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Sustainable marine debris management through integrated coastal governance: The role of digital evidence and community engagement

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Graphical abstract

Abstract

Marine debris pollution has become a major ecological and social challenge in Indonesia's coastal areas, requiring approaches that go beyond technocratic or sectoral solutions. This study integrates the framework of Integrated Coastal Management (ICM) and Community-Based Development (CBD) with digital evidence and participatory governance to address weak law enforcement and limited community engagement in coastal West Sulawesi. Using a sequential explanatory mixed-methods design, the research combined quantitative surveys (32 items, Likert scale, Cronbach's α = 0.82) with 250 respondents, qualitative interviews and FGDs with key stakeholders, and spatial analysis of drone imagery (~5 cm/pixel, 500 × 500 m grids, validated with ground surveys) collected over six months. Findings reveal that while 100% of respondents reported smartphone access, only a minority were aware of digital reporting for environmental purposes, indicating a significant gap between technological access and environmental digital literacy. Survey and spatial data also showed variations in marine debris accumulation, where some densely populated settlements maintained relatively clean coastlines due to strong local norms and social capital. Weak coordination between government agencies, the private sector, and oversight bodies further undermines effective law enforcement. In response, this study proposes a digital evidence–based ICM model, where communities document pollution through geo-tagged photos/videos, data are validated by multi-actor teams, and results feed into transparent dashboards to support environmental law enforcement and policy decisions. The findings highlight the potential of combining digital technology, participatory governance, and legal frameworks to strengthen ecological sustainability and social accountability. This model provides insights for replication in other archipelagic and coastal regions facing similar marine debris challenges.

Keywords: Marine debris, ICM, digital evidence, coastal communities, environmental law enforcement

1. Introduction

Coastal zones represent highly strategic areas where ecological, social, and economic systems intersect in complex ways. In recent decades, these areas have come under increasing pressure from human activities, with marine debris emerging as one of the most persistent threats to coastal sustainability (Galgani *et al.* 2019; Purba *et al.* 2024). For archipelagic countries such as Indonesia—with the second-longest coastline in the world—the stakes are particularly high. Despite national commitments, including Presidential Regulation No. 83 of 2018 on Marine Debris Management, effective implementation at the local level remains constrained by weak institutional capacity, poor inter-agency coordination, and limited community engagement (Hendar *et al.* 2022; Laitupa *et al.* 2024).

West Sulawesi Province exemplifies this challenge. Daily debris accumulation in several coastal districts exceeds 2,000 m^3, with severe ecological consequences including mangrove degradation, seagrass loss, and declining water quality (Rafsanjani Fajrin *et al.* 2024; Tamaruddin *et al.* 2024). These ecological impacts directly translate into socio-economic vulnerability for traditional fishing communities, deepening forms of environmental injustice where the poorest bear the heaviest burdens (Sultana & Luetz 2022).

While Integrated Coastal Management (ICM) has long been promoted as a holistic solution—integrating

ecological, economic, social, and institutional dimensions—its success has been uneven across different contexts (Quesada *et al.* 2018). Studies in Southeast Asia and beyond show that ICM often fails when implemented through overly bureaucratic, top-down models that neglect community agency and technological innovation (Russell-Smith *et al.* 2018). Parallel to this, research on *citizen science* and *digital environmental monitoring* highlights the potential of community participation combined with new technologies to improve environmental governance outcomes (Christensen *et al.* 2021a; Jones *et al.* 2024). However, these initiatives often remain confined to data collection without strong integration into law enforcement mechanisms.

This study seeks to address that gap by developing a digital evidence-based ICM model that explicitly links community participation with environmental law enforcement. The novelty lies in positioning coastal communities not only as data collectors but as agents of ecological justice, whose digital evidence can be verified, institutionalized, and utilized within legal frameworks. By combining drone-based spatial documentation, participatory surveys, and community-led reporting mechanisms, the study provides a framework that is both technologically grounded and socially legitimate.

This contribution is particularly relevant for decentralized governance systems such as Indonesia's, where coordination challenges between central and local institutions often weaken environmental enforcement. More broadly, the findings from West Sulawesi can inform other archipelagic and developing nations facing similar struggles at the interface of marine debris management, digital transformation, and participatory governance.

2. Theoretical Framework

2.1. Integrated Coastal Management (ICM) and Community-Based Development (CBD)

ICM is widely recognized as a strategic approach that integrates ecological, economic, social, and institutional dimensions of coastal governance. Its core principle is cross-sectoral and cross-scalar coordination, aiming to overcome fragmentation in marine, fisheries, forestry, tourism, and spatial planning policies (Quesada *et al.* 2018). However, evidence from multiple countries demonstrates that ICM implementation often fails when it disregards local culture and community participation (Duxbury & Jeanotte 2010).

Community-Based Development (CBD) addresses this limitation by positioning communities not as passive beneficiaries but as co-creators of governance. CBD emphasizes local knowledge, social norms, and collective action, which have proven critical in enhancing the legitimacy and sustainability of coastal management programs (Abdullah *et al.* 2020; Judijanto *et al.* 2023). In contexts such as West Sulawesi, CBD helps bridge the gap between policy design and on-the-ground practice by embedding ICM within existing community structures and values.

2.2. Environmental Governance, Justice, and Participatory Democracy

The broader field of environmental governance highlights the importance of inclusive, accountable, and participatory systems in managing natural resources (Christensen *et al.* 2021a). Particularly relevant is the concept of environmental justice, which emphasizes fair distribution of environmental benefits and burdens, as well as equitable access to decision-making processes (Sultana & Luetz 2022). In decentralized states, the success of environmental governance depends not only on regulatory frameworks but also on the active involvement of local communities, civil society, and oversight institutions. Participatory democracy in environmental management ensures that marginalized groups—such as artisanal fishers and coastal women—can exercise agency in shaping governance outcomes (Guerrato & Gonçalves 2025).

2.3. Digital Environmental Monitoring and Law Enforcement

Recent advances in digital technologies—from drones and GIS to mobile-based reporting platforms—have opened new opportunities for community-based environmental monitoring (Purba *et al.* 2024; Singh *et al.* 2024). Research on citizen science platforms demonstrates that digital tools can expand data availability, increase transparency, and accelerate government responses (Jones *et al.* 2024). However, most initiatives stop short of transforming digital evidence into enforceable legal instruments. The question of how community-generated digital evidence can be validated, recognized, and acted upon in environmental law enforcement remains underexplored.

Emerging scholarship on digital environmental governance suggests that technology-enabled monitoring can enhance compliance and accountability, provided that issues of verification, privacy, infrastructure, and governance coordination are addressed (Deng 2024). Beyond environmental monitoring, studies on digital transformation in sustainability demonstrate how digital systems—such as blockchain applications in supply chain management (Chen *et al.* 2025), corporate environmental performance improvements through digital investment (Jin *et al.* 2023), and links between environmental policies and sustainable development outcomes (Jin & Lei 2023)—can institutionalize accountability and drive behavioral change. This literature provides a useful foundation for extending the role of digital evidence from mere documentation to legally relevant enforcement mechanisms in environmental governance.

2.4. Positioning this Study

Previous studies have explored citizen science, mobile-based pollution reporting, and participatory monitoring in coastal contexts (Jones *et al.* 2024). What distinguishes this study is its attempt to institutionalize community-generated digital evidence within an ICM framework, explicitly connecting participatory monitoring with environmental law enforcement in a decentralized governance system. The proposed model is not limited to

awareness-raising or data visualization but aims to create enforceable accountability pathways by combining:

1. Community reporting (via digital tools),
2. Verification mechanisms (multi-stakeholder validation), and
3. Integration into enforcement systems (government agencies, Ombudsman, and judicial processes).

This theoretical positioning underlines the study's novelty: advancing the literature from participatory monitoring toward digital evidence-based governance, where technology and community action converge to strengthen ecological justice and sustainable coastal management.

3. Literature Review

Previous research on marine debris management in Southeast Asia has largely emphasized ecological mapping, public awareness, and cleanup initiatives. For example, large-scale cleanup programs have provided important baseline data but often lacked integration into formal policy mechanisms (Purba *et al.* 2024). More recent studies have introduced citizen science approaches for marine debris monitoring in remote Indonesian islands, highlighting both opportunities and challenges in sustaining volunteer-based data collection.

Comparative analyses demonstrate that participatory governance can be highly effective in archipelagic and decentralized contexts, where social integration and informal institutions strongly influence environmental outcomes. Yet, the legal recognition of community-generated evidence remains limited, constraining its potential to contribute to enforcement and policy accountability.

To strengthen the theoretical basis, this study also draws on the emerging literature on digital environmental governance, particularly research on how blockchain applications can improve transparency in supply chain sustainability (Chen *et al.* 2025), how corporate environmental performance benefits from digital investment (Jin *et al.* 2023), and how environmental policies are linked to sustainable development outcomes (Jin *et al.* 2023). These works illustrate the broader significance of digital transformation in environmental management, though applications to marine debris management in archipelagic regions remain underdeveloped.

Building on these literatures, the present study situates West Sulawesi as a case study to explore how community-generated digital evidence can be verified, legitimized, and institutionalized into Integrated Coastal Management (ICM) frameworks. In this way, the research extends prior debates on citizen science and digital monitoring into the domain of participatory environmental law enforcement, responding to ongoing calls for stronger theoretical and practical integration in this field.

4. Materials and Methods

4.1. Research Design

This study employed a mixed-methods sequential explanatory design, in which quantitative data collection and analysis were conducted first, followed by qualitative exploration, and then integrated with spatial analysis. This design was chosen to provide both breadth and depth: the survey generated measurable patterns of awareness, perception, and digital readiness; the interviews and focus group discussions (FGDs) explored the socio-cultural and governance dynamics underlying those patterns; while GIS analysis offered objective and visual ecological evidence.

The integration aimed to achieve three objectives:

1. Quantitative evidence to establish general trends.
2. Qualitative insights to explain mechanisms and contradictions behind the numbers.
3. Spatial analysis to provide visual and verifiable ecological documentation.

Such integration reflects contemporary trends in environmental governance research, which increasingly combine statistical, participatory, and spatial approaches to capture the complexity of socio-environmental systems (Cai *et al.* 2025b, 2025a).

4.2. Sampling and Respondents

A purposive sampling strategy was adopted to ensure the inclusion of respondents most relevant to marine debris governance. Five districts in West Sulawesi were selected—Mamuju, Central Mamuju, Pasangkayu, Majene, and Polewali Mandar—based on their socio-ecological variation, including:

1. Different ecological assets (mangroves, seagrass, reefs).
2. Varying degrees of urbanization and market activity.
3. Documented marine debris accumulation (DLH West Sulawesi 2024).

Within each district, a quota system was applied to maintain balance across livelihood groups (fishers, aquaculture farmers, traders, women's groups, and youth). In total, 250 respondents were surveyed, distributed as follows:

District	Respondents	Dominant Livelihoods
Mamuju	50	Fishers, fish traders
Central Mamuju	45	Aquaculture farmers, traders
Pasangkayu	55	Coastal farmers, vendors
Majene	50	Fishers, youth, women groups
Polewali Mandar	50	Artisanal fishers, tourism
Total	**250**	

Inclusion criteria: (i) resident for ≥ 5 years, (ii) primary livelihood dependent on coastal resources, and (iii) direct experience with marine debris impacts.

Limitation: As purposive sampling is non-random, the findings cannot claim statistical generalizability to all coastal populations in Indonesia. Instead, the representativeness lies in reflecting socio-ecological diversity of West Sulawesi, which offers lessons for comparable coastal regions.

4.3. Survey and Questionnaire

The structured questionnaire consisted of 32 items, divided into four sections:

1. Demographics (age, gender, education, occupation).
2. Awareness and knowledge of marine debris (e.g., "I know what marine debris is").
3. Perceptions of impacts (e.g., "Marine debris reduces fish catches").
4. Participation and technology use (e.g., "I am willing to report waste pollution via a mobile application").

Most items used a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree), supplemented with categorical and open-ended questions.

4.3.1. Validity & Reliability

1. Content validity ensured through review by three coastal governance experts.
2. A pilot test with 30 respondents outside the study area yielded a Cronbach's alpha = 0.82, indicating good reliability.

This approach is consistent with contemporary environmental behavior studies that stress testing both validity and reliability of community-based perception instruments (Cai *et al.* 2025b).

4.4. Interviews and FGDs

A total of 25 semi-structured interviews were conducted with key stakeholders:

1. Local government officials (Environmental Agency, Fisheries Office, village heads).
2. Traditional leaders and community elders.
3. Civil society organizations and academic representatives.

Additionally, five FGDs (one per district) were organized with 10–12 participants each, involving fishers, women's groups, and youth activists.

These qualitative methods served two purposes:

1. To explain survey patterns, including contradictions such as high smartphone ownership but low digital literacy.
2. To provide governance perspectives, highlighting institutional challenges and informal community practices.

The triangulation of survey and qualitative data allowed for deeper exploration of mechanisms that quantitative findings alone could not explain.

4.5. GIS and Spatial Data

Spatial data collection was conducted from January to June 2025 using drone-based aerial imagery and GIS mapping.

1. Resolution: ~5 cm/pixel with 500 × 500 m grids along selected coastal transects.
2. Variables mapped: debris hotspots, mangrove and seagrass coverage, shoreline changes.
3. Validation methods:
    a. Cross-check with official DLH monitoring records.
    b. Ground truthing at 10 random coastal points.
    c. Independent verification by GIS experts at the University of West Sulawesi.

This multi-layer validation ensured accuracy and comparability, aligning with recent practices in dynamic governance analysis for resource allocation and spatial planning (Cai *et al.* 2024).

4.6. Data Triangulation

The study employed a convergent triangulation approach, integrating:

1. Quantitative survey data → broad patterns of awareness, perception, and readiness.
2. Qualitative interviews & FGDs → interpretive depth on cultural norms, governance dynamics, and social capital.
3. Spatial GIS data → visual and verifiable ecological evidence of marine debris and ecosystem degradation.

Weighting was not equal: quantitative data formed the foundation of the analysis, qualitative data explained contextual dynamics, and spatial evidence visually reinforced the findings.

This integrated approach follows recommendations from recent environmental governance research, which emphasizes multi-method integration for robust insights into complex socio-environmental systems (Cai *et al.* 2025a).

5. Results

5.1. Descriptive Findings

The drone-based spatial mapping and field measurements across the five districts of West Sulawesi revealed considerable daily marine debris accumulation. Estimated volumes ranged from 1,200 m^3/day in Central Mamuju to 2,500 m^3/day in Majene, with hotspots concentrated near fish landing sites, traditional markets, and river mouths. These values are consistent with local Environmental Agency records but provide finer resolution due to continuous six-month monitoring.

Survey results (n = 250) indicated that:

1. Demographics: 62% male, 38% female; average age 38 years; 70% dependent on fisheries-related livelihoods.
2. Awareness: 74% of respondents recognized the term "marine debris," while 86% could correctly identify plastics as the most problematic waste type.
3. Perceived impacts: 80% reported declining fish catches attributed to debris, 72% observed ecosystem damage (e.g., mangrove roots clogged with plastic), and 65% linked debris with increased flooding risk.

4. Participation: Only 44% had participated in clean-up initiatives, yet 90% expressed willingness to report violations via mobile applications if provided with proper guidance.

These findings illustrate a high level of problem recognition but relatively low levels of structured engagement in debris management activities.

5.2. Contradictions: Smartphone Access vs Digital Literacy

One of the most striking results was the apparent contradiction between 100% smartphone ownership among respondents and their limited capacity to use digital tools for environmental reporting. While all participants regularly used smartphones for social media and messaging, none were familiar with how photos, videos, or geotagged data could serve as formal evidence in environmental monitoring.

This contradiction highlights the distinction between infrastructure readiness (hardware availability, internet penetration) and functional literacy (capacity to generate, verify, and submit digital evidence). The result reflects patterns found in other Southeast Asian participatory governance studies, where communities are technologically connected but lack institutional channels and capacity to link digital documentation with formal governance (Christensen *et al.* 2021b; Jones *et al.* 2024)

This gap must be acknowledged as a limitation: while communities are well equipped with devices, the absence of training, verification protocols, and legal recognition of community-generated evidence constrains the potential of digital participation. This suggests that any proposed model must incorporate capacity building and institutional embedding, rather than assuming that device ownership automatically translates into effective digital governance.

5.3. Social Dynamics and Local Variations

Although debris accumulation was generally higher in densely populated settlements, several exceptions emerged. In some high-density fishing villages in Majene and Polewali Mandar, coastlines appeared significantly cleaner compared to less populated areas.

Qualitative evidence from interviews and FGDs revealed that these outcomes were shaped by local social dynamics rather than population pressure alone:

1. Social capital: strong neighborhood networks organized regular clean-ups without external funding.
2. Local norms: customary taboos against dumping waste in the sea, enforced by traditional leaders.
3. Informal institutions: youth groups and women's associations established self-regulated waste monitoring practices tied to cultural pride and eco-tourism opportunities.

These findings demonstrate that population density is not a deterministic driver of debris accumulation. Instead, variations can be explained by community-level governance mechanisms, aligning with environmental governance literature that highlights the role of informal institutions and participatory norms in shaping outcomes (Sultana & Luetz 2022).

Thus, governance effectiveness in marine debris management depends not only on state policy or infrastructure, but also on leveraging existing forms of collective action and local legitimacy. This reinforces the need to embed digital evidence models into socio-cultural contexts where informal institutions already have proven efficacy.

6. Discussion

6.1. Linking to Theory

The findings of this study provide empirical support for the theoretical foundations of Integrated Coastal Management (ICM) and Community-Based Development (CBD). As theorized, ICM requires cross-sectoral coordination and multi-level governance (Quesada *et al.* 2018). However, our evidence from West Sulawesi shows that implementation gaps persist when governance frameworks fail to engage communities as active partners.

The observed contradiction—universal smartphone access but limited digital literacy for environmental reporting—underscores the importance of moving beyond technological determinism. Digital tools alone are insufficient without capacity building, verification protocols, and legal frameworks that recognize community-generated evidence. This finding resonates with broader scholarship on participatory governance, which argues that citizen participation must be embedded in institutional frameworks to translate into enforceable accountability (Christensen *et al.* 2021b; Jones *et al.* 2024).

The social dynamics observed in high-density but clean villages highlight the influence of informal institutions and social capital in shaping environmental outcomes. This aligns with governance literature emphasizing that collective norms, cultural taboos, and community networks can substitute for weak formal enforcement (Sultana & Luetz 2022). The implication for environmental law enforcement is that digital evidence-based ICM must integrate not only formal legal systems but also informal governance structures, ensuring complementarity rather than conflict.

6.2. Contribution to Literature

This study contributes to the growing literature on digital environmental governance by advancing beyond existing models of citizen science and digital monitoring platforms. While previous research has demonstrated the value of citizen-generated data in expanding ecological knowledge (Christensen *et al.* 2021b), most initiatives remain limited to awareness-raising or supplementary data collection.

The novelty of this study lies in proposing a model where community-generated digital evidence is not only collected but also verified, legitimized, and embedded into formal environmental law enforcement processes. This positions communities not as passive data collectors but as agents of ecological justice, capable of triggering formal accountability mechanisms.

The contribution is particularly relevant for archipelagic nations with dispersed communities and fragile ecosystems, such as Indonesia, the Philippines, and Pacific

island states. In such contexts, centralized monitoring is logistically unfeasible, making decentralized, digitally-enabled participation indispensable. Moreover, in decentralized governance systems, where local institutions hold significant authority but often face coordination problems, embedding digital evidence in both community and institutional practices offers a practical pathway to accountability.

This also echoes broader findings in digital transformation research: investments in digital systems have shown measurable improvements in governance performance, whether in corporate environmental management (Jin *et al.* 2023) or in supply chain transparency through blockchain applications (Li & Lei 2024). Similarly, policy-level integration of digital tools has been linked to sustainable development outcomes (Jin *et al.* 2023). By situating community-generated evidence within this broader literature, this study underscores how digital participation can be institutionalized as enforceable governance, not merely as voluntary action.

7. Limitations

While the study provides important insights, several limitations must be acknowledged:

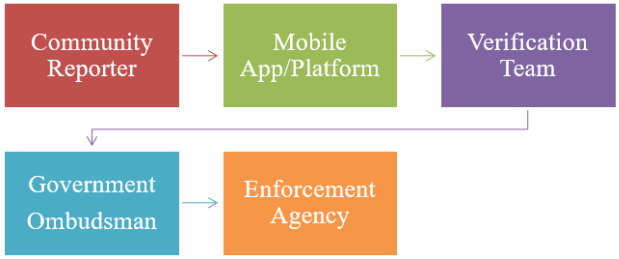
1. Contradictory findings on technology use
   Although smartphone access was universal, digital literacy for environmental reporting remained low. This highlights the gap between infrastructure readiness and functional capacity, reinforcing the need for future interventions that focus on self-efficacy and training (Cai *et al.* 2025b).
2. Sampling constraints
   The purposive sampling design, while ensuring socio-ecological diversity, limits statistical generalizability. Findings should be interpreted as case-specific insights, rather than universally representative trends.
3. Digital literacy and institutional readiness
   While communities showed willingness to participate, limited skills and weak institutional mechanisms hinder the translation of willingness into actionable governance. As seen in other governance contexts, adaptive resource allocation and institutional coordination will be required (Cai *et al.* 2024).
4. Legal validity of digital evidence
   At present, Indonesian law lacks explicit recognition of community-generated digital evidence in environmental enforcement. Without robust verification protocols, privacy safeguards, and institutional mandates, the legal enforceability of such evidence remains uncertain. This limitation highlights the importance of aligning digital innovations with the broader political economy of environmental governance in decentralized systems.

8. Model Digital Evidence-Based ICM

8.1. Model Description

The proposed model integrates community participation and digital reporting mechanisms into the framework of Integrated Coastal Management (ICM). The process flow can be summarized as follows:

1. Community members document marine debris incidents through smartphones (photos, videos, geotagged locations).
2. Reports are submitted to a digital platform accessible at village and district levels.
3. A verification team—composed of government officials, academics, and civil society representatives—reviews the submissions for authenticity and relevance.
4. Verified cases are forwarded to government agencies and/or the Ombudsman, who have the authority to initiate formal follow-up actions.
5. Law enforcement bodies (local Environmental Agency, Maritime Affairs, and judicial authorities) act on verified reports to ensure accountability.



This schematic clarifies that community-generated evidence is not merely informational but forms part of an institutionalized enforcement cycle within ICM.

8.2. Feasibility & Implementation Challenges

While innovative, the model requires careful consideration of feasibility and potential obstacles:

1. Data verification protocols: Without standardized verification, reports may face challenges of credibility and admissibility. Peer review mechanisms, expert validation, and metadata checks are required.
2. Privacy and data security: Protection of community reporters' identities is crucial to prevent retaliation or misuse of personal data.
3. Technical infrastructure: Digital platforms require stable internet connectivity, secure servers, and integration with existing e-governance systems.
4. Budget and maintenance: Sustaining the platform involves initial development costs, routine maintenance, and training, which may exceed local government budgets. Similar to corporate experiences, however, long-term investment in digital infrastructure has been shown to enhance environmental performance (Jin *et al.* 2023).
5. Coordination barriers: Indonesia's decentralized governance system often suffers from fragmented institutional responsibilities. Adaptive allocation of roles, as demonstrated in low-carbon pilot city governance (Cai *et al.* 2024), will be necessary.
6. Legal recognition of community evidence: Current Indonesian law does not explicitly regulate the use of citizen-generated digital data in environmental litigation. Recognition of such evidence will require legal reform and strong institutional backing.

8.3. Risk Mitigation Strategies

To enhance feasibility, the following risk mitigation strategies are proposed:

1. Digital literacy training
    a. Community capacity building to improve functional literacy, beyond smartphone ownership. Training modules can focus on photo verification, metadata use, and ethical reporting.
    b. Strengthening individual efficacy is essential, as it has been shown to predict conservation-oriented behavior (Cai *et al.* 2025b).
2. Multi-stakeholder verification teams
    a. Establishing cross-sectoral teams (government, academia, CSOs) reduces risks of bias and increases trust in the verification process.
    b. Blockchain-inspired approaches may be adapted to ensure transparency and tamper-proof reporting (Chen *et al.* 2025).
3. Budget allocation across time horizons
    a. Short-term: Pilot projects funded by local government and donor agencies.
    b. Medium-term: Institutionalization within district environmental budgets.
    c. Long-term: Integration into national digital governance systems, supported by inter-ministerial funds.
4. Integration into decentralized governance
    a. Embedding digital reporting into existing district-level coastal management plans ensures compatibility with Indonesia's decentralized governance framework.
    b. Alignment with national sustainable development targets will further legitimize the system (Jin *et al.* 2023).

8.4. Policy Recommendations

Building on the findings and model feasibility analysis, the following policy recommendations are proposed to guide the institutionalization of a Digital Evidence-Based Integrated Coastal Management (ICM) system in Indonesia. Recommendations are structured across short-, medium-, and long-term horizons to ensure gradual but sustainable implementation.

8.5. Implementation Time Line

Time Horizon	Key Actions	Institutional Focus	Expected Outcomes
Short-term (1–2 years)	- Develop pilot digital reporting platform (basic mobile app). - Conduct community training on digital literacy, environmental reporting, and evidence protocols. - Initiate local awareness campaigns involving youth and women's groups.	Local Environmental Agencies (DLH), village governments, CSOs	Proof-of-concept established, communities gain functional digital literacy, early trust-building in digital evidence mechanisms.
Medium-term (3–5 years)	- Formal integration of digital reporting into **district DLH systems**. - Establish **multi-stakeholder verification teams** (government, academia, CSOs). - Provide budget allocation within district environmental planning.	District DLH, regional universities, NGOs	Verified reporting system institutionalized at district level, enhanced credibility of community evidence, improved enforcement capacity.
Long-term (>5 years)	- Allocate **dedicated budget line** for digital reporting and platform maintenance in provincial/national environmental programs. - Scale system to **national level**, integrated into Ministry of Environment and Forestry (KLHK) databases. - Enact **legal regulations** formally recognizing community-generated digital evidence as admissible in environmental law enforcement.	National government (KLHK, Ombudsman, Ministry of ICT), parliament	Nationwide adoption of digital evidence-based ICM, strengthened law enforcement legitimacy, improved compliance and accountability in coastal governance.

8.6. Political Economy of Decentralization

Implementation must also consider Indonesia's decentralized governance system, which creates both opportunities and challenges:

1. Opportunities: Local governments have significant authority to design and pilot innovative governance models. Embedding digital reporting within district DLH programs leverages this autonomy for adaptive local solutions.
2. Challenges: Fragmented authority across ministries and districts often hampers coordination. For example, waste management, fisheries, and coastal zoning fall under different jurisdictions, creating gaps in accountability.
3. Mitigation:
    a. Strengthen vertical coordination through inter-ministerial task forces linking district DLH with the Ministry of Environment and Forestry.
    b. Incentivize horizontal coordination across districts through provincial forums on digital governance and marine debris management.
    c. Anchor reforms in national sustainable development targets, ensuring alignment with international commitments (Jin *et al.* 2023).

9. Summary

By sequencing actions across short, medium, and long-term horizons, and addressing the political economy of decentralization, Indonesia can gradually establish a

sustainable and enforceable digital evidence ecosystem for marine debris management. Such an approach not only strengthens environmental governance but also advances participatory democracy and justice in coastal communities.

10. Conclusion

This study examined marine debris management in five coastal districts of West Sulawesi, Indonesia, through a mixed-methods sequential explanatory design integrating surveys, interviews, FGDs, and GIS analysis. Three main findings emerged: first, while awareness of marine debris is high, active participation in management remains limited; second, universal smartphone ownership does not translate into digital literacy for environmental reporting, revealing a gap between infrastructure readiness and functional capacity; and third, local social capital, informal norms, and community networks play a critical role in shaping environmental outcomes, often compensating for weak formal enforcement.

Theoretically, the study contributes to environmental governance and Integrated Coastal Management (ICM) by proposing a digital evidence-based model that integrates community participation into formal enforcement processes. Unlike previous citizen science or digital monitoring initiatives, this model emphasizes the verification, legitimacy, and institutional embedding of community-generated evidence, offering a pathway to strengthen participatory governance and environmental justice in decentralized governance contexts.

Practically, the findings highlight the need for multi-level interventions: from community training on digital literacy, to district-level verification systems, to national regulations recognizing the legal validity of digital evidence. The proposed policy roadmap outlines short-term pilots, medium-term institutionalization, and long-term national integration, while also acknowledging the political economy challenges of Indonesia's decentralized system.

The novelty of this research lies in demonstrating that digital participation can be transformed into enforceable governance, not merely voluntary environmental action. By situating West Sulawesi as a case study, the research also provides comparative insights for other archipelagic nations where dispersed geographies and decentralized governance create similar challenges for environmental monitoring and law enforcement.

Future research should explore:

1. Comparative case studies across different archipelagic and decentralized governance settings.
2. Experimental pilots of digital evidence platforms, including blockchain-inspired verification mechanisms.
3. Longitudinal studies to assess the sustainability of community participation and the durability of institutional reforms.

In sum, bridging technology, community participation, and governance structures offers a promising pathway to address the persistent challenge of marine debris management, advancing both the theory and practice of participatory environmental governance.

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