Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.2, April 2026, pp. 02602013-01 ~ 02602013-023
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i2.2059

Mangrove Biodiversity for Coastal Resilience and Sustainability: A Dynamic Case Study from Indonesia

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Abstract. Mangrove degradation and socio-economic vulnerability in the Kendal coast require an integrated approach. The study used ecological surveys (mangrove vegetation analysis, avifauna) and socio-economic (n=186 households). Integrated Coastal Management (ICM) analysis and model were developed using a dynamic approach, encompassing problem identification, conceptual model formulation, and validation preparation. 14 mangrove species (H' index = 1.58–1.80) and 61 bird species (H' = 3.50) were found. Community participation reached 97%, but women's participation was only 3%, with 58% of households being landless and 61% unproductive land. Infrastructure was severely damaged (36% of roads) and 97% of the area was flooded. The dynamic model of ICM in Kendal Regency highlighted coastal biodiversity conservation, enhanced community capacity and participation, and secure land ownership as the primary drivers of sustainable coastal governance. Despite ongoing pressures from coastal hazards and urban expansion, biodiversity conservation remained the pivotal intervention, sustaining ecosystem integrity, improving household incomes, and reinforcing socio-economic resilience through positive feedback loops within the coastal social–ecological system.

Keywords: biodiversity indicators, coastal vulnerability, dynamic approach, Resilience modeling, integrated coastal management

(Received 2025-06-01, Revised 2025-07-31, Accepted 2026-01-29, Available Online by 2026-03-18)

1. **Introduction**

Mangrove forests play a critical role in coastal resilience by shielding shorelines from erosion, storms, and tsunamis through their intricate root systems [1], [2]. As vital blue carbon ecosystems, mangroves sequester carbon up to three to five times more efficiently than terrestrial forests, making them indispensable in global climate change mitigation efforts [2], [3]. However, global mangrove cover is declining at a rate of 0.13% per year, driven by overexploitation for fuelwood, conversion to aquaculture, and increasing coastal development pressures [1], [4]. This degradation threatens biodiversity, including fish species and migratory birds that rely on mangrove habitats [2], [3]. Addressing these challenges requires transdisciplinary restoration approaches that integrate ecological conservation with the economic needs of coastal communities to ensure long-term sustainability [4], [5].

Kendal Regency, located in Central Java Province, is a coastal region designated for mangrove areas spanning 183 hectares [6], [7]. The mangrove ecosystems are distributed across seven subdistricts: Rowosari, Kaliwungu, Kendal, Brangsong, Cepiring, Kangkung, and Patebon. However, by 2022, it was reported that 40% of these mangrove areas had suffered degradation [8], [9]. This damage is attributed to abrasion, eroding approximately 42.4 kilometers of coastline, with shifts ranging from 36.59 to 53.39 meters [10], [11]. In addition to climate anomalies, geophysical conditions and anthropogenic activities have significantly influenced the dynamics of Kendal's coastline. The addition of built-up land due to industry, including on the Kendal coast, has caused a decline in environmental quality [12]. As a result, the coastal area of Kendal Regency has been identified as a climate hotspot and included in climate resilience priority programs.

One of the areas most severely affected by abrasion is Kartikajaya Village in Patebon Subdistrict. Between 2017 and 2020, the region experienced an average land loss of 2.5 hectares per year, threatening local attractions like the *Pulau* Tiban beach, which is on the verge of submersion [13]. This phenomenon has also caused significant economic impacts, including a 90% decline in tourist visits. The mangrove ecosystem in the area is not only a critical source of livelihood through tourism but also supports aquaculture, provides food resources, and offers various ecosystem services. Previously, the mangrove ecosystem in Kartikajaya Village had an estimated total economic value of IDR 1,449,469,338 per year, derived from direct benefits, indirect benefits, and option values. However, this economic value is likely to decline due to the increasing threats posed by climate change [14],[15]. Although conservation efforts through the planting of *Rhizophora* and *Avicennia marina* have been implemented, the dominance of monoculture practices risks undermining ecosystem resilience to disturbances while constraining the economic potential derived from mangrove biodiversity, depriving coastal communities of diversified livelihood opportunities [16].

In 2023, mangrove diversity in Kartikajaya Village was dominated by the species *Avicennia marina*, *A. officinalis*, *Bruguiera gymnorrhiza*, *Rhizopora apiculata, R. mucronata,* and *R. stylosa* [16]. Meanwhile, the coastal area of Kendal Regency predominantly features three mangrove species: *R. a mucronata*, *R. stylosa*, and *A. marina* [8]. These mangrove ecosystems play a vital role in mitigating coastal abrasion. One type of mangrove, *B. gymnorrhiza*, also has the potential to be a food source because it contains Glucomannan [17]. Efforts to protect the coast have been undertaken through collaborations between local communities, government, NGOs, and the private sector. Initiatives include mangrove planting, tourism development, and alternative livelihood programs utilizing mangrove-derived materials [18]. Multi-stakeholder collaboration in Kendal's mangrove rehabilitation initiatives remains hampered by systemic gaps in holistic frameworks that analyze causal linkages between mangrove stand composition, fisheries yield dynamics, and alternative income streams, creating critical bottlenecks for achieving durable socio-ecological sustainability [19].

Integrated studies that explicitly link mangrove biodiversity with village-scale socio-economic systems remain notably scarce in Indonesia, despite mangrove ecosystems' critical role in supporting the livelihoods of a significant portion of coastal populations. Existing research often remains fragmented, focusing either on ecological assessments or socio-economic analyses in isolation, rather than addressing the complex interplay between mangrove species diversity, fisheries productivity, and local livelihood dynamics [19]–[21]. The implementation of Integrated Coastal Management (ICM) in Indonesia continues to face challenges such as regulatory fragmentation [22] and limited local institutional capacity [23], while community-based strategies, like those observed in Semarang, have yet to be fully integrated with broader policy frameworks [24]. In contrast, experiences from the Bay of Fundy in Canada demonstrate the effectiveness of holistic approaches that align ecosystem conservation with economic needs [18]. Nevertheless, such integrated models are underutilized in the Indonesian archipelago, presenting even greater ecological and cultural complexity. This study bridges critical research gaps by systematically analyzing the interdependencies between mangrove biodiversity, coastal socio-economic dynamics, and the operational efficacy of Integrated Coastal Management (ICM) frameworks in Kendal Regency, to develop an evidence-based coastal governance model that synergizes ecological conservation with community resilience-building mechanisms.

This study uses a system dynamics approach to synthesize a dynamic interaction model within the Integrated Coastal Management (ICM) framework. This methodology has effectively addressed complex environmental challenges, particularly within coastal and mangrove ecosystems [25], [26]. Previous applications include modeling the interactions between shrimp aquaculture and mangrove conservation in Vietnam and examining water resource management in urban coastal areas through the integration of social, technical, and ecological dimensions [27], [28]. These empirical studies reinforce the credibility of system dynamics as a robust analytical tool capable of capturing multidimensional relationships between mangrove ecosystems and human systems, thereby supporting the development of adaptive, evidence-based coastal governance models. It was important to note that this research focused solely on the synthesis of the dynamic interaction model and did not extend to the simulation or analysis of the system's behavior over time.

2. **Methods**

2.1. Research Focus and Approach

This study adopted a system dynamics modeling approach to formulate an Integrated Coastal Management (ICM) framework for Kendal Regency. The research focused on synthesizing dynamic interactions among key subsystems, including ecological coastal conditions, socio-economic structures, institutional arrangements, and coastal assets and access. Data collection was based on primary sources such as ecological, socio-economic, and institutional records. These datasets were used to parameterize and structure the model components within a system dynamics framework. The modeling process involved identifying key variables and establishing causal relationships represents the dynamic behavior of the coastal system. The study did not include simulation or scenario analysis; instead, it emphasized the conceptual synthesis of interdependence to support future model-based decision-making in coastal governance.

2.2. Location and Duration

The research was conducted in Kartikajaya Village, located within Kendal Regency. The study spanned eight months, from April to December 2024. The research phases included sampling, data collection, analysis, and refinement of results and discussion. Figure 1 illustrates the research location.

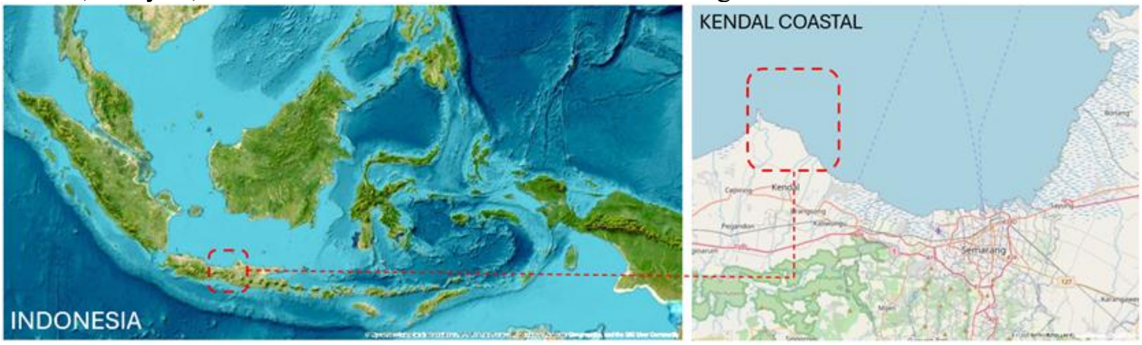

Figure 1. Research Site

2.3. Ecological Surveys

2.3.1. Mangrove Vegetation Analysis

Mangrove biodiversity will be quantified using a stratified plot-based sampling adapted from methodologies validated in tropical mangrove ecosystems. Four plot sizes will be established to capture ontogenetic stages: 20 × 20 m for mature trees (>10 cm DBH), 10 × 10 m for poles (5–10 cm DBH), 5 × 5 m for saplings, and 2 × 2 m for seedlings. Species-specific density, frequency, and dominance of keystone taxa (*Avicennia marina*, *Rhizophora apiculata*) will be calculated. Biodiversity metrics will be computed to assess structural complexity and ecological resilience, including the Shannon-Wiener index (*H'*) for species richness and evenness and Simpson's index (*D*) for dominance patterns.

2.3.2. Avifauna Biodiversity Assessment

Bird diversity will be evaluated using standardized point-count surveys at four critical habitats: upstream mangrove zones, downstream estuarine interfaces, aquaculture pond edges, and coastal transition areas. Observations will follow protocols with abundance recorded as individuals per hectare and distribution analyzed via the Morisita-Horn similarity index. Key parameters include:

1. Species richness: Total count of unique bird species per habitat.
2. Relative abundance: Ratio of individual species to total observations.
3. Habitat specificity: Identification of indicator species linked to mangrove structural features (e.g., canopy cover, understory density).

Data will be triangulated with vegetation metrics to model species-habitat relationships, ensuring methodological alignment with integrated ecosystem assessments.

2.4. Socio-Economic Surveys

2.4.1. Sample size

A representative sample of 186 households was selected from 359 total households in Kartikajaya Village using the Krejcie-Morgan formula [1,2] at a 95% confidence level and 5% margin of error. This method ensures statistically robust representation for coastal socio-ecological studies.

$$n = \frac{X^2 \cdot N \cdot P \cdot (1-P)}{d^2 \cdot (N-1) + X^2 \cdot P \cdot (1-P)}$$

Where:

- n = the required sample size
- X^2= the Chi-square values 1 degree of freedom at the 95% confidence level (3.841)
- N = the population size
- P = the assumed population proportion (commonly set at 0.5 to maximize sample size)

- d = the desired margin of error (0.05 for a 5% precision level)

2.4.2. Respondent profile

Table 1. Respondent profile

Parameter	Profile
Gender	52% female, 48% male
Age	23–38 years (50%), 39–54 (31%), >55 (19%)
Education	Junior high (55%), senior high (36%), bachelor's (9%)
Primary occupation	Fishermen (15%), aquaculture farmers (27%), entrepreneurs (12%)
Monthly income	64% below Kendal's minimum wage (IDR 2.6 million), 36% above

2.4.3. Data collection

A structured questionnaire employing a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) was administered to quantify the Sustainable Livelihoods Index (SLI), adapted from the Department for International Development's (DFID) Sustainable Livelihoods Framework. Asset categories were weighted to reflect coastal ecological priorities: natural capital (30%, e.g., mangrove cover, fisheries access), human capital (25%, e.g., education, skills), social capital (20%, e.g., community networks), financial capital (15%, e.g., income diversity), and physical capital (10%, e.g., infrastructure quality).

2.5. Dynamic Model Development

The dynamic interaction model for Integrated Coastal Management (ICM) in Kendal Regency was developed through a structured system dynamics modeling process. The procedure consisted of three main stages: problem identification, conceptual model formulation, and validation preparation.

1. Problem Identification and Boundary Definition, the research began by defining the scope and boundaries of the coastal socio-ecological system under study. Key subsystems were identified, including:
   - Ecological coastal conditions (mangrove diversity and avifauna)
   - Socio-economic structures (community participation, land ownerships, and alternative livelihoods)
   - Institutional arrangements (coastal community groups and stakeholder roles)
   - Coastal assets and access (infrastructure and resource accessibility) The system boundary was set to include both biophysical and socio-economic interactions within Kendal Regency's coastal zone.
2. Conceptual Model Formulation, Causal Loop Diagrams (CLDs) were developed to visualize the cause–effect relationships among variables. Feedback loops were identified and categorized into reinforcing loops. The CLDs served as the foundation for translating qualitative relationships into quantitative model structures. The CLDs were subsequently constructed using Vensim PLE.
3. Model Validation Preparation, the model was validated through expert review and comparison with credible prior studies on similar coastal socio-ecological systems. Experts in mangrove ecology, socioeconomics, and coastal governance assessed the model's structure, variables, and causal linkages for accuracy and contextual relevance. Findings from peer-reviewed literature were used to reinforce the model's theoretical soundness and applicability. This modeling process resulted in a comprehensive dynamic interaction framework integrating ecological, socio-economic, and institutional dimensions of coastal management in Kendal Regency. The model is intended as a decision-support tool for future scenario simulations and policy analysis, although such simulations were beyond the scope of the present study.

3. Results and Discussion

3.1. Ecological Analysis

Identification revealed 14 mangrove species from 10 families, comprising 8 true mangroves and 6 associates (Table 2). The most common were *Avicennia marina* and *Rhizophora mucronata*, typically inhabiting tidal and riverine zones with clay or soft mud substrates. The mangrove stands in Kartikajaya Village, primarily from community planting, grow on varied substrates: soft mud supports *A. marina*, *A. alba*, *A. officinalis*, and *Excoecaria agallocha*; fine sandy mud hosts *Sonneratia caseolaris*; clay along riverbanks supports *R. mucronata*, *R. stylosa*, and *Bruguiera gymnorhiza*; and hard clay in open areas supports associated species such as *Talipariti tiliaceum*, *Terminalia catappa*, *Leucaena leucocephala*, *Trema orientalis*, and *Ficus septica*. The mangrove species found at the research site are classified as Least Concern according to the IUCN Red List. This status indicates that these mangrove species have a low risk of extinction, as their population size and distribution are still abundant and stable. However, they could decline and become at risk of extinction if large-scale mangrove destruction occurs [31], [32].

Table 2. Composition of Mangrove Species in Kartikajaya Village

No	Species Name	Local Name	Family	IUCN	N	Remarks
1	*A. alba*	Api-api hitam	Acanthaceae	LC	6	True Mangrove
2	*A. marina*	Api-api putih	Acanthaceae	LC	246	True Mangrove
3	*A. officinalis*	Api-api ludat	Acanthaceae	LC	23	True Mangrove
4	*B. gymnorrhiza*	Tancang	Rhizophoraceae	LC	35	True Mangrove
5	*E. agallocha*	Buta-buta	Euphorbiaceae	LC	2	True Mangrove
6	*Ficus septica*	Awar-awar	Moraceae	LC	7	Association Mangrove
7	*Leucaena leucocephala*	Petai cina	Fabaceae	-	41	Association Mangrove
8	*Muntingia calabura*	Kresem	Muntingiaceae	LC	18	True Mangrove
9	*R. mucronata*	Bakau hitam	Rhizophoraceae	LC	113	True Mangrove
10	*R. stylosa*	Bakau kurap	Rhizophoraceae	LC	5	True Mangrove
11	*Sonneratia caseolaris*	Bogem	Sonneratiaceae	LC	6	Association Mangrove
12	*Talipariti tiliaceum*	Waru	Malvaceae	-	5	True Mangrove
13	*Terminalia catappa*	Ketapang	Combretaceae	LC	3	Association Mangrove
14	*Trema orientalis*	Mengkirai	Cannabaceae	LC	3	Association Mangrove

Remarks: N: Number of individuals. IUCN Red List of Threatened Species: LC (Least Concern/Low Risk).

Analysis of density, species diversity, and evenness across mangrove growth stages (trees, poles, saplings, seedlings) showed the highest species richness in trees and the lowest in seedlings, with diversity indices in the moderate range (1–2) and evenness values near 1, indicating stable, evenly distributed communities. *Avicennia marina* dominated the tree and pole stages, which had low densities of 260 and 833 individuals/ha due to large trunk sizes (10–32 cm), broad canopies, and extensive roots. Saplings reached 2,133 individuals/ha, with *A. marina* comprising 63.59%, while seedlings exhibited very high density (44,444 individuals/ha), dominated by *Rhizophora mucronata* (37.50%), reflecting strong regeneration potential in a supportive habitat.

Table 3. Species Diversity Index, Evenness Index, and Mangrove Species Density in Kartikajaya Village

Parameter	**Value/index**			
	Tree	**Sapling**	**Pole**	**Seedling**
Number of Species	13	10	10	7
Number of Individuals	187	150	96	80
Diversity Index (H')	1,58	1,47	1,74	1,80
Evenness Index (E)	0,6	0,6	0,8	0,9
Species Density (K) (ind/Ha)	260	833	2.133	44.444

Source: analysis result, 2024

In general, mangroves grow and thrive in estuarine areas with muddy substrates, although some species grow on rigid substrates, such as mangrove associations and species of Rhizophora. The water temperature at the study site is 28.7°C, which falls within the optimal temperature range for mangrove life, which is between 20-35°C [33]. The salinity result of 27‰ also falls within the optimal range for mangrove growth, which is 0.5-35‰ [34], [35]. Mangrove plants can adapt to salt levels through secretion via their leaves. The water pH result was neutral, as pH levels influence nutrient absorption by the roots [36], [37].

A total of 61 bird species from 30 families were recorded in Kartikajaya Village, supported by mangrove forests that provide essential habitats, shelter, and food sources. The Ardeidae (heron) family was the most abundant, with nine species and 507 individuals, dominated by the Cattle Egret (*Bubulcus ibis*, 156 individuals). Several species are protected nationally under PERMENLHK P.106 and internationally under the IUCN Red List and CITES. These include the Endangered Siberian Sand Plover (*Charadrius mongolus*), Vulnerable Javan Coucal (*Centropus nigrorufus*) and Javan Starling (*Acridotheres javanicus*), Near Threatened Asian Darter (*Anhinga melanogaster*), two species in CITES Appendix II, the Asian Honey Buzzard (*Pernis ptilorhynchus*) and Javan Owl (*Tyto alba*), and seven species protected by national regulation, such as the Great Egret (*Ardea alba*) and Glossy Ibis (*Plegadis falcinellus*).

Figure 2. Fauna (a) *Ardea alba*, (b) *Anhinga melanogaster*, (c) *Pernis ptilorhychus*, (d) *Charadrius javanicus* (Source: field photo, 2024)

The bird species diversity index in Kartikajaya Village was 3.50 (H'> 3), indicating high diversity and a mangrove ecosystem that effectively supports wildlife by providing shelter, breeding grounds, and food resources. Among four observation transects, the downstream area recorded the highest diversity (H' = 3.10) due to its dominant mangrove cover. In contrast, the upstream area had the lowest (H' = 2.80, moderate), characterized by farmland and settlements dominated by Estrildidae and Cisticolidae species. The mangrove aquaculture zone hosted the most significant number of species (48) owing to its heterogeneous habitats, including farmland, mangroves, fishponds, rivers, and associated vegetation. The species richness index was 8.2, reflecting the good condition of dense-canopy mangroves that provide essential resources for birds. Evenness was high (E = 0.80), with the downstream mangrove area reaching 0.92, indicating stable and balanced species distribution. In contrast, the aquaculture area showed the lowest evenness due to dominance by the Cattle Egret (*Bubulcus ibis*).

Table 4. Species of Richness, Diversity, and Evenness Index of Birds in Kartikajaya Village

Parameter	Coastline	Upper Mangrove	Aquaculture Mangrove	Lower Mangrove	Grand Total
Number of Species (S)	25,0	29,0	48,0	29,0	61
Number of Individuals (N)	136,0	291,0	648,0	316,0	1391
Richness Index (R)	4,9	4,9	7,3	4,9	8,3
Diversity Index (H')	2,9	2,7	3,1	3,1	3,5
Evenness Index (E)	0,9	0,8	0,8	0,9	0,9

The high avifaunal diversity recorded in Kartikajaya Village, with a Shannon index of 3.50 (H′ > 3), carries substantial conservation significance, as it exceeds the threshold indicative of ecosystems with high diversity and optimal ecological stability. Previous studies have identified bird diversity as a direct indicator of mangrove ecosystem health, with a significant weight of 20.97% [38]. The presence of protected species such as *Charadrius mongolus* (Endangered), *Centropus nigrorufus* and *Acridotheres javanicus* (Vulnerable), and *Anhinga melanogaster* (Near Threatened) reflects strong habitat integrity and underscores the critical role of the Kartikajaya mangroves as a regional refuge for threatened species. The dominance of the family Ardeidae, represented by nine species and 507 individuals, most notably *Bubulcus ibis* with 156 individuals, demonstrates that the mangrove ecosystem provides abundant food resources and suitable habitats for piscivorous and insectivorous bird guilds. These findings align with evidence that mangroves with high canopy cover and complex structural diversity support greater avian species richness by offering a wide range of ecological niches [38].

Spatial variation in avian diversity across four transect zones revealed complex ecosystem dynamics with significant implications for sustainable management. The downstream zone exhibited the highest diversity (H′ = 3.10) due to extensive mangrove cover, contrasting with the upstream zone's moderate diversity (H′ = 2.80) linked to agricultural and settlement conversion, highlighting the impact of habitat fragmentation on community structure. The mangrove aquaculture zone supported the most remarkable species richness (48 species) but the lowest evenness, driven by *Bubulcus ibis* dominance, indicating a trade-off between habitat heterogeneity and community balance. These patterns underscore the need for stricter protection of high-diversity areas, particularly medium- to large-sized fragments (>50 ha), to ensure long-term conservation effectiveness [39], [40].

3.2. Socio-Economic

The social participation data from coastal Kendal reveal a striking paradox in community engagement patterns that underscores the complex dynamics of rural Indonesian coastal governance. While the community demonstrates exceptionally high levels of participation in traditional cooperation activities (97% often participate) and social security programs (100% always participate), this engagement occurs alongside virtually absent social conflict (91% report none) and significantly limited involvement in formal development deliberations, where only 79% maintain consistent participation above the 30%

threshold (Figure 3). This disparity suggests a bifurcated participation structure where communities actively engage in culturally embedded cooperative mechanisms and state-mandated social programs yet remain marginally involved in formal planning processes that directly affect their development outcomes [41], [42]. While potentially indicating social harmony, the negligible presence of social conflict may also reflect suppressed dissent or limited agency in expressing grievances within formal institutional frameworks [43]. Furthermore, the minimal women's participation in development deliberations (3%) and the predominance of nuclear family structures (14%) highlight persistent gender inequalities and changing social structures that compound the challenges of achieving inclusive community participation (Figure 3). These findings illuminate the critical need for development interventions that bridge traditional cooperative values with formal participatory governance mechanisms to enhance community agency in coastal adaptation planning [42].

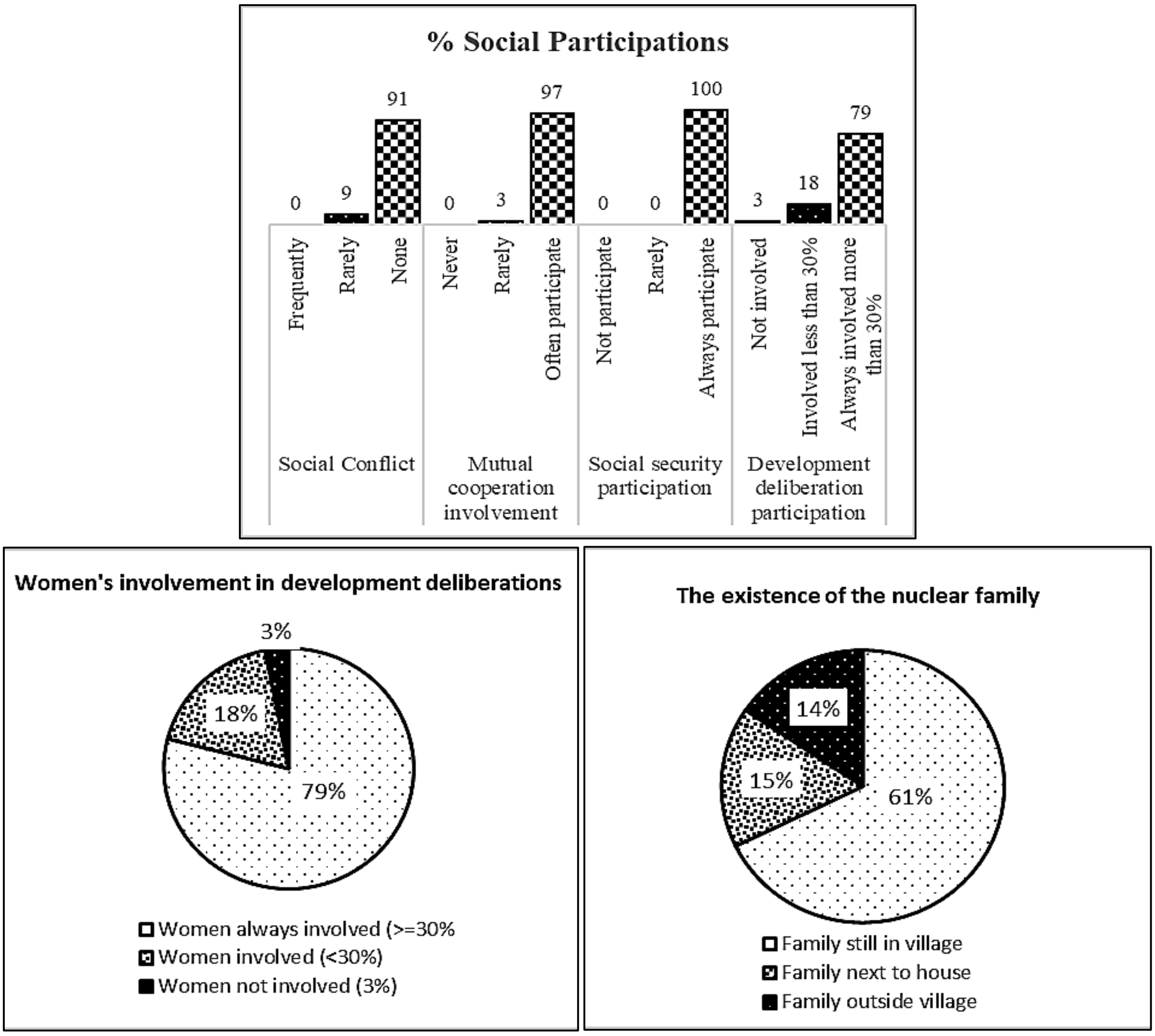

Figure 3. Social participation and modal social

The bifurcated participation patterns in coastal Kendal's social fabric directly intersect with land tenure challenges, creating cyclical barriers to sustainable development. While high engagement in traditional mutual aid reflects strong communal bonds, the lack of meaningful involvement in formal planning processes perpetuates systemic inequities in land access and resource governance [44], [45]. Studies demonstrate that communities excluded from decision-making forums are less likely to advocate for tenure security reforms or challenge exploitative leasing arrangements [46]. This exclusion is exacerbated by gender disparities, as women's minimal representation in deliberations [45] correlates with their disproportionate lack of land ownership, a pattern observed globally where patriarchal norms restrict female access to productive assets despite their critical role in agricultural labor [47]. Furthermore, the absence of social conflict reporting may signal resignation to inequitable land distribution rather than genuine consensus, mirroring cases in Sub-Saharan Africa where marginalized groups avoid contesting tenure disputes due to distrust in institutional mechanisms [48].

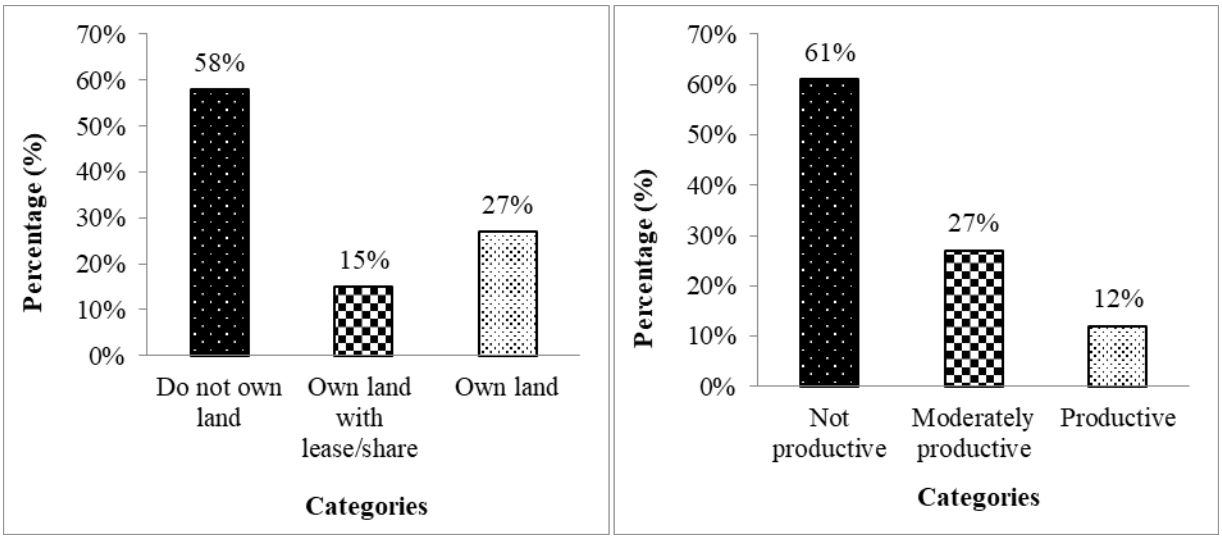

Figure 4. Land ownership status and productivity

The land ownership and productivity patterns in coastal Kendal reveal a profound structural vulnerability that fundamentally undermines community resilience and sustainable development prospects. The data demonstrates that 58% of coastal residents do not own land. In comparison, only 27% possess full ownership rights, creating a precarious tenurial landscape where most of the population lacks secure access to productive assets essential for livelihood stability. This landlessness is compounded by alarmingly low productivity levels, with 61% of available land classified as non-productive and merely 12% achieving productive status, indicating severe constraints in agricultural potential that may stem from environmental degradation, inadequate infrastructure, or limited access to agricultural inputs and technical knowledge (Figure 4). The intersection of high landlessness rates with predominantly unproductive land creates a double burden for coastal communities, where those who do manage to access land through leasing arrangements (15%) face uncertainty in long-term planning and investment, while the broader community confronts limited opportunities for agricultural-based livelihoods. These findings underscore a critical development challenge where traditional coastal livelihoods are undermined by both insecure tenure arrangements and environmental constraints, necessitating comprehensive land reform initiatives coupled with productivity enhancement programs to address the fundamental structural barriers limiting community economic advancement and adaptive capacity in the face of coastal environmental pressures.

The precarious land tenure system in coastal Kendal exerts direct pressure on SME development by constraining access to critical capital and destabilizing long-term enterprise planning. Studies demonstrate that formal land ownership serves as primary collateral for commercial loans, with registered titles increasing credit access by 38% for small enterprises in comparable Global South contexts [49]. However, Kendal's 58% landlessness rate forces SMEs to rely on microfinance institutions charging 22–35% higher interest rates than commercial banks [50], disproportionately affecting enterprises like Batik Handicraft that require extended production cycles. The resulting economic fragmentation mirrors patterns observed in West African coastal zones, where tenure insecurity reduced SME survival rates by 27% over five years [51], underscoring how land governance failures perpetuate livelihood precarity and blue economy stagnation.

Table 4. Existing conditions of coastal Small and Medium Enterprises (SMEs**)**

No.	Business Name / Contact	Production Capacity	Number of Workers	Monthly Revenue (IDR)
1	Mangrove Processing Mulya Jaya	10 packs/day. Price per pack: 10,000 IDR, weight: 250g	5	4,600,000
2	Abon Ayam Handalku	2 productions/month, 1 production uses 20kg chicken. Sold in 50g, 100g, 250g, 500g packages	4	1,000,000
3	Abon and Bandeng Crackers Nicky Eco	50 packs/production for 200g crackers at 15,000 IDR/pack; 12 packs/production for abon bandeng	6	6,000,000
4	Batik Handicraft	1 cloth (2m x 1m) every 3 days at 250,000 IDR. Complex motifs take 5–6 months, priced 800,000–900,000 IDR	10	2,650,000

The economic landscape of coastal Small and Medium Enterprises (SMEs) in Kendal demonstrates significant heterogeneity in production capacities, revenue generation, and labor utilization, reflecting the complex dynamics of Indonesia's blue economy development at the micro-enterprise level [52], [53]. The data reveals stark disparities in monthly revenue streams, ranging from Abon Ayam Handalku's modest 1,000,000 IDR to Abon and Bandeng Crackers Nicky Eco's substantial 6,000,000 IDR, indicating varied market positioning and operational efficiency within the coastal SME ecosystem (Table 4). Mangrove Processing Mulya Jaya exemplifies the potential for sustainable resource utilization with daily production of 10 packs generating 4,600,000 IDR monthly revenue through five workers, demonstrating how coastal communities can leverage mangrove resources for economic development while maintaining environmental sustainability [54], [55]. The labor-intensive nature of traditional crafts is particularly evident in Batik Handicraft operations, where ten workers produce intricate textiles requiring 5-6 months for complex motifs valued at 800,000-900,000 IDR, representing the intersection of cultural preservation and economic activity characteristic of Indonesian coastal regions. This enterprise diversity underscores both the resilience and vulnerability of coastal SMEs, where production scales remain relatively small and revenue generation is constrained by limited technological adoption, market access challenges, and traditional production methods that, while culturally significant, may limit scalability and competitiveness in the broader blue economy framework [52], [56].

3.2. Institutional

The coastal community groups in Kendal exhibit a heterogeneous organizational landscape characterized by significant disparities in legal recognition, economic specialization, and operational challenges that collectively reflect the complex vulnerabilities inherent to Indonesia's coastal livelihood systems. Only half of the six documented groups possess formal legal status, with legally recognized entities including the Tourism Awareness Group, Karang Taruna Group, and Mangrove Nursery. In contrast, critical productive groups such as the Minat Jaya Fishermen Group and Berkah Lele Group operate without formal institutional recognition, potentially limiting their access to government support programs and financial services. The production portfolios reveal stark sectoral diversity, ranging from marine capture fisheries (Blana fish, milkfish, rebon shrimp) and aquaculture (Sangkuriang catfish, pearl catfish, masamo) to terrestrial agriculture (corn, chili, banana) and emerging blue economy activities, including mangrove cultivation and tourism services (Table 5). However, each group confronts distinct operational constraints that threaten livelihood sustainability: environmental challenges including coastal abrasion disrupting Tiban Island tourism, tidal fluctuations affecting fisheries yields, and aquaculture disease outbreaks caused by Aeromonas bacteria and fungi; institutional failures exemplified by the Karang Taruna Group's prolonged inactivity due to member work commitments; market volatility affecting mangrove nursery operations where demand fluctuations correlate with community interest levels; and ecological degradation manifested through infertile agricultural lands constraining the Kartika Usaha Farmers Group's productivity. These multifaceted challenges underscore the urgent need for integrated coastal management approaches that simultaneously address the legal recognition of informal groups, environmental restoration, disease management protocols, and market stabilization mechanisms to enhance the resilience of coastal community livelihoods in the face of accelerating environmental and socio-economic pressures.

Table 5. Profile of coastal community groups in Kendal

No	Group Name	Group Legality	Commodities	Main Issues
1	Tourism Awareness Group	Yes	Tiban Island tourism	Abrasion caused the cessation of tourism activities on Tiban Island
2	Minat Jaya Fishermen Group	No	Blana fish, milkfish, rebon shrimp	Catch fluctuates due to tidal influences
3	Berkah Lele Group	No	Sangkuriang catfish, pearl catfish, masamo	Catfish diseases (Aeromonas bacteria and fungi)
4	Karang Taruna Group	Yes	Tourism support services	The group was inactive for several years due to members' work commitments
5	Mangrove Nursery	Yes	Mangrove (Rhizophora, Bruguiera)	Demand increased and decreased according to community interest
6	Kartika Usaha Farmers Group	Yes	Corn, chili, banana	Infertile land, making cultivation difficult

The institutional landscape of coastal community groups in Kendal reveals a complex mosaic of formal and informal organizational structures that reflects broader challenges in integrated coastal management (ICM) governance frameworks. The presence of six distinct community groups operating across diverse sectors, from tourism and fisheries to aquaculture and agriculture, demonstrates the inherently multi-sectoral nature of coastal ecosystems that necessitates coordinated institutional arrangements for effective management [57], [58]. However, the bifurcated legal status of these organizations, with only 50% possessing formal recognition, highlights critical gaps in institutional coordination mechanisms that are fundamental to successful ICM implementation. This institutional fragmentation undermines the establishment of comprehensive stakeholder participation platforms essential for addressing the “wicked problems” characteristic of coastal zones, where environmental, social, and economic challenges intersect across multiple scales and jurisdictions [57]. The absence of formal legal status for productive groups such as the Minat Jaya Fishermen Group and Berkah Lele Group creates institutional vulnerabilities that limit their capacity to participate meaningfully in formal planning processes and access government support programs, thereby perpetuating the exclusion of critical coastal resource users from decision-making frameworks [58].

Differentiating legal recognition among coastal community groups fundamentally shapes their institutional capacity to participate in integrated coastal management coordination mechanisms. It influences their ability to access resources essential for sustainable coastal development. Legally recognized entities, including the Tourism Awareness Group, Karang Taruna Group, and Mangrove Nursery, possess formal institutional legitimacy that enables their integration into government planning processes and enhances their eligibility for financial support and technical assistance programs [58]. This legal status creates an institutional hierarchy that mirrors broader patterns observed in ICM implementations across the East Asian Seas region, where formal institutional arrangements often prioritize legally recognized organizations while marginalizing informal community groups despite their critical roles in coastal resource management [57]. The institutional exclusion of unrecognized fishermen and aquaculture groups perpetuates governance gaps that undermine the comprehensive stakeholder participation essential for effective ICM, as these groups represent primary coastal resource users whose local knowledge and management practices are fundamental to sustainable coastal development. This institutional divide reflects systemic weaknesses in national ICM frameworks that fail to accommodate the diverse organizational forms through which coastal communities engage with marine and terrestrial resources, thereby limiting the effectiveness of coordination mechanisms designed to integrate multiple sectors and stakeholders [57], [58].

The remarkable sectoral diversity these coastal community groups represent spans marine capture fisheries, aquaculture, tourism, ecosystem restoration, and terrestrial agriculture. The complex coordination challenges inherent to integrated coastal management systems must harmonize multiple resource use sectors within a unified governance framework. The institutional separation of marine-focused groups (fishermen, aquaculture) from terrestrial-oriented organizations (farmers) and service-based entities (tourism) reflects sectoral silos that contradict ICM principles, emphasizing the integration of terrestrial and marine components of coastal systems. Each sector confronts distinct operational challenges that require specialized technical expertise and management approaches: environmental stressors affecting tourism (coastal abrasion), biological challenges in aquaculture (disease outbreaks), ecological variability in fisheries (tidal fluctuations), and soil fertility constraints in agriculture. However, the absence of formal inter-institutional coordination mechanisms among these groups prevents the development of integrated management strategies that could address cross-sectoral linkages and cumulative impacts on coastal ecosystems. This institutional fragmentation limits the capacity for adaptive management approaches essential for addressing the dynamic and interconnected nature of coastal systems, where actions in one sector can generate cascading effects across multiple resource use domains and community livelihoods [57], [58].

3.3. Infrastructure

The village infrastructure conditions in coastal Kendal reveal critical vulnerabilities that fundamentally challenge the integrated coastal management (ICM) paradigm of maintaining resilient coastal communities capable of withstanding environmental and socio-economic stressors. The data demonstrates alarming infrastructure degradation across multiple sectors, with highways exhibiting 36% severe damage, health facilities showing 36% severe deterioration, and educational facilities displaying 33% severe damage. In comparison, only toilet facilities achieve relatively acceptable conditions, with 94% rated as good (Figure 5). This infrastructure vulnerability pattern directly contradicts ICM principles that emphasize the necessity of robust foundational infrastructure to support sustainable coastal development and climate adaptation strategies [59]. The disproportionate damage across critical service sectors, particularly transportation networks that enable emergency response and healthcare facilities essential for community welfare, indicates systemic infrastructure planning and maintenance failures undermine the adaptive capacity fundamental to effective ICM implementation [60], [61]. Such infrastructure deficits create cascading vulnerabilities where communities become increasingly susceptible to coastal hazards, as damaged highways impede evacuation capabilities during storm events, while degraded health facilities compromise post-disaster recovery capacity, thereby violating core ICM objectives of protecting lives and maintaining community resilience.

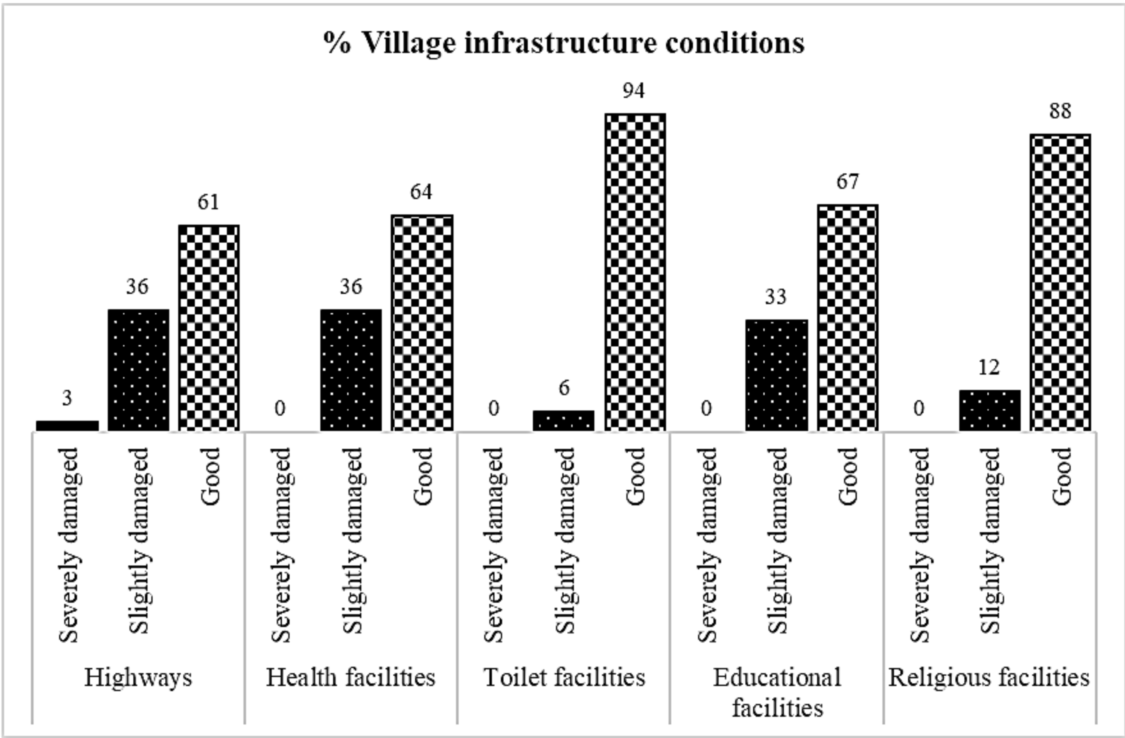

Figure 5. Village infrastructure profile

The fragmented infrastructure conditions across different sectors highlight critical coordination failures, contradicting ICM's fundamental principle of integrated, multi-sectoral planning approaches essential for sustainable coastal zone management. The stark disparity between infrastructure conditions, ranging from severely compromised transportation and health systems to relatively functional sanitation facilities, reflects the absence of comprehensive infrastructure planning frameworks that ICM methodologies explicitly require for effective coastal governance. This sectoral fragmentation undermines the ICM emphasis on holistic area-wide coverage, where infrastructure development must be coordinated across multiple domains to ensure synergistic benefits and avoid conflicting investments that compromise overall system resilience [62].

The infrastructure conditions documented in coastal Kendal demonstrate profound deficiencies in meeting ICM requirements for adaptive infrastructure capable of supporting community resilience in the face of climate change impacts and coastal hazards [63]. The predominance of damaged critical infrastructure across transportation (36% severe damage), health (36% severe damage), and education (33% severe damage) sectors creates systemic vulnerabilities that undermine the adaptive capacity essential for effective climate change adaptation in coastal zones [60], [61]. ICM frameworks explicitly emphasize integrating green and gray infrastructure solutions to enhance coastal resilience. However, the current infrastructure conditions suggest limited consideration of nature-based solutions or climate-resilient design principles that could provide multiple co-benefits, including hazard mitigation, ecosystem services, and economic development [64]. The concentration of infrastructure damage in sectors critical for disaster response and recovery, particularly transportation networks and healthcare facilities, indicates insufficient application of ICM risk-based planning approaches that prioritize infrastructure investments based on vulnerability assessments and climate projections [61], [63]. Furthermore, the relatively better condition of sanitation infrastructure (94% good condition) compared to other sectors suggests potential for leveraging existing institutional capacity and financing mechanisms to address broader infrastructure deficits, aligning with ICM principles of building upon existing strengths while addressing systemic weaknesses through integrated planning and sustainable financing strategies [65].

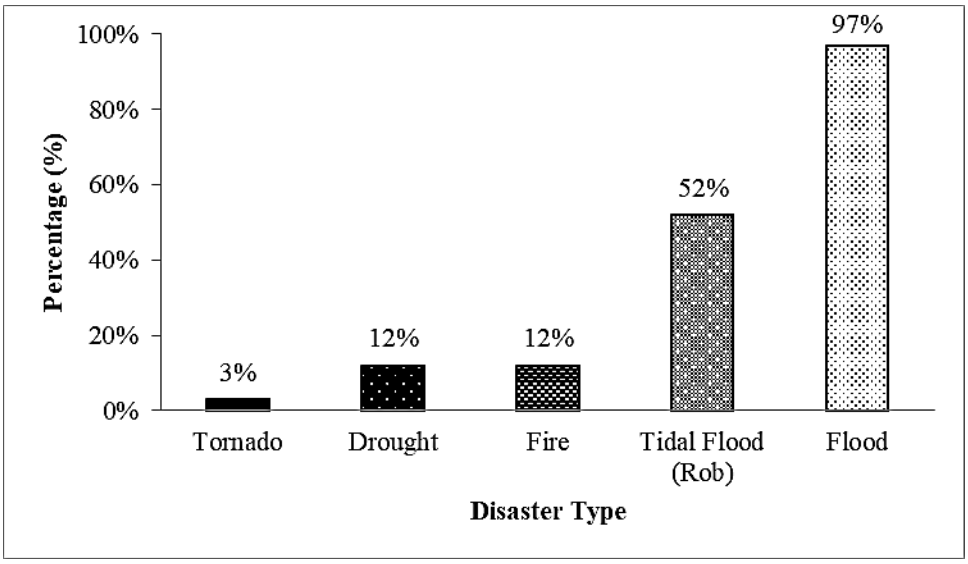

Figure 6. Intensity of coastal disaster events

The infrastructure vulnerability profile in coastal Kendal demonstrates a critical mismatch between existing infrastructure conditions and the intensity of coastal disaster exposure, fundamentally challenging the integrated coastal management (ICM) principle of maintaining resilient infrastructure systems capable of withstanding multiple hazard scenarios [66]. The data reveal that 97% of the community experiences flooding while simultaneously confronting severely compromised critical infrastructure, with highways showing 36% severe damage, health facilities exhibiting 36% severe deterioration, and educational facilities displaying 33% severe damage. This convergence of high disaster exposure and degraded infrastructure creates what coastal resilience literature identifies as "compound vulnerability," where the cumulative effects of infrastructure deficits and recurrent hazards exponentially increase community risk rather than merely adding incremental threats [67], [68]. The disproportionate infrastructure damage across multiple sectors violates fundamental ICM principles that emphasize the necessity of robust, interconnected infrastructure networks to support disaster preparedness, emergency response, and post-disaster recovery capabilities. Such systematic infrastructure vulnerabilities compromise the adaptive capacity essential for climate-resilient coastal development, as damaged transportation networks impede evacuation and relief operations while degraded health and educational facilities undermine community welfare and long-term resilience building.

The differential vulnerability patterns across infrastructure sectors reveal critical insights into the systemic weaknesses undermining integrated coastal management effectiveness in building disaster-resilient communities [69]. While sanitation infrastructure achieves relatively acceptable conditions with 94% rated as good, the severe deterioration of transportation (36% severe damage), health (36% severe damage), and educational infrastructure (33% severe damage) creates a fragmented service delivery landscape that contradicts ICM requirements for comprehensive, multi-sectoral resilience planning [70]. This sectoral disparity suggests uncoordinated infrastructure investment strategies that fail to recognize the interconnected nature of infrastructure systems essential for disaster response and recovery operations [67]. The relatively better condition of religious facilities (12% severe damage, 88% good condition) compared to critical service infrastructure highlights misaligned priorities that may reflect cultural preferences rather than evidence-based resilience planning aligned with ICM principles. Furthermore, the poor condition of educational infrastructure poses concerns for long-term community resilience, as schools serve dual functions as learning centers during normal operations and emergency shelters during disaster events, making their structural integrity essential for everyday community welfare and disaster preparedness.

The coastal disaster intensity profile reveals a multi-hazard environment dominated by hydrological threats that requires sophisticated risk management approaches aligned with ICM principles of comprehensive hazard assessment and adaptive management strategies. The overwhelming prevalence of flooding events (97%) combined with significant tidal flooding exposure (52%) demonstrates the community's position within a high-risk coastal zone where sea-level rise, storm surges, and extreme precipitation events create compound flooding scenarios that exceed the capacity of current infrastructure systems [66]. The presence of secondary hazards, including fire (12%) and drought (12%), indicates complex risk interactions where flood-damaged infrastructure may become more susceptible to fire hazards due to compromised electrical systems, while seasonal drought conditions can exacerbate infrastructure deterioration through soil subsidence and structural stress. The relatively low frequency of tornado events (3%) suggests that while extreme wind events are less common, the primary infrastructure challenges stem from sustained hydrological pressures requiring long-term adaptation rather than episodic disaster response measures. This multi-hazard profile necessitates integrated risk reduction approaches that address acute disaster impacts and chronic infrastructure deterioration through nature-based solutions, early warning systems, and climate-resilient infrastructure design principles fundamental to effective ICM implementation.

3.4. Integrated Coastal Management Dynamic Framework

Integrated Coastal Management (ICM) in Kendal Regency was conceptualized through a dynamic framework. This approach effectively addressed complex environmental challenges, particularly within coastal and mangrove ecosystems [25], [26]. Empirical applications further validated the credibility of system dynamics as a robust analytical tool capable of capturing multidimensional interactions between mangrove ecosystems and human systems, thereby informing the development of adaptive, evidence-based coastal governance frameworks [27], [28]. The dynamic ICM framework developed for Kendal Regency was presented in Figure 7.

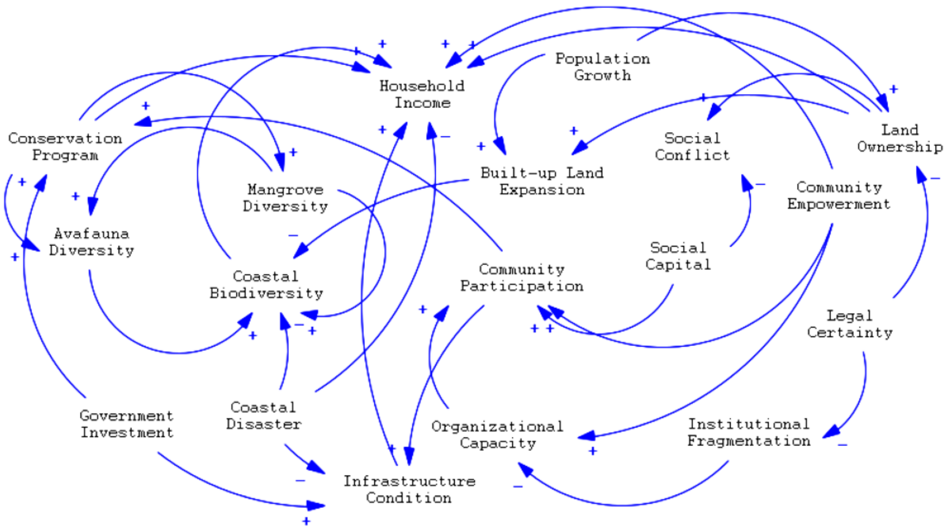

Figure 7. Dynamic framework based on ICM in Kendal Coastal

Coastal dynamics in Kendal Regency, viewed through the lens of Integrated Coastal Management (ICM), revealed a complex system in which coastal biodiversity directly shaped household incomes through diverse ecological and economic pathways. Mangrove ecosystems provided essential services—such as fish nursery habitats, shoreline protection, and ecotourism—that supported income generation [16]. Mangrove-dependent fisheries contributed significantly to local economies, with household values ranging from $359–490 USD annually in comparable Southeast Asian regions [71], [72], while marine fisheries accounted for 56% of household income. Beyond extraction, coastal and marine ecosystems offered indirect economic benefits, including carbon sequestration and disaster mitigation, with coastal protection services valued at over $18 million annually in a similar context [73]. The SME sector further demonstrated biodiversity's economic potential through value-added marine products, mangrove-based enterprises, and cultural crafts, enhancing livelihood resilience through income diversification.

The coastal biodiversity dynamics in Kendal Regency revealed a complex interplay between positive conservation forces and multiple pressure systems that operated through distinct but interconnected feedback loops. These dialectical processes demonstrated how coastal biodiversity integrity was simultaneously enhanced through community-based conservation programs while threatened by socio-economic pressures and infrastructure vulnerabilities, creating a dynamic equilibrium that determined the long-term sustainability of coastal ecosystems and their associated services. The positive conservation loop in Kendal Regency demonstrated how community-based mangrove conservation programs created reinforcing cycles that enhanced coastal biodiversity and strengthened local livelihoods [16]. The ecological analysis revealed that community-led mangrove planting initiatives had successfully established diverse mangrove stands comprising 14 species from 10 families, with 8 true mangroves and 6 associates distributed across varied substrate conditions. *A. marina* and *R. mucronata* dominated the established stands, representing successful adaptation to local environmental conditions, including clay and soft mud substrates typical of tidal and riverine zones.

In Kendal Regency, the socio-economic pressure loop driven by population growth, insecure land tenure, and expanding built-up areas intensified coastal biodiversity loss by accelerating habitat conversion, fragmentation, and pollution. Rapid urbanization disrupted natural coastal processes, degraded water quality, and diminished ecosystem functions, while land reclamation and aquaculture expansion, particularly mangrove conversion, caused irreversible habitat destruction. These short-term economic pursuits undermined long-term ecological stability and community livelihoods, illustrating the deep interdependence between human development pressures and the decline of vital coastal ecosystems [7], [8], [12].

The infrastructure pressure loop in Kendal Regency showed how recurrent coastal disasters and structural weaknesses triggered cascading failures that reduced community capacity to protect coastal biodiversity. High exposure to flooding and tidal inundation, combined with damaged transport, health, and education facilities, created compound vulnerabilities where disruption in one sector amplified failures in others. These breakdowns isolated communities, limited access to conservation areas, disrupted biodiversity-based livelihoods, and reduced the ability to engage in restoration activities such as mangrove planting [74], [75]. Amid these pressures, community-based conservation programs successfully established diverse mangrove stands and supported high avifauna diversity, reinforcing ecological and socio-economic benefits cycles. From mangrove product processing to coastal heritage crafts, nature-based enterprises demonstrated that biodiversity conservation could deliver tangible income while maintaining ecosystem integrity. However, these gains remained fragile within broader socio-economic and infrastructural constraints. Formal conservation groups provided a foundation for scaling efforts. Nevertheless, the informal status of key actors such as fishermen's cooperatives limited their influence in governance, reflecting persistent institutional fragmentation in managing complex coastal pressures.

The government's provision of legal certainty represented a fundamental structural intervention for addressing the complex governance challenges of the coastal zone in Kendal Regency. This legal certainty functioned as an institutional foundation that addressed two critical issues: institutional fragmentation and land tenure insecurity. The intervention produced a series of cascading positive effects by resolving these constraints. Social conflict was reduced, creating a more stable community environment. Household incomes improved as secure tenure supported sustainable livelihood activities. Institutional capacity was strengthened through more explicit mandates and coordination mechanisms [76]. Community participation increased, reinforced by the high levels of social capital that had long characterized Kendal's coastal communities.

4. Conclusion

This study reveals the complexity of integrated coastal management (ICM) challenges in Kendal Regency, Central Java, focusing on coastal diversity, socio-economic dynamics, institutional community, and infrastructure vulnerability. Despite having 14 mangrove species and 61 bird species (diversity index H'=3.50), Kendal's mangrove ecosystem is under pressure from 40% area degradation and coastal abrasion. High community participation (97%) is not in line with gender inclusivity (3% female participation) and economic resilience, where 58% of households are landless and 61% of land is unproductive. The coastal community's capacity for high resilience was reflected in the prevalence of nuclear family ties, with 61% of such families residing in the village. Institutional fragmentation (50% groups without legal status) and infrastructure damage (36% roads are severely damaged) exacerbate vulnerability to flooding (97%) and rob (52%). The dynamic model of ICM in Kendal Regency identified coastal biodiversity conservation, strengthened community capacity and participation, and secure land ownership as the core drivers of sustainable coastal governance. Government action was most effective when combining strategic investment, adequate infrastructure provision, and legal certainty through land tenure and institutional formalization. Despite persistent pressures from recurrent coastal hazards and expanding built-up areas, biodiversity conservation remained the pivotal intervention, sustaining ecosystem integrity, enhancing household incomes, and reinforcing socio-economic resilience through positive feedback loops within the coastal social–ecological system.

Declaration of AI and AI assisted technologies in the writing process
During the preparation of this work the authors used Microsoft Copilot and Perplexity to support language refinement, improve clarity, and assist in synthesizing references. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment
The authors gratefully acknowledge the financial support provided by the Institute for Research and Community Service (*Lembaga Penelitian dan Pengabdian Masyarakat*, LPPM) of Universitas Negeri Semarang (UNNES). This study was funded through the *Daftar Pelaksana Anggaran* (DPA) research scheme under grant number DPA 023.17.2.690645/2024.10.

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