

Can Frugal Restoration Rebuild Coastal Communities? Fostering Local Agency and Citizen Science in Indonesia's Post- Disaster Archipelagic Frontier

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ABSTRACT

Post-disaster recovery in archipelagic frontiers is frequently undermined by a persistent land-centric emergency bias and state institutional voids that treat coastal communities as passive recipients of aid. This study examines how standardized marine restoration hardware can be re-conceptualized as a frugal sociotechnical boundary object to bridge institutional voids and foster local agency in disaster-impacted island settings. Focusing on the LEMBU BERSERI initiative in Kupang Bay, Indonesia, following Tropical Cyclone Seroja, we analyze a polycentric partnership linking PT Pertamina Patra Niaga, state conservation authorities, and the local youth group Kelompok Anana Laut. Employing a qualitative case study design grounded in Social-Ecological Systems Resilience, Sociotechnical Boundary Object Theory, and Amartya Sen's Capability Approach, we track the deployment of Web-Spider technology fabricated through localized corporate competency transfer. The findings reveal that deconstructing complex restoration technology into frugal, locally manufacturable tools catalyzed knowledge democratization, transforming disaster-stricken fishers into proficient citizen scientists. Longitudinal monitoring by these citizen scientists documented substantial coral fragment survival and a marked recovery in fish density. This empirical data earned the group formal legal recognition as official community conservation monitors, unlocking territorial co-management rights. Valorizing these restored marine assets through a community-managed edu-tourism enterprise successfully diversified livelihoods away from reliance on primary fishing and significantly elevated average household incomes among active participants. However, anomalies in substrate material oxidation and thermal bleaching highlight the biophysical boundaries of localized frugal interventions against macro-level climate shocks. We conclude that frugal restoration functions not as a standalone solution to global environmental crises but as an indispensable localized climate-adaptation bridge that builds human capabilities, redefines corporate social responsibility, and restructures post-disaster archipelagic governance.

Keywords: Frugal Innovation; Sociotechnical Boundary Object; Citizen Science; Capability Approach; Polycentric Governance; Post-Disaster Recovery; Archipelagic Frontier; Coral Reef Restoration.

INTRODUCTION

Disasters are rarely purely natural events; rather, they are structural mirrors that expose deep socio-ecological fractures within society (Oliver-smith, 2022). When Tropical Cyclone Seroja struck East Nusa Tenggara Province, Indonesia, in April 2021, the catastrophic destruction of shallow-water coral reefs in Kupang Bay was not merely an ecological loss (Djawa, 2022). It exposed the institutional vulnerabilities of coastal pockets within an archipelagic frontier adjacent to 3T (Tertinggal, Terdepan, Terluar—Disadvantaged, Frontier, and Outermost) regions (Bawias et al., 2025). In these island frontiers, physical isolation, administrative voids, and climate vulnerabilities intersect to form systemic socio-ecological fragility (Martino et al., 2026). Traditional post-disaster interventions operate under a persistent land-centric bias, prioritizing land-based infrastructure reconstruction and short-term emergency aid while systematically ignoring sub-surface marine

natural capital (He & Faure, 2024). This conventional emergency response treats coastal communities merely as passive recipients of state and corporate charity, reinforcing structural dependency and failing to address the long-term poverty-environment trap in isolated island settings (Vlachakis et al., 2020).

Despite growing scholarship on climate adaptation, socio-ecological resilience, and post-disaster governance, existing literature exhibits three fundamental conceptual and empirical limitations. First, current disaster recovery studies remain heavily biased toward terrestrial infrastructure and top-down state safety nets (Diazaldret & Becerril, 2026), leaving an empirical void regarding how marine ecosystem recovery serves as a prerequisite for human development in small-island contexts (Hilmi et al., 2025). Second, marine conservation research extensively evaluates physical restoration instruments (Higgins et al., 2022)—such as Web-Spider or Reef Star technologies deployed globally (Karisa et al., 2026)—yet treats them almost exclusively through a biologically reductionist lens, focusing on coral cover growth while failing to analyze how such tools can be operationalized as frugal sociotechnical instruments that foster local knowledge democratization (Anthony et al., 2020). Third, Corporate Social Responsibility (CSR) studies in the Global South focus overwhelmingly on land-based extractive industries or urban philanthropy (Wilson, 2022), largely ignoring how corporate-community-state partnerships can bridge state institutional voids in remote island frontiers through citizen science, transforming marginalized fishers from aid recipients into active co-managers of marine protected areas (Akporiaye & Webster, 2022).

To bridge these literature gaps, this study investigates how standardized coral restoration hardware can be strategically re-conceptualized not merely as a bio-ecological medium (Ambariyanto et al., 2021), but as a sociotechnical vehicle for rebuilding human capital (Lloyd & Lewis, 2024), mobilizing citizen science, and fostering local agency in post-disaster archipelagic frontiers (Hilmi et al., 2025). The empirical investigation centers on the LEMBU BERSERI (Lestarikan Terumbu, untuk Berdaya, Sejahtera, dan Mandiri) initiative—a polycentric alliance linking PT Pertamina Patra Niaga Integrated Terminal Tenau, state conservation authorities (BKKPN Kupang / BKSDA NTT), and the local youth group Kelompok Anana Laut in Kupang Bay. By framing Web-Spider technology through the lens of Frugal Innovation, this paper demonstrates how low-cost, accessible sociotechnical interventions can democratize scientific practice, enabling disaster-affected youth to move beyond passive reliance on external expertise and become competent citizen scientists and marine eco-tourism entrepreneurs.

Synthesizing Social-Ecological Systems (SES) Resilience (Zhang et al., 2025), Sociotechnical Boundary Object Theory (Reddy et al., 2020), and Amartya Sen's Capability Approach (Jamil, 2024), this article argues that sustainable recovery in remote island frontiers depends not on capital-intensive state interventions, but on the democratization of technical tools that expand substantive human capabilities. Specifically, this study addresses three interrelated research questions: First, in what ways does Web-Spider technology operate as a frugal sociotechnical instrument to bridge state institutional voids and catalyze local agency in disaster-impacted archipelagic frontiers? Second, through what mechanisms does the epistemic transformation of local youth into citizen scientists reconfigure coastal socio-economic resilience? Third, how can corporate-community-state partnerships redefine the paradigm of post-disaster recovery and human capital development in the Global South?

RESEARCH METHODOLOGY

Research Design

To capture complex sociotechnical transformations and institutional dynamics in a post-disaster archipelagic setting, this study adopts a qualitative (Stroparo, 2025), exploratory single-case study design with embedded units of analysis (Creswell, 2020). The qualitative case study approach is particularly well-suited to this inquiry, as it facilitates an in-depth, contextual examination of contemporary phenomena—specifically, how frugal marine conservation technology is operationalized to expand human capabilities and bridge administrative voids—within a real-world disaster site. Rather than examining ecological restoration in isolation, the design focuses on the interactive processes between corporate social responsibility mechanisms, state conservation governance, and local youth agency across structurally disadvantaged coastal pockets.

Study Site and Empirical Context

Empirical fieldwork was conducted in the Kupang Bay Marine Recreation Park (Taman Wisata Alam Laut Teluk Kupang) and adjacent coastal waters, focusing on the coastal community of Tenau, Alak District, Kupang City, East Nusa Tenggara. This site was purposefully selected for several key characteristics: it was the epicenter of catastrophic subsurface damage caused by Tropical Cyclone Seroja in April 2021, which destroyed most shallow-water coral habitats (Kurniawan et al., 2021). Additionally, the area reflects a coastal pocket with 3T-like characteristics marked by economic vulnerability and heavy reliance on artisanal fisheries (Tje et al., 2025). It also served as the operational site for the LEMBU BERSERI initiative, providing a rich empirical setting for observing multi-stakeholder dynamics among corporate energy entities, state conservation authorities, and local youth groups (Khidhriyah et al., 2024).

Informant Selection and Sampling Strategy

Informants were selected using a combination of purposive and snowball sampling strategies tailored to capture multi-perspective insights across the public, private, and community sectors (Zickar & Keith, 2023). Sampling was guided by the principle of theoretical saturation rather than statistical representativeness, continuing until additional interviews yielded no new thematic insights. A total of 33 key actors participated, categorized into three primary analytical cohorts:

- **Community Cohort (26 informants):** Members of the Kelompok Anana Laut youth group and local artisanal fishers actively involved in manual frame fabrication, underwater deployment, and tourism management.
- **Corporate Cohort (3 informants):** Community Development Officers and HSSE Supervisor and Manager from PT Pertamina Patra Niaga Integrated Terminal Tenau who facilitated technical training and financial planning.
- **State & Academic Cohort (4 informants):** Technical conservation officers from BKKPN Kupang / BKSDA NTT, municipal coastal officers, and local university marine scientists.

Data Collection

Fieldwork was conducted over 3 months, employing a triangulated data collection methodology to ensure empirical rigor and analytical validity:

- **Primary Data:** Gathered through semi-structured, in-depth interviews covering personal disaster trajectories, technical skill acquisition, shifts in ecological perceptions, and organizational power dynamics. Participatory field observations complemented this during on-land steel-welding workshops, underwater fragment-attachment procedures, and routine citizen-science monitoring dives.
- **Secondary Data:** Systematically collected from Social Mapping (SOSMAP) reports, quarterly CSR progress audits, internal monitoring logbooks of the Kelompok Anana Laut group (2021–2025), conservation zoning archives, and post-Seroja damage assessment reports.

Data Analysis Techniques

Data were systematically analyzed using an inductive-deductive thematic approach structured around the Gioia methodology, which provides a rigorous, transparent analytical pathway for converting raw qualitative field data into theoretical insights (Gioia, 2021). This multi-stage analytical process ensured data trustworthiness, thematic coherence, and clear alignment between empirical observations and the study's theoretical framework (Social-Ecological Systems Resilience, Sociotechnical Boundary Object Theory, and the Capability Approach) (Bowen, Glenn, 2009). Data analysis proceeded through four interconnected phases:

Phase 1: First-Order Empirical Concepts (Open Coding). Raw transcriptions from semi-structured interviews, field observation notes, Sosmap reports, and community logbooks. Through line-by-line open coding, primary data were assigned initial descriptive labels using informants' own terminology (Scheelbeek et al., 2020). This phase yielded 42 first-order codes capturing raw empirical dynamics, such as "loss of catch

post-cyclone," "fear of middle-men debt," "hands-on arc welding practice," "underwater frame interlocking," "using visual slate cards for coral counting," and "presenting data to state officials."

Phase 2: Second-Order Theoretical Themes (Axial Coding). Through continuous comparative analysis, first-order concepts were grouped into higher-level, theoretically informed second-order themes (Braun et al., 2017). In this phase, empirical patterns were systematically cross-referenced with established concepts in disaster literature, sociotechnical theory, and capability metrics. First-order codes related to hardware fabrication and skills transfer were synthesized into themes, including "Frugal Hardware Adaptation" and "Corporate Competency Transfer." Similarly, codes describing underwater monitoring routines and formal interactions with state authority were abstracted into "Epistemic Empowerment via Citizen Science" and "Legal Co-management Recognition."

Phase 3: Synthesis into Aggregate Dimensions. Second-order themes were further distilled into three core theoretical aggregate dimensions that directly structure the findings and discussion of this paper:

- **Frugal Sociotechnical Re-configuration:** How low-cost, locally manufactured hardware bridges state institutional voids and transforms disaster trauma into collective action.
- **Epistemic Empowerment and Capability Expansion:** How the democratization of scientific tools expands substantive human freedoms, converts local youth into citizen scientists, and builds economic autonomy.
- **Polycentric Governance and Resilience Boundaries:** How tripartite institutional alliances govern common-pool resources while confronting the physical boundaries of material oxidation and global climate shocks.

Phase 4: Data Triangulation and Trustworthiness. To establish qualitative rigor, data triangulation was performed across analytical cohorts (community, corporate, and state officials) and data sources (interview transcripts versus quantitative biological monitoring logs and SOSMAP report audits) (Zairul, 2021). Member-checking sessions were conducted with Kelompok Anana Laut leadership and BKKPN conservation officers to validate the accuracy of extracted thematic structures and ensure that theoretical abstractions faithfully represented ground-level realities (Birt et al., 2016).

RESULTS

Ecological Destruction and the Manifestation of Institutional Voids in Post-Cyclone Kupang Bay

The landfall of Tropical Cyclone Seroja in April 2021 generated an unprecedented marine environmental shock across the archipelagic waters of East Nusa Tenggara, with the epicenter of sub-surface catastrophic damage concentrated in the Kupang Bay Marine Recreation Park (Taman Wisata Alam Laut Teluk Kupang) (Khidhriyah et al., 2024). Hydrodynamic turbulence, severe storm surges, and massive displacement of subsurface debris caused widespread mechanical destruction of the shallow-water benthic architecture surrounding the coastal settlement of Tenau in Alak District, Kupang City. Systematic spatial mapping and rapid benthic transects conducted across the impacted zones confirmed that the cyclone wiped out 88.5 percent of live coral cover in shallow depths ranging from 2 to 8 meters (Setiawan et al., 2021). Healthy, multi-decadal branching *Acropora* thickets and massive *Porites* colonies were pulverized into expansive, unstable rubble fields spanning tens of hectares (Sekaranom et al., 2021). This mechanical fragmentation destroyed the structural complexity of the reef, eliminating critical microhabitats required for teleost spawning, juvenile nursery protection, and macroinvertebrate colonization (Dzikiro et al., 2025).

The immediate consequence of this sub-surface ecological collapse was a severe socio-economic shock to the surrounding coastal population, a community historically anchored in small-scale, artisanal marine fisheries. Within the first quarter following the cyclone, the local fishing fleet experienced a dramatic drop in Catch-Per-Unit-Effort (CPUE), plummeting by 64.2 percent relative to pre-cyclone seasonal baselines. Key commercial species—including snappers (Lutjanidae), groupers (Serranidae), and emperor fish (Lethrinidae)—virtually disappeared from nearshore fishing grounds due to the complete loss of structural shelter and benthic food webs. To maintain basic household survival, local fishers were forced to navigate their small, low-powered motorized canoes farther into open offshore waters, where treacherous currents and high fuel consumption were common. Consequently, average operational trips lengthened from two hours to

over seven hours, driving daily fuel expenditures up by 145 percent. The combination of dwindling catches and escalating operational costs plunged the local fishing economy into acute financial distress, triggering widespread debt accumulation with informal middlemen (*tengkulak*) who charged exorbitant interest rates for emergency operational loans.

This socio-ecological crisis laid bare a profound state institutional void that characterizes remote frontier and structurally disadvantaged archipelagic pockets. In the immediate post-disaster emergency and early recovery phases, formal state interventions carried out by national and regional disaster management agencies were characterized by a rigid terrestrial bias (Ali, 2025). Public emergency budgets and physical reconstruction funds were allocated exclusively toward visible land-based infrastructure, such as clearing road blockages, restoring electrical distribution lines, repairing municipal harbor jetties, and constructing temporary housing units. Marine natural capital recovery received zero public budget allocation, as formal disaster protocols lacked operational mandates and financial mechanisms to address sub-surface ecosystem destruction. State conservation management authorities faced severe budgetary constraints and a lack of technical diving assets, leaving them unable to initiate active habitat rehabilitation. Concurrently, early relief interventions by philanthropic organizations and charitable NGOs provided short-term food aid packages and necessities. While these hand-outs temporarily cushioned immediate hunger, they failed to address the structural ecological collapse, leaving the community trapped as passive, dependent recipients of aid in an escalating poverty-environment trap.

Sociotechnical Deployment of Frugal Web-Spider Technology and Core-Competency Transfer

To bridge this state institutional void and initiate sub-surface marine recovery, the LEMBU BERSERI partnership was established as a polycentric alliance that brings together PT Pertamina Patra Niaga Integrated Terminal Tenau, local state conservation authorities (BKKN Kupang/BKSDA NTT), and 26 local coastal youth organized under the banner of *Kelompok Anana Laut*. Recognizing that importing capital-intensive, high-technology artificial reef structures was financially unviable and operationally unsustainable in a remote island context, the alliance adopted Web-Spider (Reef Star) technology as a frugal sociotechnical platform (Nodari et al., 2025). The program established an on-land fabrication workshop directly within the Tenau coastal hamlet, turning a vacant industrial lot into an active communal engineering space. This localized manufacturing strategy eliminated transportation overheads and enabled fabrication activities to be fully integrated into the local community's daily routines.

The corporate partner, PT Pertamina Patra Niaga, operationalized a Creating Shared Value (CSV) approach by aligning its corporate social investments with the maritime operational context and coastal risk management (Porter, 2011; Korlety, 2024), and by managing a high-risk maritime energy distribution terminal in Kupang Bay. The integrated terminal prioritized coastal safety, environmental stewardship, and community empowerment within its operational ring. Moving beyond traditional caritative philanthropy, corporate personnel and sponsored technical facilitators provided structured training modules for the members of *Kelompok Anana Laut*. The initiative equipped local youth with practical skills in basic structural metalworking, arc welding, marine safety protocols, and applying anti-corrosive protective coatings mixed with local sand to ensure substrate durability in harsh marine environments (Tenci et al., 2024). Local youth were systematically trained in reading structural blueprints, operating electric arc-welding machines, executing precise metal cutting, bending round steel bars into standardized hexagonal geometries, and applying multi-layered anti-corrosive primer coatings mixed with local silica sand to optimize surface roughness for natural larval settlement.

Over a twenty-four-month continuous operational period, this localized workshop produced and deployed 450 hexagonal steel Web-Spider frames across degraded benthic zones in Kupang Bay. Each frame, measuring approximately one meter in diameter, was manually transported by boat, lowered into position by local divers, and securely interconnected with adjacent frames using heavy-duty mechanical ties to form a stable, continuous structural network over loose coral rubble fields. The local youth group led the underwater deployment, manually harvesting 5,400 resilient, wild coral fragments—primarily fast-growing *Acropora formosa* and durable *Porites cylindrica*—from healthy donor patches in deeper waters. Using plastic cable ties, the youth securely attached twelve coral fragments to each hexagonal frame. This frugal intervention stabilized

the shifting rubble substrate, provided elevated structural clearance above boundary-layer sedimentation, and created a rigid artificial framework that accelerated natural calcification and tissue fusion (Prabhu, 2017).

Knowledge Democratization, Citizen Science, and Livelihood Transformation

The deployment of Web-Spider technology served as an empirical catalyst for knowledge democratization, effectively transforming disaster-affected fishers with limited formal education into proficient, recognized citizen scientists (Fougères et al., 2021). To overcome the technical barriers associated with academic marine monitoring protocols, the research team, corporate facilitators, and state conservation rangers co-designed a simplified, visual-based monitoring methodology (Ndubuisi et al., 2025). Complex biological parameters were translated into intuitive visual metrics using standardized underwater slate cards, waterproof grid photography, and color-coded health indicators. The participating members of Anana Laut received rigorous training in underwater photography, fragment survival auditing, axial branch measurement, and macro-invertebrate counting techniques during routine scuba dives.

Logging long-term monitoring data across all 450 deployed Web-Spider structures, these citizen scientists documented an exceptional overall coral fragment survival rate of 84.1 percent over a two-year evaluation cycle. The attached *Acropora formosa* fragments exhibited rapid linear skeletal growth, averaging 9.2 centimeters per year, resulting in full structural canopy closure across interconnected frame clusters within 18 months. This rapid coral canopy development successfully recreated complex subsurface habitat, triggering swift ecological recolonization. Visual fish census data recorded by the youth showed a 210 percent increase in teleost fish density within the restoration zones, marked by the return of juvenile damselfish (Pomacentridae), butterflyfish (Chaetodontidae), and commercially vital parrotfish (Scaridae).

Presenting these monitoring logs directly to state officials earned Kelompok Anana Laut formal legal designation as official community conservation monitors (Masyarakat Mitra Polhut). This status granted them official surveillance rights to restrict destructive fishing and enforce reserve rules. The youth then leveraged restored reef assets to establish a community-managed marine edu-tourism enterprise offering guided eco-dives and an "Adopt-a-Spider" sponsorship program. As detailed in Table 1, participating household reliance on primary fishing dropped from 92.5% to 53.5%, while average monthly household income grew by 84.8%. Allocating 15% of net tourism earnings into a dedicated conservation fund created an autonomous financial buffer that covered ongoing diving operational costs without external charity.

Table 1. Key Socio-Ecological and Economic Indicators Before and After the LEMBU BERSERI Initiative

Indicator	Pre-Intervention Baseline (2021)	Post-Intervention Status (2023–2025)	Percentage Change (%)	Timeframe / Evaluation Cycle	Primary Data Source
Live Coral Cover	11.5% live cover (88.5% destruction post-Seroja)	Canopy closure across 450 frames (84.1% fragment survival)	+84.1% fragment survival	24 Months (2021–2023)	Citizen Science Diving Logs & Visual Transects
Teleost Fish Density	Severe post-cyclone collapse	Rapid ecological recolonization across restored zones	+210.0% increase	24 Months (2021–2023)	Visual Slate Card Census
Catch-Per-Unit-Effort (CPUE)	-64.2% drop vs pre-cyclone baseline	Stabilized nearshore catch rates	Recovered to pre-cyclone baseline	12–24 Months (2022–2023)	Fisher Logbooks &

Indicator	Pre-Intervention Baseline (2021)	Post-Intervention Status (2023–2025)	Percentage Change (%)	Timeframe / Evaluation Cycle	Primary Data Source
					Sosmap Reports
Daily Fishing Fuel Expenditure	+145.0% increase (7+ hours offshore trips)	Normalized due to restored nearshore grounds	Significant reduction in operational costs	18 Months (2022–2023)	Household Expense Records
Household Reliance on Primary Fishing	92.5% of active group households	53.5% of active group households	-39.0% (Livelihood diversification)	48 Months (2021–2025)	Social Mapping (Sosmap) Audits
Average Monthly Household Income	Depressed post-disaster baseline	Marked income surge among active participants	+84.8% increase	48 Months (2021–2025)	Sosmap Audits & Financial Ledgers
Edu-Tourism Enterprise Revenue	IDR 0 (Non-existent)	Autonomous commercial revenue generation	Self-sustaining growth trajectory	24 Months (2023–2025)	Enterprise Books & Tourism Ledgers
Community Conservation Fund Size	IDR 0	15% net tourism revenue allocation	Autonomous funding buffer established	Continuous (2023–2025)	Community Fund Financial Audits

Source: Researchers' Analysis, 2026

This epistemic empowerment was directly converted into structural socio-economic resilience through the valorization of restored ecological assets (Bera & Nag, 2025). Leveraging the newly rehabilitated reef site, Anana Laut established a community-managed marine edu-tourism enterprise that introduced guided underwater eco-diving tours, educational coral planting workshops for university students, and an "Adopt-a-Spider" sponsorship program for corporate donors and tourists. According to project Sosmap audits and group financial logs between 2021 and 2025, participating household reliance on primary artisanal fishing fell from 92.5 percent to 53.5 percent, as family members shifted into tourism operations, diving logistics, and hospitality management. Over the same timeframe, average monthly household income among active participating members surged by 84.8 percent. Furthermore, the group established a transparent financial mechanism by allocating 15% of all net tourism and sponsorship earnings to a dedicated, community-controlled conservation fund. This fund provided an autonomous financial buffer that covered ongoing dive gear maintenance, boat fuel, and frame fabrication costs, effectively freeing the local community from structural dependence on external charity or predatory informal credit networks.

Material Degradation Constraints and Biophysical Environmental Limitations

Despite the pronounced ecological and socio-economic successes achieved by the LEMBU BERSERI initiative, empirical field observations revealed critical material degradation constraints and environmental vulnerabilities that define the operational boundaries of frugal marine restoration. The harsh physical marine

environment of Kupang Bay posed continuous challenges to the structural integrity of the artificial substrates. Comprehensive underwater structural audits conducted at eighteen and twenty-four months post-deployment identified severe saltwater oxidation and coating degradation across 32.4 percent of the deployed steel frames. In shallow, high-energy wave zones, constant sand abrasion and wave scouring gradually stripped away the protective anti-corrosive paint and silica sand coating, exposing the underlying round steel bars to rapid oxidation. This structural rusting weakened the frame joints, requiring local youth divers to conduct routine underwater maintenance, including manual wire brushing, localized anti-corrosive epoxy patching, and physical structural reinforcement with secondary binding wire.

Furthermore, biological monitoring revealed acute vulnerabilities to oceanographic thermal anomalies and localized biofouling. During the extended thermal stress event of 2023–2024, localized Sea Surface Temperatures (SST) in Kupang Bay rose to $+1.8^{\circ}\text{C}$ above multi-year seasonal baselines for six consecutive weeks. In response to this thermal anomaly, transplanted coral fragments across the Web-Spider matrices exhibited a 28.5 percent bleaching rate, with fast-growing *Acropora* species showing greater sensitivity than massive *Porites* colonies. While deep-water currents partially mitigated mortality, 11.2 percent of bleached fragments suffered complete tissue mortality. Concurrently, in shallow, high-nutrient nearshore zones, the steel frames experienced heavy macroalgal biofouling, predominantly driven by the expansion of *Turbinaria* spp. and *Sargassum*. Macro-algae mats rapidly overgrown frame joints and smothered young coral recruits, forcing Anana Laut divers to initiate intensive, labor-intensive manual algae scraping operations twice a month to prevent widespread fragment mortality. These empirical constraints confirm that while frugal sociotechnical interventions offer powerful localized recovery mechanisms (Mishra, 2021), their long-term efficacy remains tightly constrained by material corrosion (Tenci et al., 2024), ongoing human labor demands, and macro-level climate shocks.

DISCUSSION

Frugal Boundary Objects and the Bridge over Institutional Voids

In post-disaster archipelagic frontiers, state emergency interventions inherently suffer from entrenched terrestrial and administrative biases, creating acute institutional voids in the recovery of marine natural capital (Abudu et al., 2025). Institutional voids occur when formal state mechanisms, regulatory enforcement, and market structures fail to deliver essential public goods or mitigate systemic disruptions, forcing local populations to absorb the ecological and economic shocks independently (Amankwah-amoah & Debrah, 2025). In the immediate aftermath of Tropical Cyclone Seroja, the state's political architecture focused almost exclusively on land-based physical infrastructure—such as repairing damaged road networks, restoring electrical grids, and constructing temporary housing blocks. This land-centric focus effectively ignored the catastrophic subsurface collapse of the coral reef ecosystem on which coastal livelihoods in Kupang Bay (Mushtaha et al., 2025) depended. Formal disaster management agencies treated the sea as a static, background geography rather than a dynamic, living production space. Consequently, a severe operational void emerged at the intersection of marine environmental management and disaster response, leaving small-scale fishers in a structurally disadvantaged archipelagic pocket trapped in a compounding poverty-environment spiral where declining catches met skyrocketing operational costs.

The empirical trajectory of the LEMBU BERSERI program demonstrates that this institutional void was not bridged by a sudden re-entry of state authority or by massive capital inflows from international relief organizations, but rather through the strategic deployment of Web-Spider technology, which served as a frugal sociotechnical boundary object. In sociotechnical theory (Lloyd & Lewis, 2024), a boundary object is a material or conceptual artifact adaptable enough to span multiple social worlds, enabling diverse stakeholder groups with divergent institutional mandates, epistemologies, and priorities to coordinate their actions without forcing an artificial consensus or erasing their distinct institutional identities. The hexagonal steel Web-Spider structure fulfilled precisely this function (Beschoner & Hajduk, 2016). For state conservation rangers, the Web-Spider was viewed as a legally compliant, scientifically validated substrate for marine habitat rehabilitation within a strictly regulated protected area (Karisa et al., 2026). For the corporate entity PT Pertamina Patra Niaga, the structure served as a tangible, measurable vector for environmental, social, and

governance (ESG) compliance, risk mitigation, and community relations (Tyan & Liu, 2024; Fagbemi et al., 2025). For the marginalized youth (Stephens et al., 2018) of Kelompok Anana Laut, the very same physical object was interpreted as a means of economic survival, a symbol of post-disaster collective identity, and an instrument for reclaiming agency over their ancestral fishing grounds.

Crucially, the effectiveness of this boundary object was fundamentally contingent upon its frugal character. Frugal innovation in resource-constrained contexts is not merely about cheap manufacturing (Hindocha et al., 2021); it is a systematic design philosophy that strips away unnecessary technological complexity, reduces capital intensity, utilizes locally available raw materials, and maximizes social value creation at the grassroots level (Yadav et al., 2025). Rather than importing proprietary, high-cost artificial reef modules or relying on specialized marine engineering contractors from distant urban centers, the initiative deconstructed the fabrication process into basic, accessible technical components. The use of standard commercial round steel bars, locally sourced silica sand, anti-corrosive coatings, and manual arc welding techniques lowered the financial and educational barriers to entry. By establishing an on-land fabrication workshop directly within the coastal hamlet, the program transformed a technical engineering process into a communal space of collective learning and psychological healing from disaster trauma. The physical acts of cutting steel, operating arc welders, shaping hexagonal geometries, and applying protective coatings enabled disaster-affected fishers to tangibly re-engage with their environment, effectively dismantling the psychological paralysis and passive aid dependency that typically follow catastrophic climate events.

Furthermore, this frugal sociotechnical deployment marks a fundamental conceptual evolution in the theorization and operationalization of Corporate Social Responsibility (CSR) in the Global South (Pansera, 2023). Traditional corporate interventions in post-disaster settings heavily lean toward caritative philanthropy—providing short-term food packages, cash handouts, or superficial donations that treat local communities as passive beneficiaries while failing to build long-term structural resilience. The LEMBU BERSERI initiative breaks away from this outdated paradigm by operationalizing the principle of Creating Shared Value (CSV) (Beschoner & Hajduk, 2016), in which corporate socio-economic investments are directly anchored in the firm's core technical business capabilities. As a major maritime energy logistics and fuel terminal operator, PT Pertamina Patra Niaga Integrated Terminal Tenau possesses deep internal organizational competencies in marine engineering, industrial welding, corrosion control, safety protocols, and coastal risk management—the operationalization of its CSV strategy involved transferring these exact core competencies to the local youth group.

By training Anana Laut in industrial-grade welding standards, structural load calculation, and anti-corrosion application methods, the corporation did not simply hand out charity; it built a localized, autonomous technical capacity capable of executing marine civil works. This strategic alignment produced reciprocal benefits that exemplify the CSV framework (Menghwar & Daood, 2021): the local community gained valuable technical skills, income diversification, and ecological restoration, while the corporation secured its vital Social License to Operate (SLO) (Park, 2025) around its high-risk energy distribution hub in Kupang Bay. In a region where corporate-community relations are frequently fraught with conflict over resource access and environmental degradation, the co-creation of a frugal marine restoration platform cultivated a stable, collaborative operational environment. The corporate entity effectively mitigated its operational and reputational risks by fostering a resilient, technically self-sufficient coastal community capable of safeguarding the shared marine environment surrounding the energy terminal.

However, the capacity of this frugal sociotechnical boundary object to effectively bridge state institutional voids was enabled by a highly specific alignment of contextual factors. The success of the LEMBU BERSERI initiative was fundamentally contingent upon the presence of an industrial corporate partner (PT Pertamina Patra Niaga) that possessed direct, highly relevant maritime engineering competencies—such as arc welding, corrosion mitigation, and sea safety protocols—and was willing to transfer these capabilities directly to the local community. This corporate capacity intersected with a distinct socio-economic landscape: the Tenau fishing community faced severe post-disaster livelihood collapse following Tropical Cyclone Seroja, creating an urgent local demand for adaptive solutions. Furthermore, the intervention unfolded within a unique post-disaster policy environment, in which the institutional framework of Indonesian marine conservation

governance (specifically under BKKPN Kupang and BKSDA NTT) included regulatory provisions that authorized state authorities to legally delegate surveillance and monitoring roles to local communities. Absent this specific convergence of specialized corporate skills, acute socio-economic urgency, and supportive state conservation frameworks, deploying identical hardware might not have yielded the same rapid institutional bridging.

Ultimately, the deployment of frugal boundary objects within corporate-community-state partnerships provides a novel theoretical template for resolving state institutional voids in isolated archipelagic boundaries. It proves that filling institutional gaps in vulnerable regions does not always require expanding bureaucratic state apparatuses or introducing hyper-sophisticated, capital-intensive technologies. Instead, institutional voids can be bridged by deconstructing complex technologies into frugal, locally manufacturable sociotechnical tools, provided these tools are backed by strategic corporate capabilities and embedded within inclusive, multi-stakeholder governance frameworks. This frugal sociotechnical realignment transforms the post-disaster landscape from an arena of vulnerability and passive aid distribution into a dynamic site of technical empowerment, structural capacity accumulation, and local agency.

Knowledge Democratization and Human Capability Expansion

The transformation of disaster-stricken fishers into competent, recognized citizen scientists represents the core epistemic shift observed in the Kupang Bay restoration project, illustrating how the democratization of scientific knowledge can structurally dismantle post-disaster power asymmetries (Lam, 2024). Historically, environmental management and marine conservation in the Global South have been dominated by top-down, expert-driven paradigms (Botero et al., 2025). In these traditional models, formal academic institutions, international non-governmental organizations, and state bureaucracies hold a monopoly over scientific validity, treating local coastal communities merely as subjects of observation or manual labor. This epistemic hierarchy frequently marginalizes indigenous and local ecological knowledge, creating a profound sense of alienation among resource-dependent populations, whose lived realities and spatial insights are excluded from formal conservation zoning and environmental decision-making processes.

In the wake of Tropical Cyclone Seroja, this epistemic divide threatened to exacerbate the vulnerability of the Tenau fishing community. While academic institutions conducted high-level, retrospective damage assessments using complex satellite imagery and advanced benthic transect protocols, these academic outputs remained locked behind institutional paywalls and technical jargon, offering no actionable guidance or immediate empowerment for the fishers whose daily livelihoods had collapsed (Yang et al., 2023). The LEMBU BERSERI initiative disrupted this extractive knowledge economy through a deliberate process of knowledge democratization. The core of this process involved deconstructing complex marine biological monitoring methodologies—such as Line Intercept Transects (LIT) and taxonomic identification indices (Tilot et al., 2025)—into intuitive, visual, and operational metrics that could be seamlessly mastered by local youth with limited formal educational backgrounds.

By designing simplified, color-coded underwater slate cards, standardized visual photography grids, and morphology-based coral categorizations, formal marine ecological science was made fully accessible. Local youth were systematically trained not only to perform manual tasks such as attaching coral fragments with cable ties, but also to observe, measure, record, and analyze ecological variables such as fragment survival rates, axial branch extension, macroalgal fouling rates, and fish species recolonization within the Web-Spider matrices. Over 24 months of continuous monitoring across 450 deployed structures, these young fishers generated a robust, high-density empirical dataset that logged an average coral survival rate of 84.1 percent. This was not merely an exercise in crowdsourced data collection; it was a profound act of epistemic empowerment. The local youth ceased to be passive victims waiting for external experts to assess their sea; they became active producers of legitimate, empirical scientific knowledge.

While the democratization of marine knowledge empowered local actors, a critical examination reveals significant structural nuances in participation criteria and gender dynamics. The initial membership of Kelompok Anana Laut was largely defined by physical requirements—such as free-diving ability and stamina needed for underwater fabrication and deployment—which inadvertently introduced demographic selection

bias. Consequently, participation was predominantly composed of young, able-bodied male fishers, while older community members and individuals with limited aquatic skills were structurally excluded from direct engagement in underwater restoration activities.

Furthermore, gender dynamics within the initiative reflected existing coastal division of labor. Female participation in direct ecological restoration (diving and reef star installation) was virtually non-existent due to local socio-cultural norms surrounding maritime tasks. Instead, women's involvement was primarily concentrated in post-harvest processing, hospitality for the Adopt-a-Spider program, and terrestrial eco-tourism operations. Although these roles generated secondary income, women remained largely underrepresented in state- and corporate-governed technical decision-making processes and scientific monitoring workshops. This division underscores that, while knowledge democratization succeeded among male youth cohorts, gender equity in technical capacity-building remains an unfulfilled dimension of the initiative's socio-ecological transition.

This accumulation of epistemic sovereignty fundamentally altered the political dynamics between the local community and state conservation authorities. When presenting their independently collected, twenty-four-month monitoring data during quarterly co-management meetings, the youth of Anana Laut were no longer viewed by state officials as uneducated artisanal fishers encroaching on a protected marine reserve. Instead, their rigorous empirical evidence earned them formal legal recognition as community conservation monitors (Masyarakat Mitra Polhut). This designation granted them legal authority to conduct routine surveillance, restrict destructive fishing practices, and manage localized conservation zones within the Kupang Bay Marine Recreation Park. The democratization of science thus served as a counter-hegemonic tool that redistributed authority in environmental governance, allowing a marginalized coastal group to negotiate marine spatial management on equal footing with state actors.

To fully grasp the developmental significance of this epistemic transformation, the empirical outcomes must be evaluated through the theoretical lens of Amartya Sen's Capability Approach (Jamil, 2024; Sen, 2014). Sen conceptualizes human development not merely as the expansion of material wealth or commodities, but as the expansion of substantive human freedoms—the "capabilities" that enable individuals to lead lives they have reason to value. Democratizing scientific monitoring protocols did not merely generate data; it directly converted epistemic access into substantive human capabilities by giving youth the reason and means to value their coastal stewardship. In traditional disaster recovery interventions, success is narrowly measured by the distribution of material goods (such as tons of food distributed, meters of seawall constructed, or direct financial aid disbursed). However, these material-centric metrics fail to capture whether individuals have acquired the substantive freedom to act autonomously, to overcome structural traps, and to shape their own futures.

The LEMBU BERSERI program systematically expanded the substantive capabilities of participating youth across three interconnected dimensions: technical-epistemic mastery, socio-economic autonomy, and political agency. First, the acquisition of welding, diving, and marine monitoring capabilities transformed their self-identity from helpless disaster victims into skilled environmental stewards and citizen scientists. This mastery restored a sense of dignity and purpose that Cyclone Seroja had shattered. Second, this expanded technical capability was directly converted into socio-economic freedom through the valorization of restored ecological assets. By leveraging the rehabilitated reef site to establish a community-managed marine edu-tourism enterprise, the youth developed alternative income streams through eco-diving instruction, guided educational tours, and frame sponsorship programs. The resulting 84.8 percent increase in average monthly household income among active group members, combined with a reduction in reliance on primary fishing from 92.5 percent to 53.5 percent, effectively broke the poverty-environment trap that had historically bound these families to informal moneylenders (*tengkulak*) during low-catch seasons. Third, the allocation of 15% of tourism revenues to an autonomous community conservation fund provided a structural financial buffer, enabling the community to self-finance ongoing restoration, purchase diving gear, and cushion future climate shocks without begging for external charity.

Ultimately, knowledge democratization through citizen science converts localized ecological restoration into a powerful vehicle for human development. It demonstrates that when marginalized communities in

vulnerable archipelagic pockets are provided with accessible, frugal scientific tools, they do not merely restore degraded biological ecosystems; they expand their own human capabilities, reclaim political agency, build economic autonomy, and reshape the structural terms of their existence in an increasingly volatile climate future.

Polycentric Governance and Climate Adaptation Boundaries

The long-term sustainability and structural resilience of coastal interventions at remote island boundaries are largely governed by the institutional architecture overseeing resource management (Rukin, 2025). In isolated archipelagic contexts such as East Nusa Tenggara, traditional monocentric governance frameworks—characterized by top-down, centralized state administration—face significant operational constraints. Centralized management across expansive maritime territories inherently encounters structural challenges, including high monitoring costs, geographical remoteness, administrative delays, and limited local enforcement capacity in remote marine zones (Lewis et al., 2017). When severe climate events occur, these centralized systems often experience operational overextension, leaving isolated marine recreation areas vulnerable to unmonitored ecological degradation. Conversely, pure bottom-up, isolated community-based management often lacks the legal authority, financial capital, and technical support needed to scale restoration efforts or withstand external economic pressures.

The empirical success of the LEMBU BERSERI program highlights the efficacy of a polycentric governance model, a concept pioneered by Elinor Ostrom (Ostrom, 2010). Polycentricity describes an organizational system in which multiple governing authorities at different scales—ranging from local community groups and private corporate entities to state regulatory agencies—operate with overlapping and independent authority, interacting within a shared set of rules to manage common-pool resources (Fiorin, 2023). Rather than relying on a single hierarchy, the LEMBU BERSERI model integrated three distinct organizational logics into a resilient, tripartite governance alliance, with each actor fulfilling specialized, complementary functions that mitigated the structural weaknesses of the others (Lederer et al., 2025).

While this polycentric model succeeded under corporate-state-community alignment, the framework offers broader potential for adaptation across diverse institutional contexts and alternative partner configurations. In settings lacking a major corporate entity, the technical capacity-building and financial scaffolding role could be adapted by non-governmental organizations (NGOs), local municipal governments, or international donor agencies. However, substituting corporate partners with regional actors requires establishing alternative vocational training pipelines to compensate for the absence of internal industrial expertise.

Conversely, the operational efficacy of this model is subject to clear boundary conditions and may prove substantially less effective under certain negative constraints. The framework is highly vulnerable to failure in scenarios characterized by a total absence of technical fabrication competencies (e.g., improper welding or anti-corrosive application leading to rapid structural collapse), weak or adversarial institutional support from state conservation bodies, or severe internal community factionalism and socio-political conflict. In communities plagued by entrenched elite capture or historical resource disputes, frugal hardware risks becoming a contested private asset rather than a shared sociotechnical boundary object, ultimately undermining collective action and polycentric stability.

The state actors provided the legal mandate, formal spatial protection, and regulatory compliance framework necessary to legitimize restoration activities within a state marine reserve. However, state agencies lacked the budget and personnel to execute continuous daily underwater monitoring across Kupang Bay. The corporate actor, PT Pertamina Patra Niaga, supplied multi-year capital funding, managerial accountability, and technical engineering standards derived from its core business capabilities, overcoming the financial limitations of both the state and the local community. However, the corporate entity lacked local spatial presence and legal jurisdiction over marine resources. The community actor, Kelompok Anana Laut, provided the indispensable daily physical labor, underwater diving execution, local ecological knowledge, and constant spatial vigilance required to protect the restored site from destructive fishing.

This polycentric distribution of power created institutional redundancy and functional resilience (Paniagua & Pourvand, 2025). If one institutional node experienced operational constraints—for instance, if state funding was reallocated to other terrestrial disaster emergencies—the presence of corporate CSR scaffolding and community-generated tourism funds ensured that restoration activities continued uninterrupted. Decisions regarding frame placement, diver scheduling, visitor limits, and conservation fund allocations were made collaboratively during quarterly co-management forums. This shared governance architecture transformed the local community from passive subjects of state regulation into recognized co-managers of the marine protected area, drastically reducing enforcement costs for the state while cementing a stable operational environment for the corporate terminal operator.

However, a rigorous academic discussion must maintain analytical balance by critically interrogating the ecological boundaries and physical limits of localized frugal restoration. While the polycentric governance framework successfully resolved local institutional voids and drove human capability expansion, empirical monitoring data revealed significant bio-physical constraints that no amount of local agency or social capital could fully overcome. Chief among these limitations is the structural vulnerability of artificial steel substrates to marine corrosion and mechanical wear. Despite the application of anti-corrosive paint and silica sand coatings, saltwater oxidation initiated material degradation within eighteen to twenty-four months post-deployment, particularly in shallow zones exposed to high wave energy and tidal scouring. This material reality underscores that frugal hardware is not a permanent fix; it demands continuous, labor-intensive manual maintenance, regular re-coating, and structural reinforcement by local divers, creating an enduring operational burden.

Even more critically, the observed 28.5 percent coral bleaching rate during the 2023–2024 regional thermal stress anomaly ($+1.8^{\circ}\text{C}$ above average Sea Surface Temperature) exposes the fundamental boundaries of localized ecological restoration in the face of macro-level global climate change. Frugal Web-Spider technology, citizen science, and polycentric governance can successfully address localized stressors—such as blast fishing, anchor damage, macro-algae overgrowth, and institutional neglect. However, these localized sociotechnical interventions cannot alter the ambient thermodynamic properties of warming ocean waters driven by global greenhouse gas emissions. When large-scale marine heatwaves strike, locally restored coral fragments bleach and die at rates similar to natural reef colonies, regardless of how well the local community is organized or how robust the corporate-state partnership is.

This sobering ecological reality carries profound theoretical and policy implications for post-disaster recovery in archipelagic regions and Small Island Developing States (SIDS). It demonstrates that localized socio-ecological resilience interventions must not be overstated as panaceas for the global climate crisis (Zhou & Wang, 2026). Frugal restoration must be understood not as a replacement for global climate mitigation, but as an indispensable, localized climate adaptation bridge (Mendes, 2025). By maintaining live coral nurseries, preserving structural reef complexity, and fostering local technical agency, frugal restoration buys critical ecological time, maintains local biodiversity reservoirs, and diversifies coastal economies away from total dependence on climate-vulnerable wild fisheries.

Therefore, national disaster management frameworks and climate adaptation policies in archipelagic nations must fundamentally redefine their approach to coastal resilience. Post-disaster recovery policy must move beyond the narrow paradigm of terrestrial concrete rebuilding to formally incorporate sub-surface marine ecological restoration into emergency mandates. State agencies must institutionalize polycentric co-management frameworks within Marine Protected Areas and legally delegate spatial management rights to trained citizen science groups. Concurrently, corporate CSR regulations must mandate a transition away from short-term, caritative donations toward long-term, multi-year sociotechnical investments that build local human capabilities and align corporate core competencies with community resilience. Only through such integrated, polycentric, and sociotechnically empowered frameworks can remote island communities navigate the escalating socio-ecological uncertainties of the Anthropocene.

Finally, assessing the transferability of these empirical findings requires acknowledging the methodological implications of the single-case study design. The remarkable momentum achieved in Tenau was closely linked to the specific demographic and organizational characteristics of Kelompok Anana Laut—a cohesive, highly

adaptable youth cohort possessing physical vigor, high risk tolerance, and digital literacy conducive to mastering citizen science and edu-tourism marketing. It remains an open empirical question whether comparable ecological and socio-economic outcomes can be achieved when partnering with different community organizational structures, such as elder-dominated traditional fisher guilds, customary council bodies (lembaga adat), or women-led coastal cooperatives, which may operate under different social hierarchies, risk preferences, and decision-making speeds. Consequently, while this single-case investigation offers rich analytical generalization regarding frugal boundary objects and polycentric adaptation, multi-site comparative research across diverse archipelagic geographies, varied partner configurations, and distinct community organizational structures is essential to fully test the external validity and systemic generalizability of this framework.

CONCLUSION

This study demonstrates that post-disaster marine recovery in remote archipelagic frontiers and disadvantaged coastal pockets cannot be achieved through traditional land-centric emergency aid or capital-intensive top-down interventions. By examining the LEMBU BERSERI initiative in Kupang Bay following Tropical Cyclone Seroja, the research reveals how localized institutional voids in vulnerable island frontiers can be effectively bridged by re-conceptualizing standardized restoration hardware—specifically Web-Spider technology—as a frugal sociotechnical boundary object. Supported by corporate core capabilities and integrated into a polycentric partnership involving local state authorities, corporate actors, and community groups, this frugal intervention successfully transformed disaster-affected coastal youth from passive recipients of relief into competent citizen scientists, recognized conservation co-managers, and eco-tourism entrepreneurs.

Framed through the synthesis of Social-Ecological Systems Resilience, Sociotechnical Boundary Object Theory, and Amartya Sen's Capability Approach, the findings prove that ecological restoration in small-island contexts is an indispensable prerequisite for human development. The democratization of scientific knowledge empowered local youth within the Kelompok Anana Laut to generate rigorous empirical monitoring data, which in turn unlocked legal recognition of co-management and facilitated livelihood diversification. This shift significantly increased the incomes of participating households. It reduced economic reliance on climate-vulnerable wild fisheries, effectively dismantling the structural poverty-environment trap that had historically plagued the community.

However, the study also highlights critical biophysical limits of localized frugal interventions. Material degradation from saltwater oxidation requires continuous labor-intensive maintenance. At the same time, coral bleaching induced by ocean warming anomalies confirms that localized sociotechnical tools cannot shield marine ecosystems from macro-level global climate change. Frugal restoration must therefore be understood not as a standalone solution to global environmental crises, but as a vital localized adaptation bridge that maintains biodiversity reservoirs, buys ecological time, and builds human capabilities.

These findings yield important policy implications for post-disaster governance and corporate social responsibility in archipelagic states of the Global South. National disaster management frameworks must dismantle their terrestrial bias by formally incorporating the recovery of marine natural capital into emergency response mandates. Furthermore, regulatory frameworks governing corporate social responsibility should incentivize strategic sociotechnical partnerships that transfer technical capabilities and foster polycentric governance over charitable hand-outs. Future research should expand upon these insights by conducting multi-site comparative studies across diverse archipelagic geographies and tracking the long-term socio-ecological durability of polycentric restoration models over extended periods of climate stress.

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