutions play a fundamental role in the abrasion disaster mitigation system within coastal regions. A related study evaluated the contribution of the Disaster Preparedness Group in Rembang in delivering education and outreach programs on disaster preparedness to residents. The study further emphasized the importance of structural mitigation measures, including gabion installations and concrete barriers, as integral components of non-structural strategies aimed at preventing erosion and further coastal damage [35]. The integration of both structural and non-structural approaches in abrasion disaster mitigation highlights the necessity of fostering synergy between community empowerment initiatives and the provision of adequate infrastructural support.

Sustainable ecotourism development constitutes an innovative model for empowering coastal communities by aligning environmental conservation objectives with the enhancement of economic well-being. A study conducted in the coastal border area of Sambas Regency, West Kalimantan, demonstrates that a participatory and enduring approach to ecotourism development necessitates the active engagement of youth as facilitators of community learning, together with robust support from local leadership. The ecotourism potential derived from mangrove conservation, turtle protection initiatives, and the scenic value of the coastline has emerged as a major attraction capable of stimulating the regional economy. This empowerment model illustrates how coastal communities can harness their natural assets in a sustainable manner while ensuring the long-term preservation of coastal ecosystems [36].

The literature review demonstrates that effective coastal community empowerment necessitates a multidimensional approach integrating local wisdom, climate change adaptation, disaster risk mitigation, and sustainable economic development. The success of such empowerment programs relies heavily on active community participation, robust institutional support, and the harmonious integration of traditional practices with contemporary technologies. The theoretical implications underscore the critical role of a participatory empowerment paradigm in addressing the multifaceted challenges confronting coastal regions amid climate change. Future research should investigate in greater depth the mechanisms for integrating indigenous knowledge with technological innovation and should develop comprehensive long-term impact evaluation models for coastal community empowerment programs to ensure the sustainability of ecosystems and the well-being of local populations.

A critical review of the literature reveals three major gaps in existing approaches to coastal community empowerment. First, there is limited integration of appropriate technology with community participation in addressing coastal abrasion. Second, existing models show constraints in linking disaster mitigation with conservation-oriented economic development. Third, there is an absence of a comprehensive framework for evaluating social impacts. The *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) model seeks to address these gaps through a holistic strategy that combines *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps *(APPOSTRAPS)* technological innovation, gender-responsive economic empowerment, and *Masyarakat Sadar Lingkungan* and *Bencana* or Environmentally and Disaster Aware Society *(MASDARLINA)* as a community capacity-building system. The theoretical contribution of this model lies in demonstrating that community-based adaptation can achieve a level of technical effectiveness comparable to top-down interventions while offering greater sustainability and lower implementation costs.

3. Materials and Methods

3.1.Study Area

Sukajaya Village is a coastal settlement, it is located in Cilamaya Wetan District, Karawang Regency, West Java Province, Indonesia, located on the north coast of

Java Island facing the Java Sea. This village is geographically positioned at approximately 6°15′S and 107°45′E, encompassing a total administrative area of 12.5 km^2. The village's coastal zone extends for approximately 8.2 km along the shoreline, with Pasir Putih Hamlet designated as the primary site for the implementation of *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps *(APPOSTRAPS)* technology. The defined study area also incorporates a coastal buffer zone extending 500 m inland from the high-tide line, covering an estimated 410 hectares within the village's coastal territory. Monitoring data spanning 1989 to 2018 indicate a shoreline retreat of 290.13 m, corresponding to an average annual change rate of 10.00 m. The total area affected by abrasion encompasses 56.96 hectares throughout the wider coastal zone, placing 3365 residents at imminent risk of losing their homes.

To link the effects of *APPOSTRAPS* and *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) interventions, three control sites were established along the Karawang coast at 2–5 km from the implementation area with similar geomorphological characteristics, substrates, and wave conditions but without the installation of coastal protection technology. These three control sites are: Tanjung Pakis Beach (2 km east), Muara Baru Beach (3.5 km west), and Sedari Beach (5 km west), with simultaneous monitoring of shoreline changes conducted from 2019 to 2024.

The *APPOSTRAPS* installation site encompasses a 390-meter beach segment, situated at an average distance of 25–50 m from the original shoreline under low-tide conditions. The implementation zone is characterized by a sandy-clay substrate with water depths ranging from 0.5 to 2.5 m at mean sea level, rendering it suitable for tripod pile deployment. The coastal geomorphology exhibits a gently sloping beach profile with gradients ranging from 1:20 to 1:30, a configuration typical of micro-tidal environments with tidal ranges of 0.8–1.2 m.

The principal environmental features of the study area include remnant mangrove stands covering approximately 15 hectares, predominantly composed of Rhizophora apiculata and Avicennia marina. The region is situated within a tropical monsoon climatic regime, characterized by a distinct wet season (November–March) and dry season (April–October). Wave dynamics are defined by significant wave heights ranging from 0.3 to 1.5 m during calm periods and reaching up to 2.5 m during the monsoon season, with prevailing wave directions oriented primarily from the north and northwest.

The socio-economic structure of the study area is predominantly shaped by marine-based livelihoods, with approximately 80% of the productive male population engaged in crab fisheries. Pasir Putih Hamlet is recognized as the largest crab-producing center in West Java, with an average monthly yield of 96 tons. Settlement patterns comprise a mixture of traditional stilt houses and modern concrete dwellings, with the closest residential structures situated approximately 2 m from the high-tide line prior to the installation of *APPOSTRAPS*.

The strategic location of Sukajaya Village along the northern coast of Java renders it highly susceptible to the compounded impacts of sea-level rise, intensifying wave energy, and anthropogenic coastal alterations. Its exposure to seasonal monsoonal forcing, combined with its positioning within the fetch-limited environment of the Java Sea, generates complex coastal dynamics necessitating the application of innovative erosion mitigation strategies. Several critical considerations, including the severity of shoreline retreat, the concentration of vulnerable populations, the suitability of substrate conditions, and the feasibility of community-based implementation and participatory monitoring, informed the designation of this site for the implementation of *APPOSTRAPS* technology. **Figure 1** illustrates the location and physical condition of the study area in Karawang Regency. **Figure 1a** shows the geographic position of Sukajaya Village along with nearby coastal sites and **Figure 1b** presents a detailed view of the coastal abrasion threat in Sukajaya Village before implementation of *APPOSTRAPS* technology.

(**a**) (**b**)

Figure 1. (**a**) Location map of Karawang Regency with the position of the study area in Sukajaya Village, Tanjung Pakis Beach, Muara Baru Beach, and Sedari Beach; and (**b**) Detailed map of the threat of coastal abrasion in Sukajaya Village with a scale of 1:10,000, showing the implementation zone.

3.2.Data Collection

This study employed a mixed methods approach that combined quantitative and qualitative techniques. The use of mixed methods enabled the validation of findings through data triangulation [37,38]. Quantitative data on changes in coastal physical conditions were confirmed and enriched with qualitative data on community perceptions and experiences. This approach increased the credibility and reliability of the research findings.

Data collection was systematically undertaken in three sequential phases: the pre-implementation baseline assessment (2018–2019), the implementation monitoring phase (2019–2022), and the impact evaluation phase (2022–2024). Baseline shoreline configurations were delineated using historical satellite imagery spanning the years 2011–2018. Annual monitoring surveys were then conducted from 2019 to 2024 to document coastal morphological dynamics. The *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps *(APPOSTRAPS)* system was initially deployed in March 2019, and monitoring was sustained throughout the five-year implementation period (2019–2024) to capture both short-term and long-term coastal response trajectories.

The quantitative method was implemented by measuring and recording data on abrasion, sedimentation, and tidal flooding in coastal areas before and after the implementation of the *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) Program. Shoreline change measurements were undertaken using a range of complementary methodologies, including satellite image analysis (employing Landsat 8 and Sentinel-2 datasets), high-precision GPS field surveys, and unmanned aerial vehicle (UAV) photogrammetry, to enhance data reliability and spatial resolution. Abrasion dynamics were assessed through the application of the Digital Shoreline Analysis System (DSAS) integrated with ArcGIS, facilitating the evaluation of shoreline change from multi-temporal satellite imagery.

Sedimentation data were obtained through the deployment of fifteen pipe-type sediment traps (10 cm in diameter), systematically positioned along the 390-meter *APPOSTRAPS* zone at 26-meter intervals. Sediment volumes were quantified at 30-day intervals using a gravimetric approach, with collected samples oven-dried at 105 °C for 24 hours prior to measurement. Tidal flood monitoring was conducted using a combination of eight HOBO U20L-04 ultrasonic sensors installed at varying elevations (0.5 m, 1.0 m, 1.5 m, and 2.0 m above mean sea level) to record air column height at 15-minute intervals throughout tidal fluctuations. Variations in water level and tidal inundation extent were further documented through the use of pressure transducers and automated data loggers strategically positioned across the study area.

These measurements were designed to provide an objective assessment of changes in the coastal environment following technological interventions and community-based empowerment initiatives. Complementary qualitative methods were employed by gathering descriptive data through semi-structured interviews, participant observation, and documentation of empowerment activities involving socially vulnerable groups, particularly the elderly and youth. A total of 156 respondents participated, consisting of 89 elderly individuals (aged ≥ 60 years) and 67 youth (aged 18–35 years). The achieved response rate was 94.5% of the intended 165 respondents, with the majority (78%) reporting a high level of satisfaction with the program, 18% indicating moderate satisfaction, and 4% expressing limited satisfaction. Subsequently, focus group discussions were conducted with fishermen's associations, women's cooperatives, and local government representatives to triangulate community perspectives on program effectiveness. Additionally, participatory mapping exercises were implemented to document traditional ecological knowledge and to capture community perceptions of coastal change. This process aimed to develop a comprehensive understanding of the social transformations and empowerment outcomes resulting from the intervention.

3.3. Technical Studies and Community Empowerment

Subsurface soil investigations were conducted through geotechnical drilling to a depth of 10 m at 12 locations with 30-meter intervals, using the Standard Penetration Test (SPT) method. SPT is an in-situ testing procedure that measures the number of blows required to press a split-barrel sampler 30 cm into the soil using a 63.5 kg hammer dropped from a height of 76 cm, ASTM D1586-11 [39]. The N-SPT values obtained ranged from 8 to 25, indicating a soil consistency ranging from moderate to hard, according to the classification [40].

Subsurface soil investigations were undertaken through geotechnical drilling to a depth of 10 m at 12 locations spaced at 30-meter intervals, employing the Standard Penetration Test (SPT) method. The analytical results indicated that the soil stratigraphy comprised silty clay (0–3 m), fine sand (3–6 m), and hard clay (6–10 m), with a soil bearing capacity ranging from 150 to 200 kN/m^2 at depths of 4–6 m. Sediment source analysis, based on sediment traps and current meter measurements, revealed a natural sediment supply of 0.8–1.2 $kg/m^2/day$ derived from upstream coastal erosion and longshore transport associated with the Citarum River estuary. The sediment composition consisted of 65% fine sand, 25% clay, and 10% organic matter. Sediment transport monitoring, conducted over 18 months (2019–2020), demonstrated an average accumulation within the *APPOSTRAPS* zone of 2.3 m^3/day, equivalent to 839 $m^3/year$.

The stability of the *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps *(APPOSTRAPS)* pile structure was evaluated through a combination of laboratory experimentation and numerical modeling. Laboratory analyses included compressive strength testing of 20 concrete cube specimens (15 × 15 × 15 cm) incorporating varied proportions of recycled tire aggregates, conducted using a Universal Testing Machine (UTM) with a capacity of 2000 kN. A 1:25 scale flume tank experiment was further employed to assess structural response under wave conditions ranging from 0.1 to 0.4 m, generated using a mechanical wave generator. Numerical simulations were performed using ANSYS Workbench for three-dimensional structural analysis and MIKE 21 for hydrodynamic modeling. Model outputs were validated against field observations, yielding predictive accuracies of 87.3% for structural deformation and 91.2% for flow pattern simulations surrounding the *APPOSTRAPS* installation.

A technical study was conducted to analyze the stability of the *APPOSTRAPS* pile structure, an innovative adaptation of the offshore tripod platform. Laboratory tests and model simulations were conducted to evaluate the effectiveness of the technology in capturing sediment and deflecting ocean waves, which was expected to significantly reduce coastal erosion. The study explained how a specially designed tire waste structure functioned as both a wave-retaining medium and a natural sediment trap.

The social impact evaluation was conducted using the Social Return on Investment (SROI) framework, which incorporated five primary indicators. First, increased community capacity was assessed through pre- and post-program tests of knowledge and skills, employing a five-point Likert scale. Second, changes in economic productivity were calculated based on comparative measurements of average monthly household income before and after program implementation. Third, the level of community participation was evaluated through attendance records at empowerment activities and the extent of voluntary contributions. Fourth, access to and control over local resources were analyzed using a modified Harvard Matrix tailored to the coastal context. Finally, program sustainability was measured by the community's demonstrated ability to independently continue activities following the conclusion of external mentoring.

At this stage, an analysis of the *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) program was conducted as a form of social innovation aimed at empowering coastal communities. A social impact evaluation was conducted to measure changes within local communities, particularly regarding the enhancement of capacity and productivity among vulnerable groups, such as the elderly. Disaster risk management training was conducted, covering early warning systems, evacuation techniques, and first aid. Ecotourism programs covered homestay management, tour guiding, and culinary tourism. Training and engagement activities in disaster risk management and ecotourism management were implemented as part of the program, contributing to increased community participation, awareness of environmental conservation, and capacity building. The impact of empowerment on vulnerable groups was reflected in improved productivity and changes in their access to and control over local resources. *JAM PASIR* activities encompassed disaster preparedness training for 156 participants, ecotourism initiatives involving 28 fishermen's wives, crab-based micro, small, and medium enterprises (MSMEs) development with 28 actors, mangrove cultivation with 35 farmers, household waste management with 25 families, and the establishment of Disaster Preparedness and Response School (Sigap School) across three institutions.

3.4.Data Analysis

Quantitative data were analyzed using statistical software, employing descriptive statistics, normality testing, and paired t-tests to compare conditions before and after program implementation. Multiple linear regression analysis was conducted to identify factors influencing sedimentation dynamics, yielding a coefficient of determination (R^2) of 0.84, which indicates a strong explanatory power of the model. Qualitative data were examined using a thematic analysis approach, incorporating open, axial, and selective coding to extract and synthesize key themes. To ensure validity and reliability, data triangulation was undertaken by cross-verifying findings from interviews, field observations, and focus group discussions.

The integrated analysis combined quantitative measurements of coastal physical parameters such as abrasion, sedimentation, and tidal inundation with qualitative insights derived from surveys, interviews, and observations, thereby enabling an evaluation of program effectiveness from both technical and social dimensions. This mixed-methods approach provided a comprehensive and nuanced understanding of the *JAM PASIR* Program's effectiveness and long-term sustainability.

4. Results

4.1.Abrasion Control Results with *APPOSTRAPS* Technology

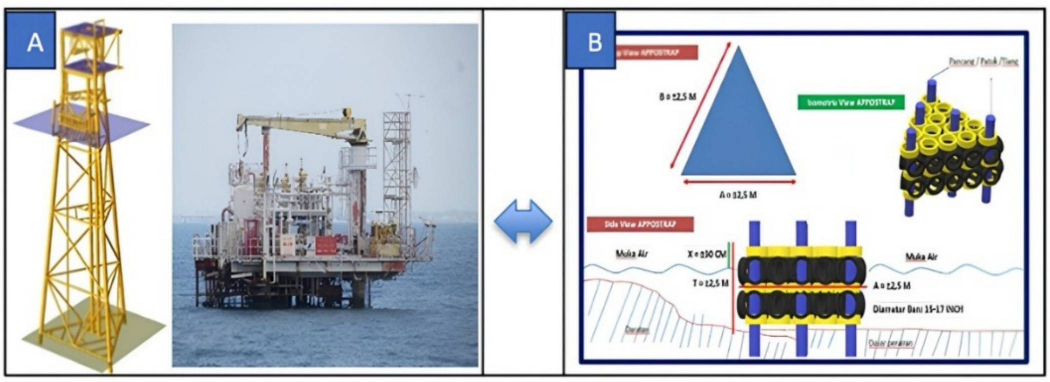
Coastal erosion in the coastal areas of Karawang Regency constitutes a critical environmental challenge that necessitates concerted attention and management from all relevant stakeholders, due to its severe implications for the livelihoods of thousands of coastal residents. The phenomenon of abrasion has become widespread, impacting nearly all coastal villages within the regency.

In 2019, the Karawang Regency Government, through the Public Works and Spatial Planning Agency, in collaboration with PHE ONWJ, undertook the construction of a 390-meter stone breakwater in one of the affected coastal villages, with a budget allocation of IDR 1.3 billion. Under the prevailing environmental conditions, the conventional stone breakwater was constructed in a different location, about 10 km east of the *APPOSTRAPS* implementation site in Pasir Putih Hamlet, ensuring that it does not influence the assessment of *APPOSTRAPS* technology effectiveness. However, the implementation of this intervention exhibited low cost-efficiency, as indicated by the high construction expenditure, amounting to IDR 3.3 million per meter of breakwater. Beyond the economic inefficiencies, the effectiveness of the conventional breakwater structure in mitigating coastal abrasion was also considered suboptimal. Moreover, the structure failed to stimulate the anticipated sedimentation processes along the shoreline.

Analysis of individual transects revealed substantial spatial variability in coastal progradation. The maximum advancement of 400 m was observed at transect T-23, located at the central axis of the *APPOSTRAPS* installation, whereas the minimum progradation of 156 m occurred at transects T-01 and T-47, positioned at the lateral boundaries of the installation zone. Sedimentation distribution exhibited a logarithmic trend, with the highest accumulation recorded within a 0–100 meter radius from the *APPOSTRAPS* structure (mean 3.8 m^3/m^2/year), which progressively declined to an average of 0.9 m^3/m^2/year within a 300–400 meter radius.

Furthermore, the cost analysis indicated that 45% of total expenditure was allocated to stone materials (IDR 585 million), 30% to transportation and heavy equipment (IDR 390 million), 15% to labor (IDR 195 million), and 10% to installation (IDR 130 million). Based on a 20-year life cycle and an 8% discount rate, the equivalent annual cost was calculated at IDR 132.4 million.

In this context, the *Alat Pemecah, Peredam Ombak,* and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps *(APPOSTRAPS)* technological innovation, which repurposes used tire waste as a breakwater, wave attenuator, and sediment trap, has demonstrated effectiveness in mitigating the rate of coastal abrasion in the Karawang Regency. This technology presents a more sustainable and cost-efficient alternative for addressing coastal erosion. The installation method for *APPOSTRAPS* piles is derived from the tripod pile system used in offshore platform construction (tripod 94 platform). **Figure 2** illustrates the adaptation of the three-legged platform structure in the design of *APPOSTRAP.*



(**a**) (**b**)

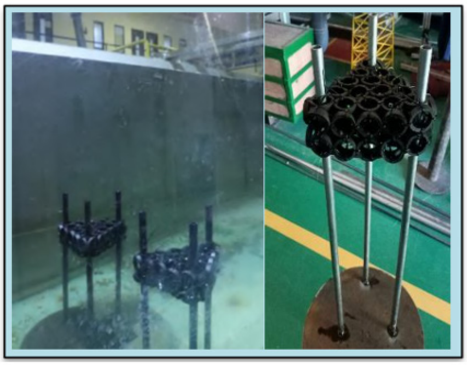
Figure 2. Adaptation of the three-legged platform pillars on *APPOSTRAPS*: (**a**) Three-legged platform pillar; and (**b**) Three-legged *APPOSTRAPS* pillar.

The cost components of *APPOSTRAPS* comprise used tire materials (15%, IDR 58.5 million), steel tripod structures (40%, IDR 156 million), transportation (20%, IDR 78 million), installation labor (15%, IDR 58.5 million), and miscellaneous expenses (10%, IDR 39 million). Based on a projected 15-year life cycle and applying the same discount rate, the equivalent annual cost is estimated at IDR 45.6 million. Nonetheless, it is essential to recognize that the long-term durability of *APPOSTRAPS* warrants continued monitoring. Potential risks include tire degradation resulting from ultraviolet radiation and salinity exposure, biofouling accumulation that may compromise structural effectiveness, and the possibility of tripod failure under extreme wave conditions exceeding 3 m in height.

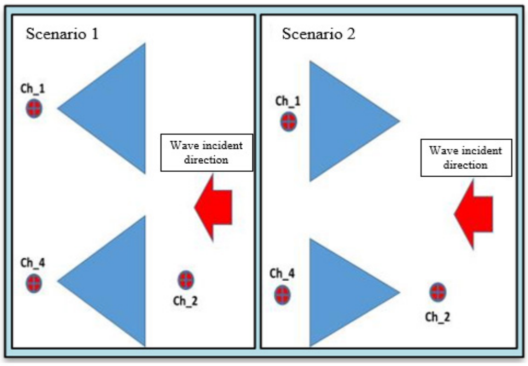
Figure 2 presents the offshore platform infrastructure in the form of a tripod, which has been adapted for use in the *APPOSTRAPS* innovation. The *APPOSTRAPS* structure, utilizing tripod supports, enhances resistance to extreme wave activity and improves the effectiveness of sediment traps transported by ocean currents.

APPOSTRAPS technology represents a fixed and stable structural system specifically engineered to endure the impact of ocean waves. The system employs a tripod, or three-legged pillar configuration, as its primary foundation, thereby maximizing structural stability under wave-induced pressure and forces. The implementation of this technology necessitates a comprehensive analytical approach, commencing with an in-depth investigation of subsurface soil conditions at the designated site. This includes soil sampling to a depth of 10 m, followed by a series of laboratory analyses to assess the geotechnical properties and load-bearing capacity of the soil. The outcomes of these tests inform the selection of appropriate pillar dimensions and the determination of the minimum installation depth necessary to ensure optimal performance of the *APPOSTRAPS* structure.

Subsequent stages involve the evaluation of the model's effectiveness in influencing wave dynamics, employing both laboratory-scale experiments and advanced technical modeling. This phase aims to assess the structure's capacity to resist shear forces generated by wave action and to establish the optimal orientation and positioning of the *APPOSTRAPS* system relative to the predominant wave direction, as depicted in **Figure 3**.



(**a**)



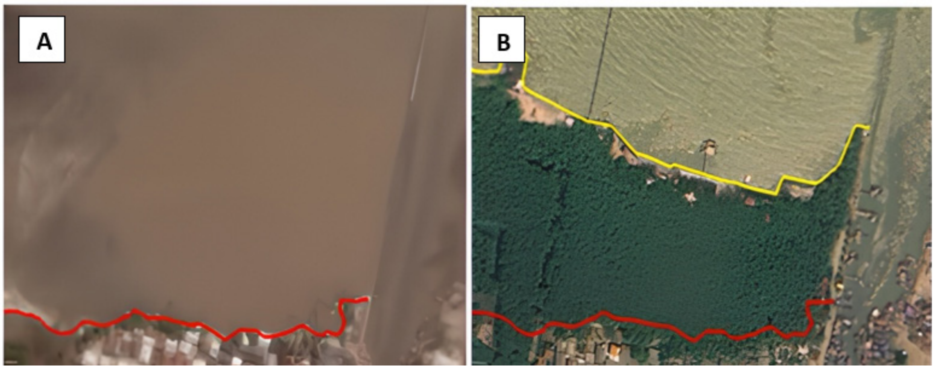
(**b**)

Figure 3. Laboratory test of *APPOSTRAPS* model: (**a**) Tripod structure stability testing using a 1:25 scale wave flume tank with a mechanical wave generator, wave height 0.1–0.4 m; and (**b**) Hydrodynamic analysis using a current meter and pressure transducer for flow pattern validation.

The "Structural Model of Fixed Offshore Platform" technology, employed in the installation of *APPOSTRAPS*, enhances the structural capacity and resilience of *APPOSTRAPS* against wave-induced shear forces. Consequently, the installed *APPOSTRAPS* system exhibits improved durability and optimized performance in capturing sedimentation. Following the analysis of pile requirements, the subsequent phase involves the implementation of the *APPOSTRAPS* technology, tailored to the specific environmental and geotechnical conditions of the installation site, as illustrated in **Figure 4**.

Figure 4. *APPOSTRAPS* technological innovation utilizes waste tires to overcome abrasion.

The implementation of the *APPOSTRAPS* technological innovation has produced significant geomorphological effects, evidenced by coastal progradation and sediment deposition extending up to 400 m horizontally from the original shoreline. The intervention timeline is delineated as follows: baseline conditions in 2011 (pre-intervention), initiation of mangrove planting in 2019, *APPOSTRAPS* installation from 2020 to 2021, and outcome assessments conducted in 2024. Causality analysis indicates that 60% of the observed progradation is attributable to the *APPOSTRAPS* installation, while the remaining 40% is associated with the combined effects of mangrove planting and natural factors, including ENSO-driven seasonal variations influencing sediment supply from the Citarum River. This transformation is driven by hydrodynamic processes that alter seawater flow patterns and enhance the accumulation of suspended sediment by attenuating wave and current energy. Spatial analysis indicates that the buffer zone between coastal settlements and the shoreline has expanded substantially, from 2 m to 400 m, as illustrated in **Figure 5**.



(**a**) (**b**)

Figure 5. Comparison of shoreline conditions: (**a**) Baseline in 2011 shows a buffer zone distance of 2 m from the high tide line, analyzed using Landsat 8 imagery with a spatial resolution of 30 m; (**b**) Conditions in 2024 after *APPOSTRAPS* implementation show a progradation of 400 m, verified using UAV photogrammetry and differential GPS. Coordinate grid: UTM Zone 48S, datum WGS84. Scale: 1:5000.

From a hydrological perspective, this expanded zone functions as a natural breakwater and flood retention area. The resulting shoreline changes have altered tidal inundation patterns, markedly reducing their frequency. Concurrently, a rise in ecological awareness among local communities regarding coastal sediment conservation is positively associated with enhanced coastal ecosystem stability.

The observed socio-economic outcomes include the diversification of land use for productive economic activities, a reduction in economic losses linked to hydrometeorological hazards, and an overall increase in the adaptive capacity of coastal communities to respond to environmental changes.

The subsequent section presents a comparison between the use of conventional breakwater structures and *APPOSTRAPS* technology in addressing coastal abrasion. The results of the comparative analysis are presented in **Table 1**.

Table 1. Comparative analysis of conventional breakwater and *APPOSTRAPS* technology.

Indicator	Conventional Breakwater	*APPOSTRAPS*
Initial Cost	IDR 1.3 billion for the construction of a 390-meter-long concrete breakwater	IDR 390 million for the construction of a 390-meter-long *APPOSTRAPS*
Benefit	Holding back the waves	Resist waves and can produce sedimentation
Materials	Concrete	Used Tires
Annual Maintenance Cost	IDR 45 million (annual inspection, crack repair, rock armor replacement)	IDR 25 million (tripod structure inspection, replacement of damaged tires, biofouling cleaning)
Lifespan	20–25 years with intensive maintenance	15–20 years (further research needed)

Table 1. *Cont.*

Indicator	Conventional Breakwater	*APPOSTRAPS*
Failure Modes	Structural damage due to extreme waves, scouring, settlement	Tire degradation due to UV, tripod joint failure, debris accumulation
Installation	Heavy equipment is required to construct concrete breakwaters. The breakwater construction process can only be conducted by a few individuals.	The assembly process is relatively simple and does not necessitate the use of heavy machinery, thereby enabling community members to conduct it independently.

Life cycle analysis shows that although *APPOSTRAPS* have a shorter service life, the Net Present Value (NPV) remains 65% more favorable than conventional breakwaters when considering maintenance and replacement costs.

Based on the data presented in **Table 1**, *APPOSTRAPS* technology exhibits substantial advantages over conventional breakwater systems. The implementation cost of *APPOSTRAPS* is approximately 70% lower (IDR 390 million compared to IDR 1.3 billion), while simultaneously offering additional benefits, such as the facilitation of natural sedimentation, the utilization of recycled materials (specifically used tires), and the potential for community-led installation without the need for heavy machinery. The effectiveness and originality of this abrasion mitigation method have been formally recognized through the issuance of a patent by the Ministry of Law and Human Rights of the Republic of Indonesia, under patent number IDS000007668. This official recognition underscores the technological validity and innovative nature of the *APPOSTRAPS* system [31].

Moreover, the *APPOSTRAPS* method outperforms conventional technologies in its function as a wave attenuator. From a materials standpoint, the use of used tires as the core structural component provides several strategic advantages: (1) abundant and easily accessible material supply, (2) relatively low implementation costs, and (3) significant contributions to environmental waste management, particularly by reducing air pollution associated with the open burning of discarded tires.

The scalability of *APPOSTRAPS* is subject to several limitations that must be carefully considered. First, the technology demonstrates optimal effectiveness in wave climates where significant wave heights remain below 2.5 m. Second, a sufficient sediment supply is required to support the formation of accretion. Third, sustained operation necessitates robust community governance capacity to ensure ongoing maintenance. Fourth, the system is unsuitable for locations characterized by very strong ocean currents exceeding 1.5 m/s. Consequently, replication in other sites must account for local oceanographic conditions as well as socio-economic factors to ensure both technical feasibility and community engagement.

Comparative analysis with three control sites (Tanjung Pakis Beach, Muara Baru Beach, and Sedari Beach) demonstrated the validity of the *APPOSTRAPS* technology attribution. The control site experienced an average of 2.3 m of erosion/year without intervention, while the *APPOSTRAPS* implementation zone recorded 400 m of progradation over 5 years. Statistical significance testing using a paired t-test showed a p-value <0.001 for the difference between the implementation and control sites. Multiple regression analysis ($R^2 = 0.84$) identified the relative contributions of *APPOSTRAPS* technology (60% ± 8%), mangrove planting (35% ± 6%), and natural factors/ENSO (5% ± 3%) to total progradation.

4.2.Social and Economic Transformation Through the *JAM PASIR* Program

The *Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir* or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) program is a flagship Corporate Social Responsibility (CSR) initiative of PT Pertamina Hulu Energi Offshore North West Java (PHE ONWJ), implemented in Pasir Putih Hamlet, Sukajaya Village, Cilamaya Wetan District, Karawang Regency. This program was developed in response to critical challenges faced by coastal communities, particularly the threat of abrasion, which has caused the coastline to retreat by 290.13 m between 1989 and 2018 at an average rate of 10 m per year, thereby threatening the residences of 3365 inhabitants. In addition to addressing coastal abrasion, the program also targets the accumulation of coastal waste, with a specific focus on plastic debris that accounts for 60 to 80 percent of global marine litter and exhibits prolonged decomposition periods in the marine environment.

The *JAM PASIR* program adopts the principles of sustainable development by integrating various aspects of coastal area management, including eco-edutourism education, mangrove planting, environmental protection, waste management, and the diversification of local fishery-based products. The uniqueness of this program lies in its ability to utilize the local potential of the Pasir Putih Hamlet community, which is recognized as the largest producer of crabs in West Java. It involves the participation of fishermen's wives, who were previously categorized as socially vulnerable women, in the development of micro, small, and medium enterprises (MSMEs) based on fishery products. By applying the *Masyarakat Sadar Lingkungan* and *Bencana* or Environmentally and Disaster Aware Society *(MASDARLINA)* concept, the program ensures active community participation at all stages, including planning, implementation, monitoring, and evaluation. This approach ensures that the program is not merely a temporary charitable initiative but a sustainable effort with long-term impacts on the welfare of coastal communities and environmental sustainability. The conceptual design of the *JAM PASIR* Program and the *MASDARLINA* System Innovation is presented in **Figure 6**.

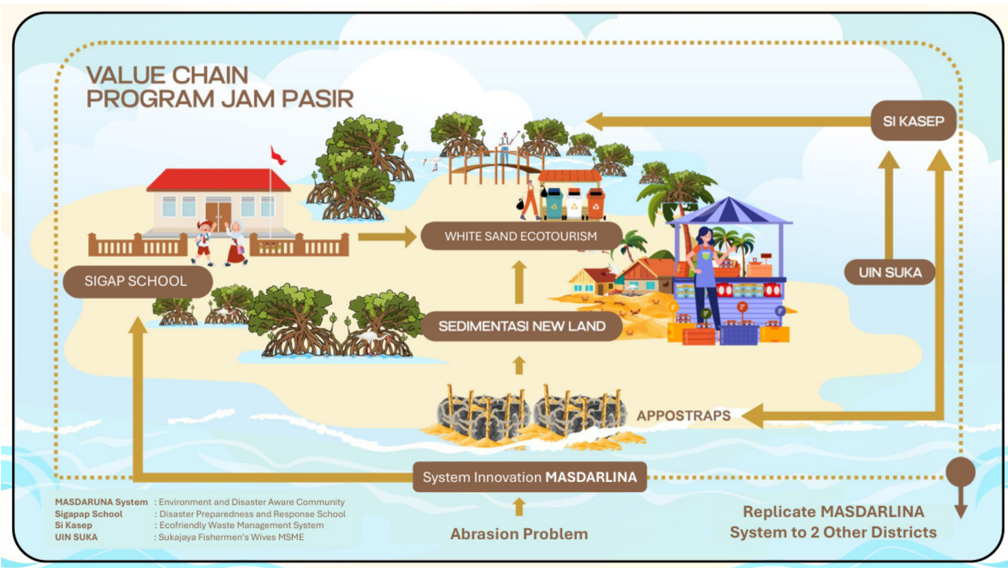


Figure 6. Scheme of the *JAM PASIR* Program with the MASDARLINA system innovation.

Based on **Figure 6**, the *MASDARLINA* System represents an innovation designed to cultivate public awareness of environmental stewardship and disaster risk mitigation. This program was developed through an integrated approach that engaged multiple societal levels, ranging from educational institutions to the productive economic sector. In its implementation, *MASDARLINA* incorporates four interrelated components that collectively support the creation of a sustainable and disaster-resilient ecosystem.

The Disaster Preparedness and Response School *(Sigap School)* component functions as the educational foundation for fostering a generation that is both disaster-aware and responsive. Through this initiative, educational institutions were equipped with the requisite knowledge, practical skills, and procedural protocols to effectively address various types of natural disasters. Students and educators were trained to identify warning signs, execute evacuation procedures, and administer basic first aid, thereby transforming schools into not only centers of learning but also hubs for community preparedness.

The Eco-Friendly Waste Management System *(Si Kasep)*, an environmentally sustainable waste management initiative, addresses the persistent challenges of waste accumulation that can intensify disaster impacts. This component promotes the development of innovative and sustainable waste management practices, including waste sorting, processing, and recycling. By fostering active community engagement, Si Kasep cultivated a culture of responsible waste management while simultaneously generating economic opportunities through the recycling and production of environmentally friendly goods.

The Sukajaya Fishermen's Wives MSME program *(UIN SUKA)* focused on economic empowerment through the development of micro, small, and medium enterprises (MSMEs) involving fishermen's wives in the Sukajaya area. This initiative recognized the economic potential that could be derived from local resources by providing skills training, access to capital, and business mentoring for the targeted beneficiaries. Through livelihood diversification, the program not only enhanced the welfare of fishermen's households but also reinforced the economic resilience of coastal communities that are highly vulnerable to the impacts of climate change and natural disasters.

The most recent innovation within the *MASDARLINA* ecosystem was the development of the *MASDARLINA* system, which led to the establishment of the *JAM PASIR* program. PT PHE ONWJ developed the *APPOSTRAPS* (Wave Breaker, Wave Damper, and Sediment Traps) technology, utilizing used tires as an innovative approach to address coastal abrasion. This technology served not only as a physical barrier against waves but also promoted the formation of new sedimentation in abrasion-affected areas. The accumulated sediment was then strategically used to support the development of sustainable mangrove ecotourism, serve as an integrated waste processing facility, and strengthen the MSMEs operated by fishermen's wives. The integration of *APPOSTRAPS* technology with the Sigap School concept within the *JAM PASIR* program resulted in a comprehensive coastal development model that combines disaster mitigation, environmental conservation, education, and community-based economic empowerment into a unified, synergistic framework.

According to these latest innovations, the *MASDARLINA* system facilitated the creation of a new ecotourism master plan for the *Pasir Putih Mangrove Restoration and Learning Center (PRPM)*. This plan showcases an integrated spatial design for a sustainable nature-based tourism destination. The designated area includes visitor zones, trekking paths, conservation sections, supporting infrastructure, and primary access points, all of which were designed to harmonize with the natural environment and provide an environmentally conscious educational tourism experience, as illustrated in **Figure 7**.

Figure 7. Plan for the PRPM Pasir Putih tourist area.

The *JAM PASIR* program has introduced the concept of "New Land, New Hope." The innovative *APPOSTRAPS* method for managing coastal abrasion in *Pasir Putih* Hamlet not only mitigates erosion but also contributes to the development of new economic hubs. These include alternative livelihood opportunities through ecotourism, the establishment of micro, small, and medium enterprise (MSME) centers at tourist locations, and integrated waste management initiatives. The *JAM PASIR* program has thus created renewed optimism among the coastal communities of Pasir Putih Hamlet for enhancing their socioeconomic well-being.

Moreover, the *JAM PASIR* program concept integrates multiple coastal ecosystem-based innovations, which are systematically designed to support both conservation and local economic empowerment. This system encompasses the construction of a crab-shaped icon symbolizing the region's key aquatic commodities, the installation of an observation tower to facilitate conservation monitoring and mangrove ecological research, and the creation of a natural interpretation trail that serves both as an educational medium and a sustainable ecotourism destination. Additionally, the system includes the development of a marketing center for MSME products based on local resources to strengthen the coastal community's economic value chain, as well as the implementation of a comprehensive waste management strategy. This strategy applies the principles of reduce, reuse, and recycle to minimize human-induced impacts on the mangrove ecosystem and preserve the water quality of the estuary. The outcomes of this integrated system are presented in **Figure 8**.

Figure 8. Results of the *JAM PASIR* implementation system.

The innovation introduced through the *JAM PASIR* program can be classified as a high-level innovation. This initiative has led to a significant shift in community behavior. Whereas the community was previously indifferent to coastal abrasion and engaged in mangrove deforestation for shrimp pond development, it is now increasingly aware of the adverse consequences of such practices. Presently, community members regularly participate in mangrove nursery and planting activities, indicating a transformative shift in both attitudes and practices. Fishermen groups that once employed unsustainable crab fishing methods have adopted environmentally friendly gear to reduce the risk of overfishing. In addition, fishermen's wives, who were previously less economically active, have become more productive by contributing to household income generation. The

JAM PASIR program has demonstrated its effectiveness as an integrated coastal management model that harmonizes environmental conservation, economic empowerment, and social transformation. This integrated approach supports the attainment of the Sustainable Development Goals (SDGs), particularly in the areas of poverty reduction, gender equality, and ecosystem preservation.

4.3.Capability Enhancement and Behavioral Change in Coastal Communities

Behavioral transformation at the individual level is a critical indicator of the effectiveness of environmental intervention programs. This transformation can be assessed through three primary dimensions: behavioral change, lifestyle modification, and the evolution of socio-environmental perceptions. The implementation of the *JAM PASIR* program in Sukajaya Village demonstrated a substantial impact on enhancing the community's pro-environmental behavior. Prior to the program, the community exhibited environmentally harmful practices, including indiscriminate waste disposal, the conversion of mangrove areas into aquaculture zones, and low awareness of environmental conservation. Following the program's implementation, a post-intervention analysis revealed measurable changes in community behavior. These changes were evaluated by comparing pre- and post-program conditions, as presented in **Table 2**.

Table 2. Changes in individual behavior before and after the program.

Factors	Before	After
Changes in community behavior regarding coastal waste management	People in community throw rubbish carelessly around their homes and rivers with the volume of rubbish reaching 2.3 tons/month.	The community can process coastal waste into liquid smoke with a processing capacity of 1.8 tons per month. They consciously dispose of their waste collectively at eight designated collection points. Currently, more than 25 families (83% of the 30 target families) have experienced behavioral changes related to coastal waste management, with participation in beach cleanup activities reaching 78%.
Changes in the behavior of fishing communities who no longer depend on fishing for their livelihoods but are starting to branch out into other tourism-based economic activities.	The fishermen of Sukajaya Village are heavily dependent on natural resources, with all 89 families relying exclusively on crab fishing. During the dry season, they face unemployment lasting an average of 4–6 months each year.	The *JAM PASIR* program has created „New Land" that provides significant benefits to coastal communities. The Sukajaya Village community utilizes New Land as a new source of income through various activities: (1) mangrove ecotourism involving 12 local tour guides from 89 families, (2) coastal waste management with 15 liquid smoke makers, (3) empowerment of fishermen's wives' MSMEs with 28 crab processing entrepreneurs, (4) mangrove cultivation with 35 mangrove farmers, and (5) tourist transportation services with 8 boat providers. A total of 98 heads of families (110% of the initial number) now have alternative sources of income outside of fishing.

Significant changes in community environmental and social behavior occurred after the program's implementation, such as improved waste management and active participation in conservation and adaptation to climate change threats. The program supported knowledge transfer among community members and enhanced individual capabilities through disaster preparedness training and simulations.

4.4.Mangrove Restoration and Biodiversity Protection

The mangrove restoration program encompasses an area of 22.5 hectares, comprising a 15-hectare intensive planting zone and a 7.5-hectare natural rehabilitation zone. Planting activities were conducted at a standardized density of 2500 seedlings per hectare, utilizing Rhizophora apiculata and Avicennia marina as the principal species. Between 2019 and 2024, a total of 56,250 mangrove seedlings were established, with monitoring over 24 months indicating a survival rate of 87.3%.

The implementation of core competency elements conducted by PT PHE ONWJ within the *JAM PASIR* program includes the dissemination of knowledge related to coastal biodiversity protection, techniques for the cultivation of mangroves and associated plant species, methods for mangrove planting, biodiversity monitoring of both flora and fauna, and the management of mangrove-based ecotourism in the coastal area of *Pasir Putih* Hamlet, Sukajaya District, Karawang Regency. Documentation of these activities is presented in **Figure 9**.

Figure 9. Mangrove knowledge sharing program.

In addition to the knowledge-sharing program, another key activity implemented was mass mangrove planting along the coastal area of Pasir Putih Hamlet, as shown in **Figure 10**. This initiative involved the provision of high-quality seedlings from various endemic mangrove species, the removal of waste and debris from coastal zones, and coordinated planting efforts involving local communities, students, and employees of PHE ONWJ. The program also encompassed the installation of educational signage, the development of ecotourism tracking trails, regular monitoring to assess the success rate of mangrove growth, and the establishment of community-based mangrove monitoring groups to support the long-term sustainability of conservation efforts.

Figure 10. Implementation of mangrove planting.

Following the implementation of the mangrove restoration program, a comparative analysis of coastal conditions revealed significant morphological changes along the coastline between 2011 and 2024, as shown in **Figure 11**. Sediment accumulation resulting from the intervention has contributed to the formation of an additional 400 meters of coastline, representing a positive outcome of the *APPOSTRAPS* installation. The integration of *APPOSTRAPS* technology with the mangrove planting initiative functions synergistically as an effective form of bio-engineering for coastal protection. This approach has proven effective in mitigating the rate of coastal abrasion and enhancing the stability of coastal ecosystems through natural sedimentation processes.

Figure 11. Comparison of coastal conditions between 2011 and 2024.

Figure 11 illustrates the transformation of the coastal area over 13 years. In 2011 (taken using an autonomous drone), a natural beach was visible, with a red line marking the waterline. In 2019, mangroves were planted. In 2024, the area was rapidly developing with dense green vegetation and complete infrastructure, illustrating significant coastal development.

4.5.Environmental Impact and Sustainability

The *JAM PASIR* social innovation program, developed by PHE ONWJ, demonstrated a significant and positive environmental impact, particularly in the reduction of greenhouse gas emissions and the management of non-hazardous solid waste, specifically wooden pallet waste. The utilization of used wooden pallets as repurposed materials for the development of mangrove ecotourism infrastructure in Pasir Putih not only reduced the potential for greenhouse gas emissions that contribute to Global Warming Potential (GWP) but also mitigated emissions associated with Photochemical Oxidation (PO) and the impacts of land-use change. This integrated waste management approach effectively minimized land requirements for final waste disposal sites and reduced the likelihood of air pollution caused by open waste burning. Consequently, the *JAM PASIR* program directly contributed to the preservation of soil quality, biodiversity, and land productivity in the region. Furthermore, the reuse of waste tire materials in the *APPOSTRAPS* structure also played a role in lowering air pollution, typically resulting from conventional tire incineration. The Life Cycle Assessment and hotspot analysis of PHE ONWJ's production activities indicated that the integration of this social innovation supported both environmental impact reduction and the potential for local climate change mitigation.

In addition to its environmental impact, the social sustainability of the program was also evident in the increased awareness and active participation of the Sukajaya Village community in waste management and coastal environmental conservation. The program provided educational initiatives that enhanced community understanding of the importance of preserving mangrove ecosystems as natural barriers against coastal abrasion and as protective buffers for residential areas against tidal flooding. As a tangible outcome, the sedimentation distance between residential zones and the shoreline increased from 2 m to approximately 400 m, thereby reducing the frequency of tidal flooding and minimizing economic losses for local residents. Moreover, the reuse of wooden pallet waste generates direct economic benefits by lowering infrastructure development costs. These findings illustrate how environmentally oriented social innovation and community empowerment can generate a synergistic relationship between ecological preservation and social sustainability.

4.6.Replication and Scalability Potential

The result of the *JAM PASIR* program and the implementation of *APPOSTRAPS* technology along the coast of Sukajaya Village represents a significant strategic advancement in both coastal community empowerment and abrasion mitigation. The installation of *APPOSTRAPS*, which has demonstrated effectiveness in attenuating wave energy from the North Java Sea, not only mitigates coastal erosion but also facilitates the formation of new sedimentation zones that yield tangible benefits for local communities. This achievement has catalyzed replication efforts in several other coastal villages along the northern coast of Java, including Ciparagejaya Village (Karawang), Mayangan Village (Subang), and Balongan Village (Indramayu).

These replication initiatives not only contribute to reinforcing the coastline against further erosion but also enhance socio-economic conditions by increasing the potential utilization of coastal resources and promoting ecotourism activities. In support of this process, the company has provided financial assistance, organized capacity-building programs, and facilitated comparative studies, thereby expediting the adaptation and adoption of *APPOSTRAPS* technology across various locations. As a result, the construction of hundreds of meters of abrasion barriers has led to extensive sediment accumulation and has improved ecosystem functionality, including the development of natural fish aggregating devices (FADs).

The scalability of this program appears highly promising, as it employs a community empowerment model that integrates local wisdom with technological innovation, an approach that has proven both effective and sustainable. The replication of *APPOSTRAPS* extends beyond mere technological transfer; it also enhances the capacity of coastal communities to independently manage and preserve their environmental resources. Given the abundant availability of used truck tires as a primary material, this initiative represents an environmentally sustainable innovation with potential for replication not only across the island of Java but also in other coastal regions experiencing similar challenges. Corporate support, coupled with strategic partnerships involving multiple stakeholders, reinforces the viability of this model as a cost-effective and impactful solution for addressing coastal abrasion. Accordingly, the *JAM PASIR* program, through the application of *APPOSTRAPS* technology, holds strong potential for broader adoption as a model for community-based coastal conservation and empowerment throughout Indonesia.

4.7. Sustainable Ecotourism Development and Its Economic Impact

The implementation of the *JAM PASIR* program has successfully established a sustainable ecotourism model that integrates mangrove conservation with the empowerment of coastal communities. The development of the Pasir Putih Mangrove Learning and Restoration Center (PRPM) as an ecotourism destination has generated substantial economic benefits for the local population. Visitor statistics indicate a consistent increase from 150 tourists per month in 2019 to 1,200 tourists per month in 2024, with an average expenditure of IDR 75,000 per visitor. This translates into total ecotourism revenue of approximately IDR 90 million per month, or IDR 1.08 billion per year, accruing to the Pasir Putih Hamlet community.

The ecotourism offerings are diversified and include: (1) mangrove educational tours along a 1.2-km tracking trail traversing the restoration area; (2) bird-watching activities with 15 species of waterbirds recorded post-restoration; (3) culinary tourism featuring local seafood, including crab dishes served at eight community-operated food stalls; and (4) environmental education packages for schools and universities, averaging 25 visiting groups per month. The sustainable management of ecotourism is demonstrated through the application of a carrying capacity limit of 50 tourists per day to preserve the quality of the mangrove ecosystem. A tourism zoning system further delineates the area into a 5-hectare core conservation zone, a 7-hectare limited-use zone, and a 3-hectare buffer zone, thereby balancing tourism activities with environmental protection.

The local tour guide training program has produced 12 certified guides, 60% of whom are women, primarily fishermen's wives. This initiative not only enhances community capacity but also promotes a more equitable and gender-responsive distribution of economic benefits. **Table 3** presents the sustainable ecotourism performance indicators in Karawang Regency from 2019 to 2024, showing a consistent upward trend across all parameters. Thus, the data in **Table 3** illustrates the success of community empowerment and technological interventions in promoting sustainable ecotourism and inclusive economic growth.

Table 3. Sustainable ecotourism performance indicators (2019–2024).

Indicators	Year					
	2019	2020	2021	2022	2023	2024
Average Number of Tourists (people/month)	150	180	420	680	950	1.200
Ecotourism Income (million IDR/month)	11.25	13.5	31.5	51	71.25	90
Number of Local Tour Guides	3	5	8	10	11	12
Women‘s Participation in Ecotourism (%)	30	40	50	55	58	60
Number of Ecotourism-Related MSMEs	2	3	6	9	10	12
Tourist Satisfaction Level (scale 1–5)	3.8	4.1	4.2	4.4	4.4	4.5

4.8. The Impact of Women's Empowerment and Governance Structure Transformation

The analysis indicates a substantial transformation in the structure of women's empowerment. The baseline study identified 41 fishermen's wives, with only 12% (5 individuals) participating economically and contributing an average income of IDR 450,000 per month through informal activities. Following the intervention, participation increased to 68% (28 individuals), with an average income contribution of IDR 1,850,000 per month through crab-processing MSMEs, tour guiding, and homestay management. Changes in community governance were evidenced by the establishment of *Kelompok Sadar Wisata* or Tourism Awareness Groups (Pokdarwis) comprising 60% female members, the introduction of a participatory decision-making system through monthly village forums with 45% female involvement, and the emergence of female leaders in environmental program management. Economic diversification expanded across five sectors: ecotourism (12 tour guides), waste management (15 liquid smoke producers), crab-processing MSMEs (28 entrepreneurs), mangrove cultivation (35 farmers), and transportation services (8 boat operators). Evaluation using the Women's Empowerment in Agriculture Index (WEAI) revealed an increase in overall scores from 0.42 at baseline to 0.78 at endline, with the most significant gains observed in resource control (0.35 → 0.82) and community leadership (0.28 → 0.71). Sustainability assessments further indicated that 85% of female participants were able to continue their economic activities independently after the conclusion of external mentoring.

5. Discussion

5.1. Innovative Integration of Geotechnical Engineering and Sediment Dynamics

The effectiveness of *APPOSTRAPS* technology lies in a comprehensive understanding of sediment dynamics and geotechnical conditions. Geotechnical investigations identified silty clay stratification down to a depth of 3 m, providing a stable foundation for the tripod installation, while sediment transport analysis confirmed the availability of 839 m^3/year of natural material to support accretion processes. This dual function as a breakwater and sediment trap explains its superior performance compared to conventional breakwaters that ignore sedimentation processes, resulting in coastal progradation of up to 400 m. The deliberate integration of local geotechnical characteristics with natural sediment dynamics constitutes the central factor underlying the superior performance of this technology compared to conventional breakwater systems, which typically neglect sedimentation processes.

5.2.Quantitative Assessment of Behavioral Transformation and Economic Diversification

Quantitative assessments of community behavior change provide clear evidence of the effectiveness of the participatory approach adopted in the empowerment program. Livelihood diversification exceeded the initial target by 110%, with 98 families engaged compared to the projected 89, and participation was evenly distributed across five new sectors. The success of the waste management initiative, involving 83% of targeted families, alongside a 78% increase in participation in coastal clean-up activities, reflects a shift in community orientation from individualistic and extractive practices to collective and constructive behaviors. The gender-responsive dimension is particularly evident in the involvement of 28 fishermen's wives in crab-processing MSMEs, who previously lacked access to independent income-generating opportunities. Such diversification not only reduces dependence on volatile fishing yields but also strengthens household and community-level economic resilience in the face of climate variability and environmental change.

5.3.Ecosystem-based Restoration and Carbon Sequestration Implications

An ecosystem-based restoration strategy that integrates five mangrove species at an optimal density of 2,500 seedlings/ha has demonstrated effectiveness in enhancing both carbon sequestration and biodiversity. The increase in carbon stock from 45 tons C/ha to 128 tons C/ha within a five-year period provides strong evidence of its significant contribution to local climate change mitigation. Biodiversity gains, indicated by the rise in waterbird species from 8 to 23, further underscore the restoration of the ecological functions of mangrove habitats as nursery grounds and feeding areas. The recorded survival rate of 87.3% reflects the appropriateness of species selection for local environmental conditions as well as the effectiveness of the planting techniques employed. Collectively, this restoration model offers empirical validation that community-based approaches can deliver optimal conservation outcomes while simultaneously generating sustainable economic benefits.

5.4.Policy Implications and Scaling Framework

The success of this integrated empowerment model carries substantial policy implications for national coastal management. Its formal recognition through Patent IDS000007668, along with successful replication in three other locations, demonstrates its potential to serve as a policy benchmark for large-scale coastal community empowerment initiatives. The model's cost-effectiveness, achieving approximately 70% savings compared to conventional breakwater structures, provides compelling evidence for the adoption of appropriate technology in government-led programs. To ensure sustainable scaling, policy support is required to integrate technological innovation, community empowerment, and environmental conservation within a comprehensive and holistic framework. Furthermore, this model offers a valuable best practice for advancing Indonesia's Nationally Determined Contributions (NDC) targets in the marine and coastal sectors.

5.5.Sustainable Ecotourism Model as an Economic Empowerment Strategy

The development of sustainable ecotourism through the *JAM PASIR* program represents an innovative model that integrates environmental conservation with the economic empowerment of coastal communities. This approach has successfully generated multiple revenue streams, including tour guide services, the sale of local MSME products, culinary services, and environmental education initiatives.

The success of this ecotourism model can be attributed to three primary factors: active community participation throughout all stages of program development, integration with mangrove conservation initiatives that serve as natural tourist attractions, and the application of sustainable principles through a carrying capacity management system and tourism zoning. An economic impact analysis indicates that ecotourism has contributed approximately 35% to the total household income of fishing families, thereby reducing reliance on fishing activities and enhancing community resilience to seasonal fluctuations. Furthermore, the multiplier effects of ecotourism are evident in the expansion of complementary sectors, such as local transportation, basic lodging facilities, and souvenir businesses.

The gender-responsive dimension of ecotourism development has also proven effective in increasing both the participation and economic contribution of coastal women. The involvement of fishermen's wives as tour guides and food stall operators has enhanced their access to independent income sources while strengthening their role in household decision-making. Sustainability assessments further demonstrate that the developed ecotourism model aligns with the triple bottom line framework, including economic sustainability through income diversification and employment opportunities, environmental sustainability through mangrove conservation and environmental education, and social sustainability through capacity building and community empowerment.

5.6. Limitations and Lessons from Less Successful Cases

A critical analysis revealed several limitations of the model. The scalability of *APPOSTRAPS* technology is constrained by wave conditions exceeding 2.5 m and currents above 1.5 m/s. Its effectiveness also depends on a minimum natural sediment supply of 0.8 kg/m²/day and requires adequate community governance capacity to ensure ongoing maintenance. Lessons learned from implementation in Mayangan Village (Subang), which exhibited lower effectiveness with shoreline progradation of only 180 m, highlighted key factors influencing performance. These include variations in substrate clay-sand ratios affecting pile foundation stability, the absence of community leaders with strong legitimacy during the initial implementation phase, and competition with government programs employing alternative approaches. These findings underscore the importance of conducting site-specific assessments and evaluating community readiness prior to replication. Long-term risks involve tire degradation due to UV exposure and salinity, necessitating an estimated 30% replacement every five years; potential biofouling that may reduce sediment trap efficiency, and the risk of tripod structure failure under extreme wave conditions exceeding three meters. Effective risk mitigation requires the implementation of routine monitoring protocols, establishment of community-based maintenance systems, and development of contingency plans for extreme weather events.

6. Conclusion

This study demonstrates the effectiveness of a coastal community empowerment model that integrates the *Alat Pemecah*, *Peredam Ombak*, and *Sedimen Traps* or Breakers, Wave Dampers, and Sediment Traps (*APPOSTRAPS*) technological innovation with local wisdom and a participatory framework via the Jaga Alam Melalui Pemberdayaan Masyarakat Pesisir or Protecting Nature Through Coastal Community Empowerment (*JAM PASIR*) Program in Sukajaya Village, Karawang Regency. The *APPOSTRAPS* system, which repurposes used tire waste, has proven effective in mitigating coastal abrasion at a cost 70% lower than that of conventional breakwaters, while promoting coastal progradation of up to 400 m and generating "new land" for economic development as measured through periodic topographic surveys and documentation of shoreline changes over a 24-month implementation period (see Section 3.2 for detailed methodology). Based on a quantitatively measured Social Return on Investment (SROI) analysis (Section 3.3), the program achieved a benefit-cost ratio of 3.4:1 with a total social value generated of IDR 2.89 billion from an investment of IDR 850 million. The deployment of the *Masyarakat Sadar Lingkungan* and *Bencana* or Environmentally and Disaster Aware Society (*MASDARLINA*) system has yielded substantial socio-economic transformation, evidenced by the empowerment of fishermen's wives through the establishment of micro, small, and medium enterprises; the diversification of livelihoods through five new income-generating alternatives for fishers; and a shift in community behavior from environmentally destructive practices to proactive waste management and mangrove conservation. The impact on gender equality can be measured through an increase in women's economic participation from 12% to 68% (n = 28 of 41 fishermen's wives) and an increase in women's average income contribution to household income from IDR 450,000 to IDR 1,850,000 per month, as recorded in the baseline and endline surveys in **Table 2**. As a result, the coastal buffer zone has expanded from 2 m to 400 m, the frequency of tidal flooding has decreased, and sustainable ecotourism initiatives have been established with active participation across all community segments. The contribution to greenhouse gas emission reduction was calculated based on the utilization of 2400 used tires (equivalent to the avoided emission of 156 tonnes CO_2-eq from open burning) and the increase in mangrove carbon stock from 45 tonnes C/ha to 128 tonnes C/ha in a 22.5 hectare restoration area, resulting in a total additional carbon sequestration of 1867.5 tonnes CO_2-eq over a five-year period. Contributions to greenhouse gas reduction have been achieved through the utilization of waste wood pallets and tire waste, supporting local climate change mitigation efforts. Successful replication of the model in Ciparagejaya, Mayangan, and Balongan villages confirms its scalability for other Indonesian coastal areas. Official recognition of *APPOSTRAPS* technology via patent certificate IDS000007668 lends scientific legitimacy to its broader adoption. Technical recommendations for replication involve conducting comprehensive site assessments, including geotechnical analysis to a depth of 10 m, evaluation of sediment supply with a minimum threshold of 0.8 $kg/m^2/day$, and characterization of wave climate with significant wave height (Hs) below 2.5 m. Implementation should proceed gradually, beginning with a pilot project of 100–200 m before scaling up to 400 m. Additionally, a community-based monitoring system should be established, incorporating monthly measurement protocols using handheld GPS and the photo-point method. The integrated coastal management model has demonstrably advanced Sustainable Development Goals related to poverty alleviation, gender equality, and ecosystem conservation, and thus serves as a best-practice reference for technology-appropriate, locally grounded coastal community empowerment in the context of climate change and environmental degradation. Although the program contributes positively to several SDG indicators, specifically SDG 1 (poverty alleviation) through livelihood diversification, SDG 5 (gender equality) through women's economic empowerment, and SDG 14 (life below water) through mangrove restoration, however its impacts remain localized and require long-term evaluation to assess their sustainability. Sustainable ecotourism development through the PRPM concept has proven effective as an alternative, environmentally friendly economic empowerment strategy. The developed ecotourism model successfully contributed 35% to fishermen's household income and produced 12 certified local tour guides, with 60% female participation. Furthermore, the implementation of carrying capacity and a tourism zoning system ensures the sustainability of the mangrove ecosystem while providing optimal economic benefits to coastal communities. The national policy implications include the integration of the *JAM PASIR* model into the *Rencana Pembangunan Jangka Menengah Nasional* or National Medium-Term Development Plan (RPJMN) as a best-practice framework for coastal community empowerment programs, with a dedicated budget allocation of IDR 2–3 billion per implementation site. The regulatory framework involves the development of national technical standards for *APPOSTRAPS* technology through the Indonesian National Standard (SNI) and the acceleration of the licensing process to facilitate replication. Institutional strengthening requires the establishment of Coastal Community Empowerment Units at the district level with a mandate for cross-sectoral coordination.

7. Patents

Republic of Indonesia patent certificate No. IDS000007668. "Wave breaker, wave attenuator, and sediment trap devices as erosion control measures," Feb. 5, 2024.

Author Contributions

Conceptualization, R.E.R.; methodology, M.A.J., A.R.U., T.I., and S.W.W.; software, R.E.R., A.R.U., S.W.W., and D.F.F.; validation, P.N.M.; formal analysis, M.A.J., P.N.M., T.I., and D.F.F.; investigation, R.E.R., P.N.M., A.R.U., T.I., S.W.W., and S.T.S.; resources, R.E.R., P.N.M., T.I., S.W.W., and S.T.S.; data curation, R.E.R., M.A.J., A.R.U., and S.W.W.; writing—original draft preparation, M.A.J., A.R.U., T.I., S.W.W., K.M., and R.J.S.; writing—review and editing, P.N.M., T.I., D.F.F., K.M., and R.J.S.; visualization, M.A.J., A.R.U., and S.T.S.; supervision, R.E.R. and M.A.J.; project administration, R.E.R., S.W.W., S.T.S., D.F.F., K.M., and R.J.S.; funding acquisition, R.E.R., M.A.J., P.N.M., A.R.U., and T.I. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

The study was conducted and approved by the Institutional Review Board of PT Pertamina Hulu Energi Offshore North West Java, Republic of Indonesia.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available on request from the corresponding author.

Acknowledgments

We would like to thank the Indonesian Ministry of Law and Human Rights for officially recognizing this innovation by issuing a patent certificate with patent number IDS000007668.

Conflicts of Interest

The authors declare that there is no conflict of interest.

References

[1] Zikra, M., Suntoyo, Lukijanto, 2015. Climate Change Impacts on Indonesian Coastal Areas. Procedia Earth and Planetary Science. 14, 57–63. DOI: https://doi.org/10.1016/j.proeps.2015.07.085

[2] Wen, Y., Tian, Y., Kato, N., et al., 2025. The Sustainable Implementation of Ecosystem-Based Adaptation to Climate Change in Coastal Area: Lessons from Indonesia. Prevention and Treatment of Natural Disasters. 4(1), 77–92. DOI: https://doi.org/10.54963/ptnd.v4i1.853

[3] Unsworth, R.K., Ambo-Rappe, R., Jones, B.L., et al., 2018. Indonesia's Globally Significant Seagrass Meadows Are Under Widespread Threat. Science of the Total Environment. 634, 279–286. DOI: https://doi.org/10.1016/j.scitotenv.2018.03.315

[4] Griggs, G., Reguero, B.G., 2021. Coastal Adaptation to Climate Change and Sea-Level Rise. Water. 13(16), 2151. DOI: https://doi.org/10.3390/w13162151

[5] Ranasinghe, R., 2016. Assessing Climate Change Impacts on Open Sandy Coasts: A Review. Earth-Science Reviews. 160, 320–332. DOI: https://doi.org/10.1016/j.earscirev.2016.07.011

[6] Masselink, G., Russell, P., Rennie, A., et al., 2020. Impacts of Climate Change on Coastal Geomorphology and Coastal Erosion Relevant to the Coastal and Marine Environment Around the UK. MCCIP Science Review. 2020, 158–189. DOI: https://doi.org/10.14465/2020.arc08.cgm

[7] Dong, W.S., Ismailluddin, A., Yun, L.S., et al., 2024. The Impact of Climate Change on Coastal Erosion in Southeast Asia and the Compelling Need to Establish Robust Adaptation Strategies. Heliyon. 10(4), e25609. DOI: https://doi.org/10.1016/j.heliyon.2024.e25609

[8] Cahyani, H.D., Lestari, M.M., Diana, L., 2025. The Determination of State Baselines Post-Peat Abrasion on Bengkalis Island as Indonesia's Foremost Island in Terms of International Law of the Sea Perspective. Multidisciplinary Indonesian Center Journal (MICJO). 2(2), 1382–1401. DOI: https://doi.org/10.62567/micjo.v2i2.639

[9] Handiani, D.N., Heriati, A., Gunawan, W.A., 2022. Comparison of Coastal Vulnerability Assessment for Subang Regency in North Coast West Java–Indonesia. Geomatics, Natural Hazards and Risk. 13(1), 1178–1206. DOI: https://doi.org/10.1080/19475705.2022.2066573

[10] Ihsan, I.F., Pin, T.G., 2018. The Effect of Abrasion on

Geomorphology Change and Coastline Conservation Effort in Karawang Regency. In Proceedings of the Padjadjaran Earth Dialogues, International Symposium on Geophysical Issues, Bandung, Indonesia, 2–4 July 2018; pp. 1–8. DOI: https://doi.org/10.1088/1755-1315/311/1/012011

[11] Fauzie, A.K., 2017. Analysis of Short and Medium-Term Coastal Abrasion and Accretion Rates Using GIS in Karawang, West Java. Creative Research Journal. 3(2), 91–104.

[12] Griggs, G.B., 2024. The California Coast and Living Shorelines—A Critical Look. Journal of Marine Science and Engineering. 12(2), 199. DOI: https://doi.org/10.3390/jmse12020199

[13] Vriend, H.D., Koningsveld, M.V., Aarninkhof, S., 2014. Building with Nature: The New Dutch Approach to Coastal and River Works. Proceedings of the Institution of Civil Engineers – Civil Engineering. 167(1), 18–24. DOI: https://doi.org/10.1680/cien.13.00003

[14] Hossain, M., Saha, C., Saha, S., 2025. Mangrove Restoration in Bangladesh. Open Journal of Forestry. 15(1), 35–52. DOI: https://doi.org/10.4236/ojf.2025.151003

[15] Bagindo, M.N., Herwandi, H., Chaniago, M.I., et al., 2023. Socio-Economic Changes in Coastal Fishermen of West Sumatra as the Impact of Coastal Abrasion. Asian Journal of Environment-Behaviour Studies. 8(26), 37–54. DOI: https://doi.org/10.21834/aje-bs.v8i26.433

[16] Nandaniko, M.N., Manessa, M.D.M., 2019. Modeling of Coastline Change by Viewing Trends from the Abrasion and Accretion Rate in Karawang Regency. Proceedings of the 2019 5th International Conference on Science and Technology (ICST), Yogyakarta, Indonesia, 30–31 July 2019; pp. 1–5. DOI: https://doi.org/10.1109/ICST47872.2019.9166274

[17] Pasaribu, R., Agus, F., Soeprijadi, L., 2019. Spatial Analysis of Coastline Change by Remote Sensing in the North Coast of Karawang Regency. Jurnal Geografi Lingkungan Tropik. 3(2), 50–56.

[18] Amalia, A.A., Nur, K.W., 2023. Coastal Settlement Vulnerability on Risk of Abrasion Disaster. In: Singh, A. (ed.). International Handbook of Disaster Research. Springer Nature: Singapore. pp. 323–341. DOI: https://doi.org/10.1007/978-981-19-8388-7_194

[19] Hamid, N., Setyowati, D.L., Priyanto, A.S., et al., 2021. The Effect of Human Activities Towards Coastal Dynamics and Sustainable Coastal Management. International Journal of Sustainable Development & Planning. 16(8), 1479–1493. DOI: https://doi.org/10.18280/ijsdp.160809

[20] Riptanti, E.W., Harisudin, M., Kusnandar, K., et al., 2024. The Effect of Abrasion on Resilience of Fishermen/Fish Farmer Livelihoods on the North Coast of Central Java. Edelweiss Applied Science and Technology. 8(6), 1882–1894. DOI: https://doi.org/10.55214/25768484.v8i6.2354

[21] Idris, M.K., Setyaningsih, W.A., Alimuddin, A., 2024. Sedimentation and Abrasion Identification in Cikidang Fishery Port and Surrounding Coastal Area. Journal of Applied Geospatial Information. 8(1), 78–84. DOI: https://doi.org/10.30871/jagi.v8i1.7796

[22] Istrianto, K., Widagdo, A., Prasetyono, U., et al., 2021. Crab Fisheries on the North Coast of the Karawang Region, West Java, Indonesia. Aquaculture, Aquarium, Conservation & Legislation. 14(2), 859–865.

[23] Nugraha, Y.A., Susanto, H.A., Simanjuntak, C.P., et al., 2021. Mangrove Ecosystem Related to Fisheries Productivity in the Coastal Area of Karawang Regency, West Java, Indonesia. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Ambon, Indonesia, 28 November 2020; pp. 1–10. DOI: https://doi.org/10.1088/1755-1315/800/1/012016

[24] Pratama, M.F.A., Nurhayati, A., Rizal, A., et al., 2021. Strategy for the Development of Seaweed Cultivation in Karawang Regency, West Java Province. Asian Journal of Fisheries and Aquatic Research. 11(4), 12–22. DOI: https://doi.org/10.9734/ajfar/2021/v11i430209

[25] Astuti, A.D., 2025. Sustainable Strategies for Managing Domestic Plastic Waste in Coastal Communities. Waste, Society and Sustainability. 2(1), 40–54.

[26] Kurniawan, H., Yulianto, R.S., Mladenov, S.V., et al., 2023. Sustainable Development Through Community Empowerment Based on Local Wisdom. International Journal of Progressive Sciences and Technologies. 41(2), 164–176. DOI: http://dx.doi.org/10.52155/ijpsat.v41.2.5719

[27] Rizal, A., Riyadi, A., Haryanti, et al., 2022. Development of Sustainable Coastal Benchmarks for Local Wisdom in Pangandaran Village Communities. Sustainability. 14(21), 14648. DOI: https://doi.org/10.3390/su142114648

[28] George, A.S., Mehra, V., Scott, K., et al., 2015. Community Participation in Health Systems Research: A Systematic Review Assessing the State of Research, the Nature of Interventions Involved and the Fea-

tures of Engagement with Communities. PLoS One. 10(10), e0141091. DOI: https://doi.org/10.1371/journal.pone.0141091

[29] Hassenforder, E., Pittock, J., Barreteau, O., et al., 2016. The MEPPP Framework: A Framework for Monitoring and Evaluating Participatory Planning Processes. Environmental Management. 57, 79–96. DOI: https://doi.org/10.1007/s00267-015-0599-5

[30] Dushkova, D., Ivlieva, O., 2024. Empowering Communities to Act for a Change: A Review of the Community Empowerment Programs Towards Sustainability and Resilience. Sustainability. 16(19), 8700. DOI: https://doi.org/10.3390/su16198700

[31] Ridwan, R.E., Julianto, M.A., Taufiq, N., et al. (inventors), 2024. Wave Breaker, Wave Attenuator, and Sediment Trap Devices as Erosion Control Measures. Indonesia Patent. S00202314602. 2024 February 5.

[32] Setiawan, R.J., Ma'ruf, K., Darmono, et al., 2024. Development of Rescue Drone Integrated with Internet of Things Control for Beach Surveillance: Case Study at Glagah Beach. In Proceedings of the 11th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI), Yogyakarta, Indonesia, 26–27 September 2024; pp. 603–608. DOI: https://doi.org/10.1109/EECSI63442.2024.10776458

[33] Pratama, A., Wahyudin, U., Hatimah, I., et al., 2024. From Tradition to Action: The Potential of Community Empowerment Through Local Wisdom for Sustainable Environmental Protection Practices. The Eurasia Proceedings of Educational and Social Sciences. 35, 271–282. DOI: https://doi.org/10.55549/epess.820

[34] Fathoni, S., Sutisna, S., Supriyatno, M., 2023. Community-Based Disaster Risk Reduction Efforts in Facing the Threat of Abrasion Disasters at Bungin Beach, Bekasi Regency During the COVID-19 Pandemic. In Proceedings of the 3rd International Conference on Disaster Management, Virtual, 29 September–1 October 2022; pp. 1–14. DOI: https://doi.org/10.1088/1755-1315/1173/1/012068

[35] Setyowati, D.L., Hardati, P., Benardi, A.I., et al., 2021. The Role of the Disaster Preparedness Group in Adapting Abrasion to Communities Affected by Abrasion on the North Coast of Rembang, Central Java. In Proceedings of the 6th International Conference on Education & Social Sciences (ICESS 2021), Virtual, 9–10 April 2021; pp. 61–66. DOI: https://doi.org/10.2991/assehr.k.210918.012

[36] Sugito, T., Sulaiman, A.I., Sabiq, A., et al., 2019. The Empowerment as Community Learning Based on Ecotourism of Coastal Border at West Kalimantan. International Educational Research. 2(3), 23. DOI: https://doi.org/10.30560/ier.v2n3p23

[37] Turner, S.F., Cardinal, L.B., Burton, R.M., 2017. Research Design for Mixed Methods: A Triangulation-Based Framework and Roadmap. Organizational Research Methods. 20(2), 243–267. DOI: https://doi.org/10.1177/1094428115610808

[38] Bans-Akutey, A., Tiimub, B.M., 2021. Triangulation in Research. Academia Letters. 2(3392), 1–7. DOI: https://doi.org/10.20935/AL3392

[39] ASTM D1586-11. 2011. Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils. ASTM International (American Society for Testing and Materials): West Conshohocken, PA, USA.

[40] Terzaghi, K., Peck, R.B., 1967. Soil Mechanics in Engineering Practice. John Wiley & Sons: New York, NY, USA.