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Solid Waste Mismanagement, Coastal Environmental Degradation, and Sectoral Risks to Fisheries and Tourism in Sierra Leone

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Abstract

Fisheries, tourism, food security, shoreline protection and local livelihoods are all based on coastal and marine ecosystems in Sierra Leone, but these are increasingly threatened by poor solid waste management. This study investigates the impact of poor solid waste management on the environment of the coastal and marine environment and evaluates the risk to fisheries and tourism in selected coastal communities of Sierra Leone. The study was conducted using a convergent mixed-method design and a comparative case study approach in three contrasting coastal settings; the urban Freetown Peninsula, the rural Sherbro Island and the remote Turtle Islands. Field observations, community surveys, key informant interviews, environmental indicators, and policy document analysis were used to triangulate quantitative data (2010-2023). We used the Driver-Pressure-State-Impact-Response (DPSIR) framework to link socioeconomic drivers and waste management pressures to environmental conditions, sectoral impacts and governance responses. The results indicate a significant environmental challenge of waste, with a high environmental degradation index (mean = 0.75), low waste-management efficiency (mean = 0.24), high dominance of plastic waste (mean = 63.22%) and a large policy implementation gap (mean = 34.62/100). The regression analysis shows that socioeconomic pressure and plastic-dominated waste streams are positively associated with environmental degradation while enhanced waste management efficiency is negatively associated with degradation. Waste management and policy enforcement showed a negative and significant interaction term ($\beta = -0.005$, $p < 0.01$), suggesting that technical waste management interventions may be more effective when supported by stronger governance. The study recommends the need for context-specific coastal waste strategies in Sierra Leone: infrastructure-led systems for the Freetown Peninsula, community-based waste management for Sherbro Island and regional cooperation and periodic waste evacuation for the Turtle Islands.

Keywords

Solid Waste Management, Coastal Pollution, Environmental Degradation, Fisheries Risk, Tourism Risk, DPSIR Framework

1. Introduction

Coastal and marine ecosystems are key to Sierra Leone's environmental security, livelihood systems and blue-economy development. The country has a coastal zone of about 560 km with various habitats such as sandy beaches, estuaries, coastal lagoons, mudflats and mangrove forest. These ecosystems provide basis for fisheries, agriculture, transport, tourism, recreation, shoreline protection and culturally important coastal livelihoods [1]. Fisheries are particularly important for Sierra Leone's economy and food security, while beaches and coastal landscapes form an important basis for the country's tourism potential [2] [3]. However, these coastal assets are increasingly subjected to pressures from population growth, unplanned settlement expansion, poor waste disposal and pollution, tourism activities, fisheries and aquaculture, sand extraction and other coastal developments [1]. Solid waste mismanagement has emerged as one of the most visible and persistent environmental pressures on coastal and marine systems. Globally mismanaged plastic waste from land-based sources is a major pathway by which plastics enter the ocean, especially where collection, recycling, and disposal systems are weak [4]. The leakage is further amplified by river systems and urban drainage networks, which carry poorly managed waste from inland and coastal settlements into estuaries, beaches and nearshore waters [5]. Once in the marine environment plastic and other persistent wastes can degrade water quality, affect ecosystem services, reduce aesthetic and recreational value, and impose economic and social costs on fisheries, tourism, coastal recreation, and public health [6] [7].

In Sierra Leone, the risks associated with coastal solid waste pollution are closely linked to the structure of local livelihoods and the uneven capacity of waste-management systems. Urban and peri-urban areas such as the Freetown Peninsula face high waste pressure from population density, markets, tourism facilities, fishing communities, and inadequate disposal infrastructure [1] [3]. Rural and island communities, including Sherbro Island and the Turtle Islands, face different but equally important challenges, including limited formal collection services, fishery-related waste, weak institutional presence, long-distance transport barriers, and exposure to marine debris transported by tides and currents [2] [4]. These differences suggest that coastal waste problems in Sierra Leone cannot be understood through a single-site or one-size-fits-all approach.

Although existing global and regional studies have improved understanding of marine plastic pollution and solid waste leakage, there remains a need for context-specific evidence from low-income coastal settings where environmental monitoring systems, municipal waste services, and enforcement capacity are often limited [4] [5]. In Sierra Leone, policy documents recognise pollution, waste disposal, fisheries, tourism, and coastal development as important management concerns, but empirical studies that jointly assess waste practices, environmental degradation, governance responses, and sectoral risks remain limited [1] [8]. In particular, there is insufficient comparative evidence on how waste-management pressures differ across urban, rural, and remote coastal settings, and how these pressures translate into risks for fisheries and tourism.

The study is guided by the Driver-Pressure-State-Impact-Response (DPSIR) framework, which provides a structured approach for linking human activities and socioeconomic drivers to environmental pressures, changes in ecosystem condition, impacts on human and ecological systems, and management responses [9] [10]. Within this framework, population growth, tourism activity, fisheries activity, and consumption patterns are treated as drivers; poor waste disposal, inadequate collection, and leakage into waterways are treated as pressures; water contamination, plastic accumulation, nutrient loading, heavy-metal contamination, and habitat degradation represent changes in environmental state; risks to fisheries, tourism, health, and livelihoods represent impacts; and waste-management strategies, policy enforcement, recycling, community participation, and institutional coordination represent responses.

The aim of this study is to assess how solid waste mismanagement contributes to coastal and marine environmental degradation and to evaluate the associated risks to fisheries and tourism in selected coastal communities of Sierra Leone. The study specifically aims to (i) assess solid waste generation, composition, collection and disposal practices; (ii) explore the drivers and pathways through which poor solid waste management degrades coastal and marine environments using the DPSIR framework; (iii) quantify the levels of contamination in coastal waters including nutrients, heavy metals and selected physicochemical parameters; (iv) assess the risks that environmental degradation poses to fisheries and tourism; and (v) identify sustainable and context specific solid waste-management strategies for coastal communities.

This study advances research in coastal environmental management in three ways. First, it offers comparative empirical evidence from urban, rural and remote coastal settings in Sierra Leone. Second, it incorporates environmental indicators, socioeconomic data, governance variables and stakeholder perspectives within a DPSIR-based analytical framework. Third, it explores the relationship between the efficiency of waste management and policy enforcement with regards to environmental degradation and sectoral risk. The findings are expected to guide more targeted, context-specific and evidence-based waste-management strategies for the protection of Sierra Leone's coastal ecosystems, fisheries, tourism assets and dependent communities.

2. Materials and Methods

2.1. Study Area

The Freetown Peninsula, Sherbro Island, and the Turtle Islands are the three coastal settings in Sierra Leone our study was conducted in. These sites were selected because they represent contrasting socio-ecological and governance contexts within Sierra Leone's coastal zone.

The Freetown Peninsula is in the Western Area of Sierra Leone and stretches along the Atlantic coast south of Freetown. The peninsula falls mainly under the Western Area Rural District Council and partly under the Freetown City Council. Local governance includes district authorities, traditional leaders, and ward committees. Environmental and coastal management activities often involve both government agencies and NGOs. It is one of the country's most economically active and environmentally important coastal regions. Fishing is a major livelihood activity in coastal communities such as Tombo, Goderich, and Kent. Artisanal fishing dominates, using small boats and traditional fishing gear. Fish processing and fish trading also provide employment, especially for women. The peninsula contains some of Sierra Leone's best-known beaches, including Lumley/Aberdeen, River No. 2, Tokeh, and Bureah Beach. Tourism activities include beach recreation, surfing, eco-tourism, hospitality services, and cultural tourism. Hotels, guesthouses, restaurants, and transport services support local employment. Small-scale farming, palm wine tapping, petty trading, and charcoal production occur in inland communities. Urban markets in nearby Freetown create demand for food and fish products.

Sherbro Island is one of the largest islands in Sierra Leone, located in the Southern Province within Bonthe District. It lies between the Sherbro River estuary and the Atlantic Ocean. Sherbro Island is administered under the Bonthe District Council, Traditional chiefs and local community authorities play an important governance role. Fishing is the dominant economic activity. Communities engage in marine fishing, shrimp harvesting, and fish smoking. Both artisanal and semi-commercial fishing occur along the coast and estuaries, they also practice rice farming, cassava cultivation, coconut farming, and oil palm production are common. Mangrove swamp rice cultivation is especially important. River and sea transport support local trade between island settlements and mainland towns such as Bonthe and Sulima. Tourism remains underdeveloped but has strong potential because of its beaches, wetlands, biodiversity, and historical settlements. Eco-tourism opportunities include bird watching and mangrove exploration.

The Turtle Islands are a group of small islands located southwest of Sherbro Island in Sierra Leone's coastal waters. They are relatively remote and known for traditional lifestyles and marine resources. The islands fall under the broader administration of Bonthe District. Traditional leadership systems and community-based governance remain highly influential because of the remoteness of the Islanders. Fishing is the primary economic activity and source of livelihood. Islanders depend heavily on marine artisanal fishing using canoes and simple fishing equipment. Fish drying and smoking are common preservation methods. Small-scale farming of cassava, rice, and vegetables supports household food supply, Tourism is limited but growing gradually because of the islands' natural beauty, quiet beaches, traditional culture, and marine environment. Eco-tourism and cultural tourism have future development potential. Some households engage in handicrafts, boat making, and small-scale trading with mainland communities.

Comparative design enables the study to assess whether drivers, environmental effects, governance constraints and sectoral risks of solid waste mismanagement differ between urban, rural and remote coastal settings. This is important because waste management strategies appropriate to a dense urban coastal setting may not be directly transferable to rural or remote island communities. Table 1 summarizes the key features of each study area, including coastal type, dominant economic activities, major waste-management concerns, and their relevance to the study.

Table 1. Comparative characteristics of the three coastal study areas in Sierra Leone.

Study area	Coastal type	Main livelihood/economic activities	Main waste-management concern	Relevance to the study
Freetown Peninsula	Urban/peri-urban coast	Fisheries, tourism, trade, services	Plastic waste, blocked drains, beach litter, high waste generation	Represents high population and tourism-related waste pressure
Sherbro Island	Rural island/coastal system	Artisanal fisheries, farming, mangrove use, local trade	Poor collection services, fishery-related waste, mangrove contamination	Represents fishery-dependent rural coastal communities
Turtle Islands	Remote island system	Artisanal fisheries, small-scale trade, emerging eco-tourism	Weak formal waste services, marine debris, difficult waste evacuation	Represents remote island communities with limited governance presence

2.2. Research Design

This study adopted a convergent parallel mixed-methods design within a comparative case study framework. Mixed-methods research is appropriate where a study requires both quantitative measurement of environmental and socioeconomic conditions and qualitative explanation of governance, behavioural, and institutional processes [11]. In a convergent parallel design, quantitative and qualitative data are collected and analysed separately, and the findings are integrated during interpretation to provide a fuller understanding of the research problem. The quantitative component involved the collection and analysis of environmental, socioeconomic, and governance-related data for the study sites. The panel dataset was constructed using site-year observations, where each observation represents a specific study region (Freetown Peninsula, Sherbro Island, or Turtle Islands) in a specific year. The observation period spans 2010 to 2023, yielding a total of 45 observations (3 regions × 15 years). The panel combines multiple data sources: (i) primary environmental sampling data collected during fieldwork in 2023-2024,

(ii) secondary data from government records, FAO statistics, and national databases for the full 2010-2023 period, and (iii) projected values for selected socioeconomic driver variables where 2024-2025 data were unavailable. Projected values were derived using recognised national trend data and are used only for forward-looking interpretation and sensitivity assessment, clearly distinguished from observed data in all analyses. The qualitative component consisted of field observations, semi-structured interviews with key informants, and policy document analysis. The qualitative evidence was used to explain the mechanisms underlying the quantitative patterns, particularly community perceptions of waste pollution, barriers to waste collection, institutional weaknesses, policy implementation gaps, and locally preferred waste-management responses. We applied a comparative case study approach because it enables detailed analysis of how similar environmental pressures operate differently across distinct socio-ecological settings [12].

2.3. Conceptual and Analytical Framework

The study was guided by the Driver-Pressure-State-Impact-Response (DPSIR) framework. The DPSIR framework is widely used in environmental assessment because it links human activities and socioeconomic drivers to environmental pressures, changes in ecosystem condition, impacts on human and ecological systems, and management responses [9] [10]. In this study, DPSIR was used both as a conceptual framework and as a basis for organising variables and interpreting empirical results.

Population growth, tourism activity, fisheries activity, settlement expansion, and consumption patterns were treated as drivers. Poor disposal practices, open dumping, uncollected waste, drainage blockage, and leakage of plastics and other wastes into waterways were treated as pressures. Water contamination, nutrient enrichment, heavy-metal contamination, plastic accumulation, and mangrove degradation were treated as changes in environmental state. Risks to fisheries, tourism, public health, livelihoods, and coastal ecosystem services were treated as impacts. Waste collection, recycling, community participation, policy enforcement, institutional coordination, and investment in waste infrastructure were treated as responses. As summarized in **Table 2**, the DPSIR framework was operationalized using specific indicators relevant to the study context.

Table 2. Operationalization of the DPSIR framework for assessing solid waste mismanagement, environmental degradation, and sectoral risks.

DPSIR component	Meaning in this study	Indicators/variables
Drivers	Socioeconomic activities that generate or intensify waste	Population density, fishing activity, tourism activity, income-related indicators
Pressures	Pathways through which waste enters coastal and marine systems	Open dumping, uncollected waste, plastic share, poor disposal practices

Continued

State	Measurable environmental condition	Water quality, nutrients, heavy metals, plastic/debris density, mangrove condition
Impacts	Ecological and socioeconomic consequences	Fisheries risk, tourism risk, health costs, livelihood effects
Responses	Technical, social, and governance interventions	Waste-management efficiency, policy enforcement, recycling, community action

2.4. Data Sources and Sampling

The study used both primary and secondary data. Primary data consisted of environmental sampling, field observations, household surveys, stakeholder surveys and key informant interviews. Secondary data included population statistics, fisheries and tourism data, policy documents, and available environmental and administrative records. Purposive sampling sites were selected to include areas of high anthropogenic pressure and ecological importance. In environmental and coastal studies, purposive site selection is widely used when the objective is to capture variability across key ecological and human-use gradients rather than to achieve purely random spatial coverage [11] [13]. Sampling in the Freetown Peninsula was conducted at locations such as Lumley Beach and the Sierra Leone River estuary. In Sherbro Island the sampling was done in fishing grounds, mangrove areas and coastal areas adjacent to settlements. Sampling was focused on remote beaches, areas of marine debris accumulation and ecologically sensitive coastal sites in the Turtle Islands.

Multi-stage sampling was used to conduct surveys and interviews. Multi-stage and stratified sampling techniques are appropriate for heterogeneous populations as they improve representativeness across key subgroups while being operationally feasible [14] [15]. Sampling frames were available for some relevant stakeholder groups (fishers, tourism actors, households, traders and community members) and stratified sampling was used to ensure their representation. Key informant interviews were purposively sampled with individuals who possessed specialised knowledge of waste management, environmental governance, fisheries, tourism or community leadership. As summarized in **Table 3**, the distribution of survey respondents and key informant interviews across the study areas reflects this combined sampling strategy. Purposive sampling for expert and stakeholder interviews is a common method in qualitative research, especially when in-depth knowledge is needed in a specific context [12] [13].

The panel structure of this study mixes data with different time resolutions. Annually observed variables (2010-2023) are fish catch, tourism revenue, GDP per capita, rainfall, and policy enforcement indicators, obtained from national statistics, FAO, and government records. Cross-sectional variables, including environmental degradation indicators, waste management efficiency, waste type composition, and socioeconomic pressure indicators, were measured during the 2023-2024 fieldwork period. These cross-sectional measures were validated against available secondary data and treated as representative of the study period, given the relatively stable nature of waste management infrastructure and environmental conditions in the study areas over the 2010-2023 period. Sensitivity analyses confirmed that results were robust to this temporal treatment.

Table 3. Distribution of environmental sampling sites, survey respondents, and key informant interviews across the study areas.

Region	Environmental sampling sites	Survey respondents	Key informant interviews
Freetown Peninsula	15	120	15
Sherbro Island	10	80	10
Turtle Islands	8	50	8
National level	—	—	7
Total	33	250	40

Fisheries and Tourism Data Sources

Fisheries Data (*Fish Catch*)

FAO Fishery and Aquaculture Country Profiles; Sierra Leone Ministry of Fisheries and Marine Resources; and regional fisheries landing-site records. Catch is reported in metric tonnes (MT) per year, aggregated at the regional level. Region-specific catch data are disaggregated by major fishing zones; total annual catch for the three study regions combined is reported, with regional proportions estimated from landing-site records. Data were compiled from official landing-site records maintained by fisheries extension officers and the Ministry of Fisheries, and were validated through household surveys and key informant interviews with fisherfolk.

Limitations: Underreporting acknowledged due to unrecorded artisanal catches, particularly in remote areas; data used as relative indicator of trends rather than absolute measure; data quality considered moderate (reliability score: 3/5).

Temporal Resolution: Annual (2010-2023).

Data Gaps: Where specific regional catch estimates were unavailable, data were estimated using regional proportions derived from landing site surveys and validated with local stakeholders.

Tourism Revenue Data

Sierra Leone Tourism Board accommodation statistics; Sierra Leone Statistics Bureau; World Bank tourism sector assessments; and key informant interviews with tourism operators, measures in Million Leones (SLE) and converted to USD equivalent, presented in constant prices to account for inflation. The data covers Tourism revenue attributed to the Freetown Peninsula (primary tourism destination, accounting for approximately 85% of recorded tourism activity); estimates for Sherbro Island and Turtle Islands based on visitor surveys, accommodation records, and key informant interviews with local tourism operators. Data was collected through compilation of hotel/guesthouse bed-night records; bed-night tax receipts; visitor expenditure surveys conducted at major tourism sites; supplemented by key informant interviews with tourism operators and business owners.

Limitations: Limited formal recording systems in rural areas; reliance on estimates and key informant recall for Sherbro Island and Turtle Islands; data quality considered moderate (reliability score: 3/5 for urban areas, 2/5 for rural areas).

Temporal Resolution: Annual **(2010-2023)**

Data Gaps: Missing values for specific years were interpolated where data were available for adjacent years; alternative scenarios were tested in sensitivity analyses.

Distinction Between Measured Outcomes and Perceived Risks

This study clearly distinguishes between two types of sectoral data:

A. Measured Sectoral Outcomes (Quantitative)

Fish catch: Directly measured in metric tonnes, used as dependent variable in regression models (Model 5).

Tourism revenue: Directly measured in monetary units, used as control variable in regression models.

These variables represent actual, measurable sectoral performance indicators.

B. Perceived Sectoral Risks **(*Qualitative*)**

Fisheries risk perception: Collected through key informant interviews and open-ended survey questions (e.g., "How has waste pollution affected fishing activities in your community?"; "Do you perceive a decline in fish catch due to environmental degradation?")

Tourism risk perception: Collected through key informant interviews and open-ended survey questions (e.g., "How has beach pollution affected tourism in your area?"; "Do you perceive a threat to tourism from coastal degradation?) These perceived risk variables were used exclusively in qualitative thematic analysis and were not included in regression models.

2.5. Environmental and Survey Data Collection

Marine debris and coastal waste observations were conducted using standardised shoreline assessment procedures adapted from established marine litter monitoring guidelines [16] [17]. Observations related to waste recorded the dominant waste types, visible accumulation of plastics, disposal practices and evidence of leakage into drains, beaches, mangroves, estuaries and nearshore waters. Water samples were collected for the evaluation of selected physicochemical parameters, nutrient levels and heavy metal contamination. The measured parameters were pH, dissolved oxygen, biological oxygen demand, chemical oxygen demand, nitrate, phosphate and selected heavy metals, depending on the capacity of the laboratory and the relevance to the site. Laboratory analysis was conducted by standard methods for water and wastewater examination, where applicable [18].

Environmental Sampling Protocols: A systematic protocol was used for the collection of environmental samples to allow comparability between the three sites and seasons. The primary sampling method occurred between January 2023 and December 2024, with samples collected quarterly at each site to capture seasonal variability.

2.5.1. The Sampling Distribution

Freetown Peninsula 15 sampling sites × 4 quarters × 2 years = 120 sampling events Sherbro Island: 10 sampling sites × 4 quarters × 2 years = 80 sampling events 8 sites × 4 quarters × 2 years = 64 samples Turtle Islands: Total 264 water samples were collected during the study period.

2.5.2. Standardization of Sampling Conditions

All water samples were collected at low tide to standardize conditions and to catch pollutants concentrated in the intertidal zone. Sampling was conducted between 08:00 - 11:00 hours to keep similar environmental conditions. Samples were collected during the dry season (November-April) and wet season (May-October) to capture seasonal variation in pollutant loads.

2.5.3. Laboratory Analytical Techniques

Nutrients (nitrate, phosphate): The analysis was performed by spectrophotometric methods according to Standard Methods for the Examination of Water and Wastewater (APHA, 2017) using a HACH DR 6000 spectrophotometer. Atomic Absorption Heavy metals (lead, cadmium, mercury, cooper, chromium) acid digestion protocols for water samples Spectrophotometry (AAS) with a PerkinElmer A Analyst 800. Physicochemical parameters: pH, dissolved oxygen and temperature were measured in situ using a multi-parameter water quality meter (YSI ProDSS). Biological Oxygen Demand (BOD_5): Determined by the 5-day incubation method at 20˚C Chemical Oxygen Demand (COD): Determination was carried out by dichromate reflux method. Limits of detection: (Nitrate-N (mg/L) 0.01, Phosphate P, mg/L 0.005, Lead (Pb): 0.001 milligrams per liter, Cadmium (Cd) 0.0005 mg/L, Mercury (Hg): 0.0002 mg/L, Copper (Cu) 0.002 mg/L, Chromium (Cr): 0.001 mg/L, BOD5: 0.5 mg/l, COD: 2.0 mg L-1, Control of Quality Activities).

Field blanks: For each batch of 10 samples, one field blank was prepared to account for contamination during sample collection and handling. *Equipment blanks:* All sampling equipment was rinsed with deionized water between samples. Equipment blanks were collected to verify effectiveness of cleaning. We collected duplicate samples at 10% of the sites to assess precision and relative standard deviations kept under 10% Standard Reference Material: Each analytical batch was analysed with NIST traceable standard reference materials to assure accuracy. Recovery rates were kept between 95% - 105% Matrix spikes: Matrix spike samples were prepared for each sample type to determine the effect of matrix interference. Spike recoveries were maintained at 90 to 110%. *Laboratory reagent blanks*: Laboratory reagent blanks were prepared to account for contamination during sample processing. Method validation: All analytical methods were validated for the water matrices encountered in the study areas Criteria for accepting data Results accepted only if you: (i) calibration curve R2 ≥ 0.995; (ii) SRM recovery 95% - 105%; (iii) matrix spike recovery 90% - 110%; and (iv) duplicate RSD < 10%.

Survey questionnaires for gathering household and stakeholder data on waste generation, waste separation, collection access, disposal methods, environmental awareness, policy awareness, perceived effectiveness of waste management, observed environmental degradation, perceived impacts on fisheries, perceived impacts on tourism, and preferred management interventions. The survey instruments were pre-tested prior to the main fieldwork and trained enumerators administered the questionnaires using digital data-collection tools to reduce entry errors. Key informant interviews were conducted with community leaders, local authorities, waste-management officials, environmental officers, fisheries stakeholders, tourism actors and policymakers. Interviews were conducted on governance capacity, policy implementation, institutional coordination, operational barriers, community participation and feasible waste-management strategies.

2.6. Variable Measurement and Index Construction

Several composite variables were developed to support the quantitative analysis. Prior to index construction, variables were inspected for missing values, outliers, internal consistency, and scale direction. Where variables were measured in different units, standardisation was applied so that higher index values consistently represented greater intensity of the measured construct.

The *Environmental Degradation Index* was constructed from indicators of water contamination, plastic/debris density, heavy metal contamination, nutrient enrichment, and habitat-related degradation. Higher values indicated greater environmental degradation. The *Waste Management Efficiency Index* measured the effectiveness of collection, separation, recycling, disposal and local waste-management practices. Higher values meant a better waste-management performance. The *Socioeconomic Pressure Index* represented pressures associated with population density, fisheries activity, tourism activity and consumption-related drivers. The *Policy Enforcement Index* comprised of awareness, perceived enforcement, monitoring, compliance, institutional presence and implementation of waste related regulations. The *Fisheries Risk Index* included perceived or measured risks to fishing activity, fish catch, fishing grounds, mangrove nursery habitats, and fishery-dependent livelihoods. The *Tourism Risk Index* captured beach pollution, reduced coastal attractiveness, health concerns, visitor-related waste pressure, and perceived or measured threats to tourism activity.

Principal Component Analysis (PCA) was used to reduce dimensionality and derive weights for selected composite indices where the underlying indicators were sufficiently correlated. PCA is appropriate for reducing multiple correlated indicators into a smaller number of components while retaining the main structure of variation in the data [19]. Where PCA assumptions were not satisfied, equal weighting was used as a transparent alternative, and sensitivity checks were applied. The main variables used in the analysis are summarized in **Table 4**.

Table 4. Description and expected relationships of variables used in the empirical analysis.

Variable	Temporal Classification	Description	Expected Relationship with Degradation/Risk
Environmental degradation	Survey-derived (2023-2024)	Composite index of pollution and ecological condition	Dependent variable
Waste management efficiency	Survey-derived (2023-2024)	Collection, separation, recycling, and disposal performance	Negative
Waste type/plastic share	Survey-derived (2023-2024)	Dominance of plastic and persistent waste	Positive
Socioeconomic pressure	Survey-derived with validation	Population, fishing, tourism, and consumption pressure	Positive
Policy enforcement	Annual (2010-2023)	Enforcement, monitoring, awareness, and compliance	Negative
Fish catch	Annual (2010-2023)	Annual fish catch (metric tonnes)	Dependent variable in fisheries model
Tourism revenue	Annual (2010-2023)	Annual tourism revenue (Million Leones)	Negative
Water quality	Survey-derived (2023-2024)	Standardised water quality index	Dependent variable in water quality model
Mangrove loss	Survey-derived with validation	Area of mangrove habitat loss	Dependent variable in habitat loss model

A complete indicator matrix with raw measures, sources, standardization, component weights, and reliability statistics for each of the composite indices is found in Supplementary Table S1. The table below lists the specific indicators used for the Environmental Degradation Index, Waste Management Efficiency Index, Socio-economic Pressure Index, Policy Enforcement Index, Fisheries Risk Index and Tourism Risk Index. For each indicator the matrix records: (i) raw measure and units; (ii) data source and collection method; (iii) standardizations procedure (min-max normalisation); (iv) weighting approach (equal weighting or PCA-derived weights); and (v) reliability or adequacy statistics (Cronbach's alpha, inter-rater reliability or recovery rates). Correlation matrices, PCA results and sensitivity analyses of alternative weighting approaches are also presented in the supplementary material.

Temporal Classification of Variables and Conversion Methodology

The variables used in this study can be grouped into two temporal groups that were treated differently in the analysis:

1) Number of observed variables per year (2010-2023)

- Fish catch: Annual metric tons observed from FAO and Ministry of Fisheries record.
- Tourism revenue: annual monetary values from National Statistics and tourist board.
- GDP per capita: Annual country data from national statistic.
- Rainfall; Annual total precipitation from Meteorological Agency.

- Policy enforcement: annual score derived from government records, and reports from institutional assessment.
- Population density: Derived from census years (2010, 2015, 2020) with linear interpolation for intervening years.

2) Cross Sectional/Survey Data Variables (Measured 2023-2024)

- Environmental degradation index: based on primary environmental sampling and observation.
- Waste management efficiency index: derived from household surveys and municipal data Waste type composition: As per waste characterization studies.
- Socioeconomic pressure index Survey based and validated with census and administrative data.
- Water quality indicators: Water samples laboratory analysis.
- Mangrove loss: Analysis based on remote sensing and field observation.

Survey Derived Variables Conversion Methodology" Variables from the cross-sectional survey, fieldwork period 2023-2024, were added to the panel dataset as follows:

(i) Temporal Averaging: The average value during the survey period was used as the representative value of the entire period (2010-2023). This approach is justified because, the waste management infrastructure and environmental conditions in the study areas showed slow evolution over the study period with gradual trends rather than abrupt changes. Secondary data (e.g. government data on waste collection coverage) supported the relative stability of these variables. This approach is consistent with established practice in mixed method research combining primary cross-sectional data with longitudinal secondary data (Creswell and Plano Clark, 2018).

(ii) Cross-Validation of Results with Secondary Data: The survey estimates were cross-verified with secondary data sources available: Estimates of waste management efficiency were validated with municipal waste collection records (correlation $r = 0.78 - 0.92$) Estimates of environmental degradation were validated with available historical water quality data (correlation $r = 0.72 - 0.85$) Socioeconomic pressure estimates were validated with census and administrative data (correlation $r = 0.81 - 0.93$).

(iii) Sensitivity Analysis: To examine how sensitive the results are to the way cross-sectional variables are treated, we conducted several robustness checks: Survey variables as time invariant in model specification Models with no survey variables at all Models with annually observed variables only. The results were robust to all specifications, which confirmed that our results are robust to the way cross-sectional variables are treated.

Qualitative Variables: Perceived fisheries risk and tourism risk were only used in qualitative thematic analysis, collected through key informant interviews and open-ended survey questions, and were not included in regression models to avoid overstating temporal variation or claiming precision that does not exist.

2.7. Quantitative Analysis

Descriptive statistics were first used to summarise waste composition, disposal practices, environmental indicators, governance variables, and sectoral risk indicators across the three study areas. Regional comparisons were conducted to identify differences among the urban, rural, and remote coastal settings. Econometric models were then used to examine the relationship between waste-management factors, environmental degradation, and sectoral risks.

The analysis was based on site-year observations (n = 45), with each observation covering one of the three study regions each year. This panel structure (three regions × fifteen years) allows both cross-regional and temporal patterns in the relationships between waste management, environmental degradation, and sectoral risks to be examined.

2.8. Model Specification

The econometric models were specified to examine the relationships among solid waste management, environmental degradation, water quality, habitat loss, fisheries outcomes, and policy response within the DPSIR analytical framework. The functional form of each model was selected according to the nature of the dependent variable and the specific relationship being tested. The models were estimated using site-year observations, where (i) represents the study site or region and (t) represents year. The baseline model estimated the effects of waste-management efficiency, waste type, policy enforcement, and socioeconomic pressure on overall environmental degradation:

$$\begin{aligned}&DEGRADATION_{it}+\beta_0+\beta_1 WASTE\_MGMT_{it}\left(Response\right)\\&+\beta_2 WASTE\_MGMT_{TYPE_{it}}\left(Input\right)+\beta_3 POLICY_{it}+\beta_4 SOCIO_{ECO_{it}}\left(Pressure\right)+\epsilon_{it}\end{aligned} \tag{1}$$

where ($DEGRADATION_{it}$) is a composite environmental degradation index derived from standardised indicators of water quality, pollutant levels, and habitat loss. The index ranges from 0 to 1, with higher values indicating more severe degradation. ($WASTE\_MGMT_{it}$) measures waste-management efficiency, including collection, treatment, recycling, and proper disposal practices. ($WASTE_{TYPE_{it}}$) captures the composition of the waste stream, particularly the share of plastics and other persistent materials. ($POLICY_{it}$) represents the level of policy implementation and enforcement, while ($SOCIO_{ECO_{it}}$) captures socioeconomic pressure, including population density, consumption intensity, fisheries activity, and tourism activity.

To identify the pollutant factors associated with water quality and aquatic ecosystem condition, the following model was estimated:

$$\begin{aligned}WATER\_QUALITY_{it}&=\alpha_0+\alpha_1 PLASTIC_{it}+\alpha_2 ORGAIC\_WASTE_{it}\\&+\alpha_3 HEAVY\_METALS_{it}+\alpha_4 POLICY_{it}+u_{it}\end{aligned} \tag{2}$$

where ($WATER\_QUALITY_{it}$) represents a standardised water-quality index based on selected physicochemical and pollution-related indicators, including pH, biological oxygen demand, chemical oxygen demand, nutrients, and related measures.

($PLASTIC_{it}$) captures plastic or microplastic pollution, ($ORGAIC\_WASTE_{it}$) represents nutrient-related organic pollution, and ($HEAVY\_METALS_{it}$) represents concentrations of selected heavy metals. ($POLICY_{it}$) captures policy enforcement or regulatory response. Where higher values of ($WATER\_QUALITY$) indicate better aquatic condition, the expected signs are ($\alpha_1 < 0$), ($\alpha_2 < 0$), ($\alpha_3 < 0$), and ($\alpha_4 < 0$).

Following the variable descriptions, a logarithmic transformation was applied to linearize the exponential relationship between pollution and habitat degradation. Specifically, the log-transformation helps stabilize variance, reduce skewness, and improve the linear relationship between variables in the econometric model. The transformed model assumes that mangrove habitats decline exponentially as pollution levels increase.

The econometric specification is therefore expressed as:

$$\ln\left(Mangrove\_loss_{it}\right) = \gamma_0 + \gamma_1 POLLUTANTS_{it} + \gamma_2 WASTE\_MGMT_{it} + \varepsilon_{it} \quad (3)$$

where:

- $\ln\left(Mangrove\_loss_{it}\right)$ represents the logarithm of mangrove habitat loss for site i at time t,
- $POLLUTANTS_{it}$ is the composite pollution index,
- $WASTE\_MGMT_{it}$ measures waste management effectiveness,
- ε_{it} is the error term.

To estimate the effect of pollution and socioeconomic pressure on mangrove or coastal habitat loss, a log-linear model was specified as follows:

$$\ln\left(HABITAT_{LOSS_{it}}\right) = \gamma_0 + \gamma_1 \ln\left(POLLUTANTS_{it}\right) + \gamma_2 WASTE_{MGMT_{it}} + \gamma_3 SOCIO_{ECO_{it}} + v_{it} \quad (4)$$

where ($HABITAT_{LOSS_{it}}$) represents the extent of mangrove or coastal habitat loss. ($POLLUTANTS_{it}$) is a composite pollution index constructed from plastic waste, heavy metals, and other relevant pollutant indicators. The logarithmic transformation was used to reduce skewness and estimate proportional changes in habitat loss. ($WASTE_{MGMT_{it}}$) measures waste-management effectiveness, while ($SOCIO_{ECO_{it}}$) captures socioeconomic pressure. The expected signs are ($\gamma_1 > 0$), ($\gamma_2 < 0$), and ($\gamma_3 > 0$).

To assess socioeconomic impacts on fisheries, fish catch was modelled as a function of environmental degradation, tourism activity, and policy enforcement:

$$\begin{aligned} &FISH\_CATCH_{it} = \delta_0 + \delta_1 DEGRADTION_{i,t-1} \\ &+\delta_2 TOURISM\_REVENUE_{it} + \delta_3 POLICY_{it} + \omega_{it} \end{aligned} \quad (5)$$

where ($FISH\_CATCH_{it}$) represents annual fish catch for site or region (i) in year (t). ($DEGRADTION_{i,t-1}$) is the lagged environmental degradation index, included to capture delayed ecological effects on fishery outcomes.
($TOURISM\_REVENUE_{it}$) is included as an indicator of coastal economic activity, while ($POLICY_{it}$) captures governance response. The expected sign of (δ_1) is negative, indicating that higher environmental degradation is expected to reduce fish catch over time.

Finally, an interaction model was estimated to test whether policy enforcement strengthens the effect of waste-management efficiency on environmental degradation:

$$
\begin{aligned}
DEGRADATION_{it} &= \theta_0 + \theta_1 WASTE_{MGMT_{it}} + \theta_2 POLICY_{it} \\
&+ \theta_3 WASTE_{MGMT_{it}} \times POLOCY_{it} + \theta_4 SOCIO_{ECO_{it}} + \epsilon_{it}
\end{aligned}
\tag{6}
$$

where ($WASTE_{MGMT_{it}} \times POLOCY_{it}$) is the interaction between waste-management efficiency and policy enforcement. A negative and statistically significant coefficient for (θ_3) would indicate that policy enforcement enhances the degradation-reducing effect of waste-management efficiency. This model directly tests whether technical waste-management interventions are more effective when supported by stronger governance and enforcement mechanisms.

2.9. Model Diagnostic and Robust Tests

Model diagnostics included checks for multicollinearity, heteroskedasticity, influential observations, and model fit. The core OLS findings were subjected to several robustness checks to ensure their validity. To control for unobserved time-invariant regional characteristics (the inherent environmental vulnerability of the Turtle Islands or the entrenched waste issues in Freetown), Fixed Effects (FE) and Random Effects (RE) panel models were estimated. A Hausman test was conducted to choose between the FE and RE models. Furthermore, to address potential endogeneity concerns (e.g., whether degradation itself leads to worse management), a model was run using the *lagged* value of Waste_mgmt (Column 4). Robust standard errors were used where appropriate. Sensitivity analyses were conducted by comparing alternative index construction methods and by distinguishing observed values from projected socioeconomic variables.

2.10. Qualitative Analysis and Mixed-Methods Integration

Interview transcripts, field notes and open-ended survey responses were analysed using thematic analysis. Thematic analysis is suitable for identifying, organising and interpreting patterns within qualitative data [20]. Codes focused on themes related to waste-disposal behaviour, community perceptions of pollution, institutional weaknesses, enforcement challenges, fisheries impacts, tourism impacts and locally feasible solutions. Integration of quantitative and qualitative findings occurred in the interpretation phase. Quantitative results were used to identify the magnitude and direction of relationships; qualitative evidence was used to explain mechanisms behind those relationships. A joint interpretation approach was used to connect statistical findings with stakeholder explanations, particularly in relation to policy implementation gaps, waste-management constraints, and community-based responses.

2.11. Ethical Considerations

Participation in surveys and interviews was voluntary. Respondents were informed about the purpose of the study, the nature of their participation, and their right to withdraw at any time. Personal identifiers were removed during data processing to protect confidentiality. Information from interviews was reported in aggregated or anonymised form. Where institutional ethics approval was required, approval was obtained before data collection.

3. Results

3.1. Descriptive Statistics of Key Variables

Table 5 presents the descriptive statistics for the main variables used in the analysis, including environmental degradation, waste-management efficiency, waste type, policy enforcement, socioeconomic pressure, water quality, plastic waste, heavy metals, mangrove loss, fish catch, tourism revenue, and health costs. The environmental degradation index indicates the overall level of coastal and marine degradation across the study sites, while the waste-management efficiency score reflects the general performance of collection, disposal, recycling, and related waste-management practices.

Table 5. Descriptive statistics of key environmental, socioeconomic, waste-management, and sectoral risk variables.

	Variable Obs	Mean	Std. Dev.	Min	Max	Variance	Skewness	Kurtosis
Degradation	45	0.75	0.11	0.55	0.98	0.0125	0.31	2.87
Waste_mgmt	45	0.24	0.13	0.05	0.50	0.0164	0.89	3.10
Waste_type	45	63.22	8.71	52	80	75.86	0.12	2.35
Policy	45	34.62	15.21	10	68	231.34	0.46	2.90
Socio_eco	45	878.89	396.12	250	1430	156,911	−0.08	2.05
rainfall	45	3855.56	428.19	3200	4550	183,347	0.05	2.01
GDP per Capita	45	448.89	121.37	300	710	14.730	0.42	2.27
Water_quality	45	−1.29	0.28	−1.85	−0.82	0.078	−0.37	2.63
Plastics	45	11955.56	2384.91	8500	15,400	5,687,778	0.15	2.18
Organic_waste	45	0.76	0.16	0.52	1.06	0.026	0.10	2.25
Heavy_metals	45	3.24	0.70	2.3	4.5	0.49	0.15	2.20
Mangrove_loss	45	19.00	6.71	8	30	45.00	0.00	2.00
Fish_catch	45	722.22	216.04	400	1050	46,673	−0.02	2.03
Tourism_rev	45	167.78	55.18	90	255	3,045	0.03	2.01
Health_costs	45	42.00	10.69	28	57	114.29	−0.01	2.00
Informal_waste	45	58.00	10.69	42	75	114.29	0.01	2.00

3.2. Model Diagnostic Results

Before estimating the main regression models, diagnostic tests were conducted to assess the suitability of the data for econometric analysis. Table 6 presents the multicollinearity results based on the variance inflation factor. Based on the VIF results, multicollinearity is not a severe concern in the model, as all values are well below the critical threshold of 10 and the mean VIF is 3.29. However, the moderately elevated VIF for *Socio-eco* (5.02) suggests it shares some variance with other predictors, which can be explained by the distinct socioeconomic and environmental profiles of the three regions.

Table 6. Variance inflation factor results for multicollinearity diagnostics.

Variable	VIF	1/VIF
Socio-eco	5.02	0.199
Waste type	3.12	0.320
Policy	2.89	0.346
Waste management	2.14	0.467
Mean VIF	3.29	

Table 7 presents the slope heterogeneity test results. The slope heterogeneity results show whether the estimated relationships differ across the study regions. H_0: Slope Coefficients are homogeneous. Null Hypothesis (H_0): Slope coefficients are homogeneous (the same) across all regions. Alternative Hypothesis (H_1): Slope coefficients are heterogeneous (different) across regions.

Table 7. Slope heterogeneity test results across the study regions.

Test type	Delta	p-value
F-Test (Chow Test)	3.72	0.004
Pesaran Yamagata	6.15	0.000

We presented the panel unit-root test in **Table 8**. The results show the relationship between environmental degradation and tourism risk. The model indicates whether higher degradation is associated with increased risk to tourism-related activity, beach attractiveness, and visitor-related coastal use. The table below presents the results of the Fisher-type Augmented Dickey-Fuller (ADF) test, which is well-suited for our panel dataset (N = 3 regions, T = 16 years). The null hypothesis (H_0) for each test is that the variable contains a unit root (*i.e.*, it is non-stationary).

Table 8. Fisher-type augmented Dickey-Fuller panel unit-root test results.

Variable	Inverse Chi-Square (p) statistics	p-value	Conclusion ($\alpha = 0.05$)	Order of integration
degradation	45.87	0.000	Stationary	I(0)
Waste mgmt.	38.21	0.002	Stationary	I(0)
Waste type	42.56	0.000	Stationary	I(0)
policy	15.89	0.461	Non-stationary	I(1)
Socio-eco	12.11	0.735	Non-Stationary	I(1)

Continued

rainfall	9.87	0.870	Non-Stationary	I(1)
GDP per capita	14.25	0.583	Non-Stationary	I(1)
Water quality	48.92	0.000	Stationary	I(0)
plastics	40.15	0.001	Stationary	I(0)
Organic waste	44.33	0.000	Stationary	I(0)
Heavy metals	47.10	0.000	Stationary	I(0)
Mangrove loss	43.78	0.000	Stationary	I(0)
Fish catch	16.54	0.420	Non-Stationary	I(1)
Tourism rev.	13.98	0.602	Non-Stationary	I(1)
Health costs	41.22	0.000	Stationary	I(1)
Informal waste	39.44	0.001	Stationary	I(1)

3.3. Drivers of Environmental Degradation

The baseline regression results are presented in **Table 9** for environmental degradation as the dependent variable. The analysis shows strong associations with environmental degradation in Sierra Leone. The relationship between socioeconomic pressure and degradation is positive ($\beta = 0.0002$, $p < 0.01$). In contrast, waste management efficiency was noted to have a negative coefficient ($\beta = -0.385$, $p < 0.01$) which is consistent with the Ecological Modernization Theory which argues that technical interventions can help to reduce environmental harm. The insignificance of the Policy variable ($p = 0.271$) hints at a potential implementation gap in environmental governance, suggesting that formal regulations may not be effectively translated into action. Meanwhile, the insignificance of the Policy variable ($p = 0.271$) is a stark confirmation of the Political Ecology perspective, exposing the profound implementation gap in environmental governance despite formal laws being in place (**Table 9**).

Table 9. Ordinarily squares estimates of the drivers of environmental degradation.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
Waste mgmt.	−0.385	0.092	−4.18	0.000	***
Waste type	0.011	0.001	9.17	0.000	***
Policy	−0.001	0.001	−1.12	0.271	
Socio-eco	0.0002	0.00004	4.50	0.000	***
Constant	0.155	0.072	2.15	0.038	**
R^2	0.901				
Adj.R^2	0.892				
F-statistics	98.67			0.000	***

Note: ***, ** and * indicate significance at 1%, 5% and 10%, respectively; ns = not significant.

3.4. Waste Management and Policy Enforcement Interaction

The interaction model presented in Table 10 examines whether enforcement of policy is associated with a stronger relationship between waste-management efficiency and environmental degradation. These results indicate the direction and the significance of the interaction effect of wast management efficiency and policy enforcement. The negative and statistically significant interaction term suggests that the effect of waste management and policy enforcement on environmental degradation combined is stronger than the effect of either one alone, indicating possible synergies of technical interventions and governance support.

Table 10. Interaction effect of waste-management efficiency and policy enforcement on environmental degradation.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
Waste mgmt. x policy	−0.005	0.001	−5.00	0.000	***
Socio-economic	0.0002	0.00003	6.67	0.000	***
Constant	0.750	0.015	50.00	0.000	***
R^2	0.872				
Adj. R^2	0.867				
F-statistics	142.75				

***p < 0.01, **p < 0.05, p < 0.1.

The regression results for factors affecting water quality and aquatic ecosystem condition are presented in Table 11. The model explained approximately 93.3% of the variation in water quality and aquatic ecosystem condition ($R^2 = 0.933$), indicating strong model fit. Plastics, organic waste, and heavy metals all had negative and statistically significant effects on water quality. Among the pollutant variables, heavy metals recorded the strongest negative coefficient ($\beta = -0.320$), suggesting that heavy-metal contamination was the most influential pollutant factor in the model. Policy enforcement showed a statistically significant positive effect, indicating that stronger governance response was associated with improved water quality and aquatic ecosystem condition.

Table 11. Regression estimates of pollutant effects on water quality and aquatic ecosystem condition.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
plastics	−0.00003	0.000004	−7.50	0.000	***
Organic waste	−0.450	0.075	−6.00	0.000	***
Heavy metals	−0.320	0.018	−17.78	0.000	***
policy	0.003	0.001	3.00	0.005	***
Constant	−0.550	0.105	−5.24	0.000	***

Continued

R^2	0.933				
Adj. R^2	0.926				
F-statistics	124.81			0.000	***

***p < 0.01, **p < 0.05, p < 0.1.

Table 12 presents the log-linear regression results for factors associated with mangrove loss across the study areas. The model explained approximately 88.5% of the variation in mangrove loss ($R^2 = 0.885$; adjusted $R^2 = 0.877$), indicating strong model fit. The overall model was statistically significant ($F = 92.34$, $p < 0.001$). The coefficient for ln(pollutants) was positive and statistically significant ($\beta = 0.920$, $p < 0.001$), indicating that higher pollutant levels were associated with increased mangrove loss. Waste management had a negative and statistically significant coefficient ($\beta = -0.950$, $p < 0.001$), suggesting that improved waste-management performance was associated with reduced mangrove loss. Socioeconomic pressure also had a positive and statistically significant effect ($\beta = 0.001$, $p < 0.001$), indicating that increasing socioeconomic pressure was associated with greater mangrove loss.

Table 12. Log-linear regression estimates of the effects of pollutants, waste management, and socioeconomic pressure on mangrove loss.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
ln (pollutants)	0.920	0.055	16.73	0.000	***
Waste mgmt.	−0.950	0.205	−4.63	0.000	***
Socio-eco	0.001	0.0001	10.00	0.000	***
Constant	0.500	0.150	3.33	0.002	***
R^2	0.885				
Adj. R^2	0.877				
F-statistics	92.34			0.000	***

3.5. Environmental Degradation and Fisheries Risk

Sierra Leone's fisheries sector is suffering heavily from environmental degradation. The results from Table 13 indicate a highly significant negative coefficient for degradation ($\beta = -980.5$, $p < 0.01$), with environment damages associated with a significant reduction in fish catch.

Table 13. Regression estimates of the impact of environmental degradation on fish catch.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
Degradation	−980.500	105.200	−9.32	0.000	***
Tourism rev.	−1.050	0.250	−4.20	0.000	***
Policy	2.100	0.850	2.47	0.018	**

Continued

Constant	1650.200	85.100	19.39	0.000	***
R^2	0.782				
Adj. R^2	0.768				
F-statistics	55.12				

***p < 0.01, **p < 0.05, p < 0.1.

This model introduces a powerful interaction term (*Waste_mgmt* x *policy*) to test whether the effectiveness of waste management is enhanced by policy support. The result revealed a highly significant negative coefficient ($\beta = -0.005$, $p < 0.01$) of a synergistic effect: the combination of waste management initiatives and supportive policy is far more effective in reducing degradation than either factor would be alone (Table 14).

Table 14. Regression estimates of environmental degradation and policy interactions on fish catch.

Variable	Coefficient	Std. Error	t-statistics	p-value	Significance
Degradation (lagged)	−980.500	105.200	−9.32	0.000	***
Tourism revenue	−1.050	0.250	−4.20	0.000	***
Policy enforcement	2.100	0.850	2.47	0.018	**
Waste_mgmt × Policy	15.200	3.400	4.47	0.000	***
Constant	1650.200	85.100	19.39	0.000	***
R^2	0.835				
Adj. R^2	0.818				
F-statistics	49.21				0.000

***p < 0.01, **p < 0.05, *p < 0.1. Note: The interaction term (Waste_mgmt x Policy) has been included to test if policy enforcement moderates the relationship between degradation and fisheries outcomes. The model is now augmented with all the variables in Model [5]. The interaction term tests for the synergies between waste management and governance in affecting fish catch.

3.6. Robustness Test Result

The core OLS findings were subjected to several robustness checks to ensure their validity. First, to control for unobserved time-invariant regional characteristics (the inherent environmental vulnerability of the Turtle Islands or the entrenched waste issues in Freetown), Fixed Effects (FE) and Random Effects (RE) panel models were estimated. The results (Table 15) showed that the significance and direction of the core variables, Waste management, Waste type, and Socio-economic, remain robust. The coefficient for waste management efficiency becomes slightly larger and more significant in the FE model ($\beta = -0.421$, $p < 0.01$), reinforcing the conclusion that improving waste systems is a powerful tool for reducing environmental degradation. The significant negative coefficient ($\beta = -0.455$, $p < 0.01$) provides stronger evidence for a causal interpretation: better waste management in one year leads to significantly less environmental degradation in the following year (Table 15).

Table 15. Robustness checks using ordinary least squares, fixed-effects, random-effects, and lagged waste-management models.

Variable	(1) OLS (Baseline)	(2) Fixed Effect (FE)	(3) Random Effect (RE)	(4) FE with Lagged Waste_mgmt
Waste management	-0.385^{***}	-0.421^{***}	-0.398^{***}	
	(0.092)	(0.085)	(0.088)	
L.Waste management				-0.455^{*}
				(0.091)
Waste type	0.011^{***}	0.010^{***}	0.010^{***}	0.010^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Policy	−0.001	0.000	−0000	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Socio-economic	0.0002^{***}	0.0002^{***}	0.0002^{***}	0.0002^{***}
	(0.00004)	(0.00003)	(0.00003)	(0.00003)
Constant	0.155^{**}	0.182^{**}	0.169^{**}	0.195^{***}
	(0.072)	(0.068)	(0.070)	(0.067)
Observations	45	45	45	42
R^2	0.901		0.925	0.928
No. of Groups		3	3	3
Hausman Test (p-value)			0.000	

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Standard errors in parentheses. Note: Model (4) uses the Note: Model (4) uses the waste_mgmt value from the previous year ($t - 1$) to explain the current degradation (t).

3.7. Summary of Qualitative Results

In Table 16, we summarized the main themes identified from key informant interviews, field observations, and open-ended survey responses. The qualitative results identify recurring themes relating to waste-management constraints, governance challenges, environmental degradation, and sectoral risks. These themes are used in the Discussion section to explain the mechanisms behind the quantitative findings.

Table 16. Summary of qualitative themes on solid waste management challenges, governance constraints, and sectoral impacts in coastal communities of Sierra Leone.

Theme	Main issue identified
Waste collection failure	Inadequate or irregular collection services.
Informal dumping	Waste disposal in drains, beaches, mangroves, or open spaces.

Continued

Weak policy enforcement	Limited monitoring, low compliance, weak institutional coordination.
Fisheries-related impacts	Pollution of landing sites, mangrove areas, and fishing grounds.
Tourism-related impacts	Beach litter, odour, reduced attractiveness, and public health concerns.
Community-based solutions	Local willingness to support clean-up, recycling, and awareness activities.

4. Discussion

4.1. Overview of the Main Findings

This study examined how solid waste mismanagement contributes to coastal environmental degradation and sectoral risks to fisheries and tourism in Sierra Leone. The findings provide evidence of a linked socio-ecological problem in which weak waste-management systems, plastic-dominated waste streams, socioeconomic pressure, and uneven governance response combine to degrade coastal and marine environments. Within the DPSIR framework, the results show a coherent pathway: socioeconomic activities and waste generation operate as drivers; poor disposal, uncollected waste, and plastic leakage act as pressures; water contamination, heavy metal pollution, plastic accumulation, and mangrove loss represent changes in environmental state; and the resulting impacts are reflected in risks to fisheries, tourism, public health, and coastal livelihoods.

The high environmental degradation index, low waste-management efficiency, high plastic-waste share, and sizeable policy implementation gap indicate that the waste problem in Sierra Leone's coastal zone is not only an environmental problem, but also a governance and development challenge. This is consistent with global evidence that land-based waste mismanagement is a major contributor to marine plastic pollution, especially where collection, disposal and recycling systems are weak [4] [5] [21]. It also supports the study's main argument that the protection of fisheries and tourism in Sierra Leone cannot be divorced from the reform of coastal solid waste governance.

4.2. Waste Management, Plastic Dominance, and Socioeconomic Pressure as Drivers of Degradation

The baseline model of environmental degradation showed associations in line with the hypothesis of the influence of waste management practices on the environmental conditions of the coast. More efficient management of higher waste was associated with a lower rate of environmental degradation, while waste streams dominated by plastics and socioeconomic pressure were associated with a higher rate of degradation. This pattern is likely to reflect processes in coastal environments where household waste, market waste, waste from tourism and waste from fisheries are discharged into waterways thru open dumping, blocked drains, riverine transport and informal disposal practices.

The positive association between socioeconomic pressure and degradation is particularly relevant for the Freetown Peninsula, where urban density, commercial activity, tourism, fishing, and waste flows associated with drainage converge. However, this association should not be interpreted as evidence that economic activity is inherently harmful. Rather, it suggests a pattern where economic and population pressures may be associated with intensifying environmental degradation when waste infrastructure and enforcement capacity lag behind development pressures. The relatively small direct coefficient for policy enforcement in the baseline degradation model is noteworthy. This does not imply that policy is irrelevant. Rather, it suggests that the existence of regulations alone may not be sufficient when enforcement, monitoring, infrastructure, financing, and local compliance mechanisms remain weak.

4.3. Water Quality and Aquatic Ecosystem Condition

Water-quality modelling showed that plastics, organic waste and heavy metals had a negative and significant association with water quality and aquatic ecosystem condition, while policy enforcement had a positive effect. This result is ecologically plausible as these groups of pollutants affect aquatic systems through different but complementary mechanisms. Plastic waste affects coastal and aquatic systems through physical blocking, ingestion, entanglement, habitat smothering and fragmentation into microplastics [22] [23]. Organic waste can increase biological oxygen demand and nutrient loading that can deplete oxygen, cause eutrophication, and reduce habitat quality for aquatic organisms. Heavy metals are of special concern because they tend to build up in sediments, to bioaccumulate through food webs, and to pose long-term risks to aquatic organisms and to people who eat fish and shellfish. The strong negative coefficient for heavy metals should be interpreted cautiously but seriously. The result indicates that heavy metal contamination is an important component of water-quality deterioration in the study sites. The primary factors for this kind of contamination may include urban runoff, informal waste disposal, industrial residues, mining-related runoff, boat maintenance, and contaminated sediments.

In Sierra Leone, artisanal and small-scale gold mining has been recognized as a sector associated with mercury-use risks, and therefore mining-related heavy metal transport through river systems may be one possible pathway where hydrological connectivity exists [24]. However, the present study should avoid attributing heavy metal pollution to any single mining area unless source-tracing data, catchment-level sampling, or geochemical fingerprinting are available. The positive effect of policy enforcement in the water-quality model suggests that targeted governance interventions may be more effective for specific environmental outcomes than for general degradation. This may occur where water monitoring, community clean-up, basin-level interventions, NGO-supported programmes, or local environmental rules are more visible and enforceable than broad waste-management laws. This result strengthens the argument that governance should be evaluated not only by whether policies exist, but also by whether they are targeted, resourced, monitored, and locally accepted.

4.4. Pollution and Mangrove Loss

The positive association between pollutants and mangrove loss ca be viewed and underscored that waste pollution may trigger mangrove degradation by interfering with root systems, diminishing sediment quality, elevation of toxic contamination, and metamorphous water exchange. Plastic debris can also collect in the root structures of mangroves and, at high coverage levels, can impact on the survival and canopy condition of mangroves [25] [26]. Sediment chemistry and oxygen availability can also affect organic waste and nutrient enrichment, and heavy metals may be retained in mangrove sediments and plant tissues, which will increase ecological stress within mangrove systems [27] [28].

The positive effect of socioeconomic pressure further suggests that pollution is not the only driver of habitat loss, but rather, settlement expansion, resource extraction, coastal development, and weak waste-control systems may act in concert to accelerate mangrove degradation [29] [30]. This result has immediate relevance to fisheries because mangroves provide nursery habitats, refuge areas, feeding grounds and other ecosystem services that support fish recruitment and coastal fisheries productivity [30] [31]. In this regard, the loss of mangroves can reduce fisheries productivity and increase the vulnerability of households dependent on fisheries [1] [2]. In this sense, the loss of mangroves links environmental degradation with socioeconomic risk. It's not just a biodiversity problem, but a food security, livelihood and coastal resilience problem.

4.5. Environmental Degradation and Fisheries Risk

The fisheries model showed a robust negative association between environmental degradation and fish catch. This finding is consistent with the study's premise that degradation of coastal and aquatic systems may have measurable socioeconomic implications for fishery-dependent populations Degradation is associated with fisheries risk via multiple pathways. It is worth noting that plastics and debris can damage fishing grounds and gear and poor water quality has the tendency to reduce the availability of suitable habitats for both fish and invertebrates. Degradation of mangroves may reduce nursery habitat, and heavy metals or microplastics can negatively affect seafood safety and market value. These methods have been used and it is in line with international research (for e.g., [7] [22] [23]) that shows marine debris impacts marine species through ingestion, entanglement, habitat alteration and chemical exposure. The results therefore support the view that waste management should be seen as part of fisheries governance and not simply as an urban sanitation problem.

The negative coefficient of tourism revenue in the fish-catch model should be read with caution. This does not necessarily mean that tourism directly decreases fish catch. Instead, it might indicate that tourism activity is in more developed or environmentally stressed coastal areas where fisheries are also affected by habitat loss, beach development, pollution and competition for coastal space. Our findings corroborate with the broader literature on coastal-zone management, thus, an indication that fisheries sector, tourism, settlement and environmental protection often compete for the same coastal resources in the absence of integrated planning [1] [30].

The positive effect of policy in the fisheries model suggests that governance can play a protective role where enforcement, habitat protection, community participation, and fisheries management are active. This is consistent with evidence from fisheries co-management research showing that leadership, social capital, incentives, and local institutional arrangements contribute to better ecological and social outcomes in fisheries [32]. For Sierra Leone, this suggests that fisher-led waste reduction, landing-site sanitation, gear-recovery programmes, mangrove protection, and community monitoring could be important components of fisheries-risk reduction.

4.6. Tourism Risk and Coastal Attractiveness

Qualitative findings identified beach litter, odour, reduced attractiveness, and public health concerns as tourism-related impacts. These perceptions are consistent with the quantitative evidence showing high environmental degradation and low waste-management efficiency.

This relationship is well established in the broader marine pollution literature. Marine plastic pollution diminishes the delivery of ecosystem services and has adverse implications for recreation, heritage, fisheries and human wellbeing [6]. Plastic pollution also has ecological and socioeconomic costs in coastal environments, including reduced amenity value and threats to marine organisms [7]. In the case of Sierra Leone, this is particularly the case of the Freetown Peninsula where tourism facilities, fishing communities, settlements and beach recreation overlap. A polluted beach is not only an environmental problem, but also affects the visitor experience, business confidence, public health and the competitiveness of coastal tourism.

The issue of tourism risk is different for Sherbro Island and the Turtle Islands. While these regions may not presently have the same level of tourism as the Freetown Peninsula, their future tourism potential is strongly tied to ecological quality, remoteness, clean beaches, biodiversity and cultural value. If waste accumulation and marine debris are not addressed early, tourism development may reproduce the same degradation cycle seen in more urbanised coastal zones. This reinforces the need for preventive waste governance rather than reactive clean-up after degradation has already reduced tourism value.

4.7. Governance, Policy Enforcement, and the Waste-Management Interaction Effect

The study found a strong negative interaction term between policy enforcement and waste-management efficiency. This pattern suggests that policy enforcement may enhance the association between waste-management systems and environmental outcomes. This finding has policy relevance, as it may help explain why technical solutions may not achieve their intended effects when implemented without adequate governance support.

This result is consistent with the ecological modernization theory that suggests that environmental improvement requires not only technology but also institutional innovation, regulatory reform and multi-stakeholder collaboration [33]. This is consistent with findings from waste governance in developing country contexts that infrastructure investments provide better results when combined with institutional capacity, formal recognition of informal waste actors, and enforceable regulatory frameworks [34] [35]. In Sierra Leone, where informal waste handling, community clean-ups, and weak municipal services coexist, the interaction result suggests that the most effective interventions will be those that combine infrastructure, enforcement, and local participation.

The qualitative themes support this interpretation. Respondents identified irregular collecting services, informal dumping, weak policy enforcement, pollution of landing sites and beaches, and community willingness to participate in clean-up and recycling activities. The themes show that coastal communities are not passive victims of pollution but potential partners in waste governance. Nevertheless, community involvement needs institutional backing, reliable services and incentives. Without these, the level of awareness of community people may not translate into sustained behavioural change.

4.8. Context-Specific Implications for Freetown Peninsula, Sherbro Island, and the Turtle Islands

The comparative design of the study shows that Sierra Leone's coastal waste problem is not uniform. The Freetown Peninsula reflects an urban and peri-urban waste-pressure model, where population density, markets, tourism, fishing, drainage systems, informal settlements, and beach recreation combine to generate high waste loads. This interpretation is in line with earlier assessments of Freetown which have characterized weak collection systems, unmanaged dumpsites, illegal dumping, clogged drains, and constant transport of waste via watercourses into the sea [36] [37]. The World Bank's circular economy assessment for Sierra Leone's tourism sector also notes that tourism-related single-use plastics remain a major challenge, with poor recycling capacity and plastic leakage associated with weak community-level waste-management systems [3]. For the Freetown Peninsula, therefore, priority should be given to infrastructure-led waste management, including regular household and commercial waste collection, drainage waste traps, beach-waste regulations, formal recycling channels, and stronger enforcement around tourism, markets, fishing landing sites, and commercial zones.

Recent implementation examples also suggest that decentralized and livelihood-linked waste models can support urban waste governance in Freetown. The Freetown Waste Management Micro-Enterprise Programme enabled youth-led waste collection using tricycles, created jobs and registered households for waste collection and contributed to the reduction of illegal dumping in informal settlements [38]. Similarly, GOAL's coastal waste and livelihoods initiative partnered with beach cleaners, fish sellers, recycling companies and coastal communities around areas such as Lumley Beach, Aberdeen and Wan Pole, combining waste sorting, protective equipment, livelihood support and recycling partnerships (GOAL, 2026). These examples support the argument that Freetown's waste response should not rely only on municipal collection but should also integrate community groups, private recyclers, youth enterprises, tourism operators, and beach-cleaning groups into a coordinated coastal waste-management system.

Sherbro Island represents a rural fishery-dependent model, where waste-management gaps interact with mangrove degradation, fishing activities, weak collection services, and limited institutional presence. In this context, highly centralized municipal waste systems are unlikely to be sufficient. Community-based waste systems may be more appropriate especially where waste is associated with fishing activities, household disposal practices, mangrove utilization and local market activities. Practical interventions might be fisher-led gear retrieval schemes, community waste hubs, mangrove clean-up programmes, local recycling initiatives and the integration of waste management into fisheries and mangrove governance. An example study that is relevant to this present study demonstrates how coastal waste interventions can be linked to livelihood support, waste sorting, recycling partnerships and community stewardship, rather than being treated as purely a sanitation issue [39].

The Turtle Islands reflect a remote-island waste-governance model. In such settings, local waste generation may be relatively low compared with urban centres, but formal collection services are weak, waste evacuation is difficult, and marine debris may arrive from outside the local community through tides and currents. The appropriate strategy is therefore different from Freetown and Sherbro Island. Periodic waste evacuation, marine-debris monitoring, community storage points, beach-cleaning support, NGO-government partnerships, and regional cooperation are likely to be more effective than conventional urban collection systems. Because remote islands often lack the scale needed to sustain formal recycling markets, waste strategies should focus on prevention, separation, safe temporary storage, removal of non-biodegradable waste, and support for local monitoring.

This context-specific interpretation is central to the study's contribution. It shows that a single national waste policy will not be sufficient unless it is translated into differentiated strategies for urban, rural, and remote coastal systems. For Freetown, the priority is infrastructure, enforcement, drainage management, and integration of informal and private waste actors. For Sherbro Island, the priority is community-based waste governance linked to fisheries and mangrove protection. For the Turtle Islands, the priority is remote-island waste evacuation, marine-debris monitoring, and partnership-based support. This is consistent with the DPSIR framework, which requires that responses be matched to the specific drivers, pressures, environmental states, and impacts of each socio-ecological context.

4.9. Contribution to Coastal Waste Governance and Blue-Economy Policy

The study contributes to coastal environmental management by linking solid waste mismanagement to environmental degradation and sectoral risks in fisheries and tourism. Many waste studies focus either on pollution levels or on waste-management behaviour. This study adds value by connecting waste-management efficiency, plastic dominance, socioeconomic pressure, water quality, mangrove loss, fish catch, tourism risk, policy enforcement, and qualitative governance evidence within one DPSIR-based framework.

For blue-economy policy, the implication is clear: fisheries and tourism cannot be sustainably developed if coastal waste systems remain weak. Waste management should therefore be integrated into fisheries management, tourism planning, coastal-zone management, and local government development plans. This requires moving from fragmented projects to coordinated coastal waste governance. Specific priorities include formalising and supporting informal waste actors, enforcing disposal regulations, expanding waste collection to coastal and island communities, protecting mangroves as fishery-supporting habitats, and linking tourism development to beach and drainage waste control.

4.10. Limitations and Future Research

The findings of this study should be interpreted in light of several important limitations. First, although the panel structure provides useful site-year evidence, the number of study regions is small (n = 3), and the findings should be interpreted as associations rather than definitive causal estimates. The observational design does not permit the same level of causal inference as a controlled experiment or a quasi-experimental design with a larger number of sites. The associations identified are consistent with the proposed pathways, but alternative explanations cannot be fully ruled out without additional research.

This study has several limitations. First, although the panel structure provides useful site-year evidence, the number of study regions is small, and the findings should be interpreted as strong associations rather than definitive causal estimates. Second, some socioeconomic variables for recent years were projected, and these values should be treated cautiously in interpretation. Third, while the heavy metal results are important, source attribution requires more detailed catchment-level sampling, sediment analysis, and pollutant-source tracing. Fourth, tourism impacts were partly captured through perceived risk and available indicators; future research should include more direct measures of visitor numbers, tourism revenue, beach-user perceptions, and business-level losses.

Future studies should extend environmental monitoring across more coastal communities and include seasonal sampling to capture rainy-season runoff, dry-season concentration effects, and changes in waste transport. Additional research should also examine microplastics in fish, sediment, and water samples; quantify the economic cost of beach pollution to tourism; and evaluate the effectiveness of specific interventions such as community waste hubs, plastic buy-back schemes, fisher-led gear-recovery programmes, and mangrove restoration. Such work would strengthen the evidence base for integrated coastal waste management and blue-economy planning in Sierra Leone.

5. Conclusions

This study assessed the associations between solid waste management, coastal environmental degradation, and risks to fisheries and tourism in Sierra Leone. Findings from a DPSIR-based mixed-methods approach implemented across the Freetown Peninsula, Sherbro Island, and the Turtle Islands reveal patterns consistent with the interpretation that weak waste-management systems, plastic-dominated waste streams, limited policy implementation, and socioeconomic pressures are important factors associated with ecosystem decline.

High levels of degradation, low efficiency in waste management and important policy gaps underline the mounting pressure on coastal ecosystems. Less environmental degradation is associated with increased waste management efficiency, whereas plastic waste and socio-economic pressures lead to more environmental degradation. Pollution of the water by plastics, organic waste and heavy metals degrades water quality and destroys mangroves. Environmental degradation impacts directly fisheries and tourism. It endangers fish stocks, fishing grounds and mangrove habitats and diminishes beach quality and the attractiveness of the coast for tourism. Our finding underscores the need for effective waste governance and ecosystem protection for sustainability of the fisheries and tourism sector in Sierra Leone.

Our study also finds that stringent policy enforcement, institutional coordination and community participation increase the effectiveness of waste management interventions. Infrastructure alone is not enough without governance capacity and public compliance. Finally, our present study stresses the need for context-specific solutions: infrastructure and enforcement in urban settings, community-based systems in rural areas, and adaptive strategies for remote islands. Integrated coastal waste governance is critical for the protection of ecosystems, livelihoods and a resilient blue economy in Sierra Leone.

Author Contributions

Each mentioned author materially, directly, and intellectually contributed to the work and consented to its publication. Conceptualisation, K.V. and R.A.S.K.; Methodology, R.A.S.K., and K.V; Formal Analysis, R.A.S.K., and M.S.B.; Writing—Original Draft Preparation, R.A.S.K; Writing—Review and Editing, R.A.S.K., and M.S.B.; Supervision, K.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table S1. Supplementary indicator matrix.

Index	Indicator (Variable)	Raw Measure	Source	Standardisation Method	Weight	Reliability/ Adequacy
Environmental Degradation	Degradation	Composite index (0 - 1)	Derived from multi-indicator model	Min-Max scaling	0.15	High (composite validated)
Waste Management	Waste_mgmt	Index (0 - 1; efficiency score)	Municipal records/survey	Min-Max (inverse where needed)	0.12	Medium (data gaps in SL context)
Waste Composition	Waste_type	% composition of dominant waste stream	Field audit/waste characterization studies	Z-score	0.08	Medium
Policy & Governance	Policy	Policy effectiveness index (0 - 100)	Govt reports/EPA assessments	Min-Max	0.07	Medium
Socioeconomic Conditions	Socio_eco	Income/expenditure proxy (USD/year)	Household surveys (e.g., SLIHS)	Log transform + Z-score	0.10	High
Climate Driver	Rainfall	Annual rainfall (mm/year)	Meteorological agency	Z-score	0.05	High
Economic Indicator	GDP per Capita	USD per capita	World Bank/Stats SL	Log transform + Z-score	0.08	High