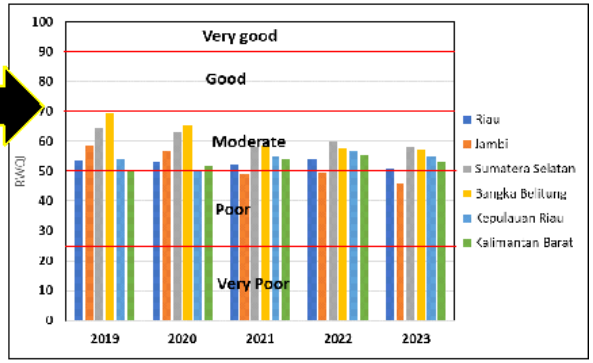
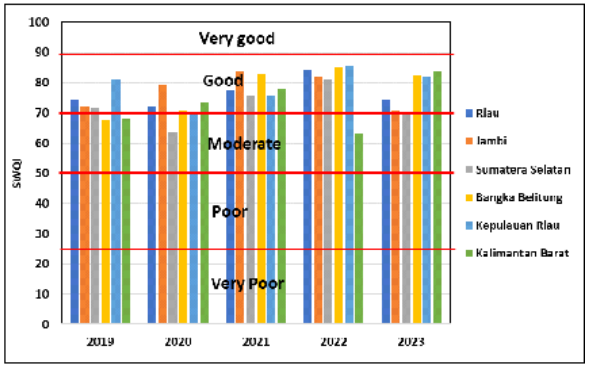
KEY FINDINGS

- Land-based pollution dominance
  poor to moderate RWQI
- IKAL (marine index)
  moderate to good,
  but with declining tred
- Hotspots:
  Bintan & Batam
- E coli
  microplastics





RISK RANKING

Oil pollution
Marine debris
Nutrients

RECOMMENDATIONS

Regional coordination
Stronger waste infrastructure
Mantime enforcement
Integrated risanbondary governance

The status and recent management of the marine pollution in the waters of the Indonesian part of the South China Sea

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Abstract

The South China Sea (SCS) represents a critical ecological and economic region for Indonesia, supporting fisheries, energy, and trade. However, it faces escalating environmental degradation driven by land-based and marine pollution. This paper examines pollution dynamics across Indonesia's SCS provinces—Riau, Riau Islands, Bangka Belitung, South Sumatra, and West Kalimantan—covering the period 2019–2024. Using national environment statistics and risk assessment analysis, five major pollution sources were evaluated: aquaculture waste, agricultural runoff, hazardous waste, domestic solid and liquid discharges, and oil pollution. Results indicate that land-based pollution dominates, with rivers such as the Kapuas and Batanghari transporting large nutrient and organic loads into coastal waters. The River Water Quality Index (RWQI) remains in poor to moderate categories, while Marine Water Quality Index (IKAL) scores range from moderate to good, with recent declines. Oil sludge strandings along Batam and Bintan beaches pose the highest transboundary risk, disrupting tourism and damaging mangroves and coral reefs. Plastic debris and microplastics also persist across coastal habitats, while domestic wastewater contributes localized E. coli contamination. Risk mapping identifies oil pollution as high-priority issues, followed by moderate risks from marine debris and nutrients. Institutional coordination involves multiple ministries and provincial governments but remains fragmented. The study recommends enhanced regional cooperation, particularly through ASEAN, strengthened waste management infrastructure, stricter maritime enforcement, and public awareness programs. Integrated transboundary governance is essential to safeguard Indonesia's SCS ecosystems and sustain coastal livelihoods.

Keywords : pollution; the South China Sea; oil sludge; plastic debris; marine debris; domestic waste

1. Introduction

The South China Sea (SCS) is one of the world's most strategic and ecologically important seas, rich in biodiversity, fisheries, and energy resources that support millions of livelihoods and global maritime trade (**Teh et al., 2017; Meierding, 2017**). For Indonesia, the northern waters around the Natuna Islands, within its Exclusive Economic Zone (EEZ), serve as a vital resource base and ecological frontier (**Pramono, 2023; Aziz et al., 2020)**. However, the region faces increasing environmental stress, primarily from land-based and marine pollution, which threatens marine ecosystems, food security, and coastal welfare. Pollution in the SCS

has intensified due to rapid coastal development, urbanization, overfishing, and weak environmental governance (**Xiao et al., 2022; McManus (2017)**.

In Indonesia, land-based pollution dominates, contributing 70–80% of total marine pollutants (**Dsikowitzky et al., 2018; Sianipar et al., 2022; Damar et al., 2020**). Major sources include untreated sewage, industrial discharges, agricultural runoff, and plastic waste entering the sea from Sumatra, Kalimantan, and Java through rivers and estuaries. These pollutants degrade water quality, coral reefs, mangroves, and seagrass beds, which are critical habitats for fisheries and tourism.

Plastic waste represents the most visible and persistent pollutant. As the world's second-largest contributor of ocean plastics (**Jambeck et al., 2015**), Indonesia releases large volumes of debris into semi-enclosed seas like the SCS. This waste breaks down into microplastics, which harm marine life, contaminate seafood, and threaten the livelihoods of small-scale fishers in Natuna. Meanwhile, agricultural and aquaculture runoff triggers eutrophication, resulting in algal blooms and oxygen-depleted zones that damage coral reefs and marine biodiversity (**Zheng et al., 2023**).

Marine-based pollution also remains significant. Heavy shipping traffic in the SCS leads to frequent oil spills and oil sludge, particularly near Bintan and Batam, where recurring oil contamination, often linked to ship tank-cleaning activities in the Strait of Malacca, has persisted for years (**Sahputra, 2024**).

This paper aims to comprehensively examine the status of the land-based pollution in the Indonesian part of the South China Sea (SCS) region (Figure 1), including the major forms of pollution, their impacts on ecosystems and economy. The paper concludes with a set of recommendations in the form of a strategic action plan, which is expected to serve as a reference for pollution management in Indonesia, particularly within the SCS region.

Figure 1. South China Sea Indonesia's part (red box)

2. Key Pollution Concerns

The Indonesian part of the South China Sea (SCS) is located in the country's western maritime region (Figure 1), bordered by eastern Sumatra (Riau and Riau Islands Provinces), the Bangka Belitung Islands to the south, and West Kalimantan to the east. This semi-enclosed sea comprises numerous small islands, straits, and shallow shelves forming part of the Sunda Shelf, including key ecological areas such as the Natuna Sea**,** Anambas Islands**,** and Karimata Strait. These waters, relatively less urbanized than other Indonesian coasts, sustain diverse marine ecosystems and play crucial roles in fisheries, hydrodynamics, and maritime transport (**Yulianto et al., 2019**).

Coastal provinces show distinct economic patterns influencing marine conditions. Riau Province (6.86 million people) depends on oil, gas, forestry, and plantations, particularly palm oil and rubber, generating both economic benefits and environmental stress. The Riau Islands (2.18 million) center around Batam, a major manufacturing and logistics hub linked to Singapore, while smaller islands rely on fisheries and tourism. Further south, the Bangka Belitung Islands (1.51 million) are shifting from tin mining to tourism and agriculture, while West Kalimantan (5.62 million) is dominated by forestry, mining, and plantations (Indonesian Statistics, 2024).

3. Current Status by indicator group

3.1. Pollution Sources and Magnitude

3.1.1. Aquaculture-generated Pollution

The estimation of the pollution load generated by aquaculture activities is approached trough the total aquaculture production volume multiplied by its Feed Conversion Ratio (FCR). It is generally assumed that approximately 25% of the total feed input is released as organic waste, contributing to nutrient enrichment and potential degradation of the surrounding aquatic environment (detail method is presented at **App.1**). South Kalimantan consistently records the highest aquaculture-derived waste (>30,000 tonnes yr^{-1} since 2020), reflecting intensive pond and cage culture with limited feed conversion efficiency. West Kalimantan follows with 20,000–22,000 tonnes yr^{-1}, indicating sustained production and feed loss. The Riau Islands exhibit greater variability (6,000–8,000 tonnes yr^{-1}) with a sharp increase in 2023, whereas Bangka Belitung remains below 5,000 tonnes yr^{-1}. These spatial disparities suggest that highly intensive systems disproportionately contribute to nutrient loading, emphasizing the need for improved feed management and ecosystem-based aquaculture governance (Figure 2).

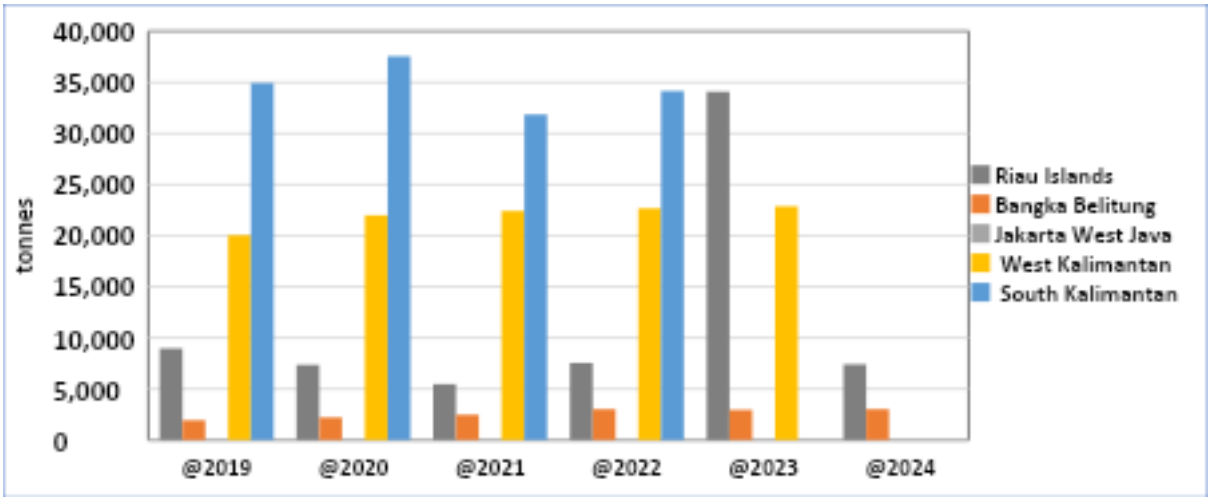

Figure 2. Estimates of total volume (tonnes) of uneaten feed (become waste) Aquaculture (tonnes) in several provinces in the area around the SCS from 2019 to 2024 (source: Indonesia Fisheries Statistics 2020, 2021, 2022, 2023, 2024).

3.1.2. Agricultural-generated Pollution

The primary pollutants derived from agricultural activities are associated with fertilization use. Fertilizer application introduces organic matter and nutrient loads into receiving water bodies, which can drive eutrophication processes.

The data (Figure 3) indicate that South Sumatra consistently contributes the highest volume of urea fertilizer used from 2019 to 2023, peaking in 2020 and gradually declining thereafter. West Kalimantan shows moderate but stable levels, while Riau Islands and Jambi exhibit lower yet increasing trends until 2021–2022 before declining in 2023. Bangka Belitung remains comparatively low and decreases sharply in 2023. Overall, the chart reflects spatial variability among provinces and a general downward trend after 2020, suggesting changes in pollutant inputs, management effectiveness, or reporting accuracy.

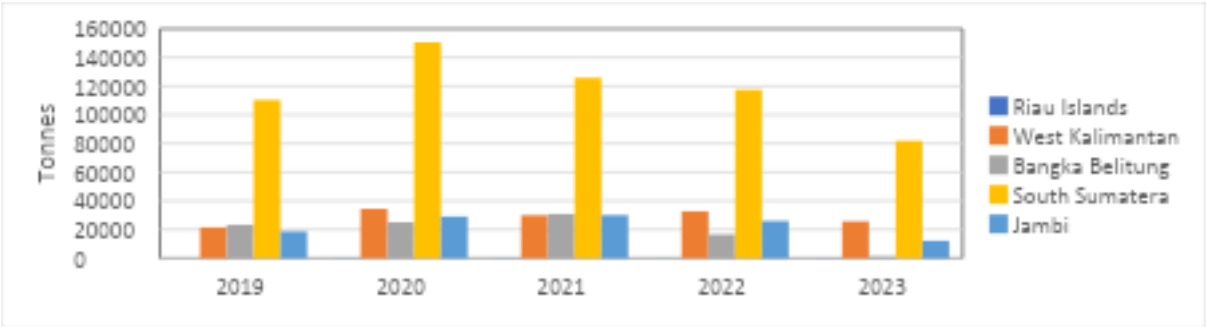

Figure 3. Distribution of subsidized urea fertilizer in the agricultural sector (tonnes) in the provinces adjacent to SCS area (source: Environment Statistics of Indonesia 2020, 2021, 2022, 2023, 2024)

3.1.3. Hazardous Waste and Heavy Metals Pollution

The chart (Figure 4) illustrates the annual generation of hazardous (B3) waste across five provinces, Riau Islands, West Kalimantan, Bangka Belitung, South Sumatra, and Jambi, from

2019 to 2023. Overall, the data show moderate fluctuations but a generally increasing trend in hazardous waste production across most provinces.

In the Riau Islands, B3 waste rose from about 82 tonnes in 2019 to a peak of approximately 84 tonnes in 2022, before decreasing slightly in 2023. West Kalimantan exhibited a steady increase from roughly 68 tonnes in 2019 to more than 82 tonnes in 2023, indicating a consistent upward trajectory. Bangka Belitung followed a similar pattern, increasing from around 67 tonnes in 2019 to over 84 tonnes by 2022, although values stabilized in 2023.

South Sumatra showed relatively stable levels, ranging between 63 and 81 tonnes, with a gradual rise through 2022 before a slight decline in 2023. Jambi demonstrated moderate variability, increasing steadily from 71 tonnes in 2019 to approximately 81 tonnes in 2022, followed by a reduction in 2023.

Overall, the provinces exhibit converging waste volumes over time, with West Kalimantan and Bangka Belitung showing the most pronounced growth.

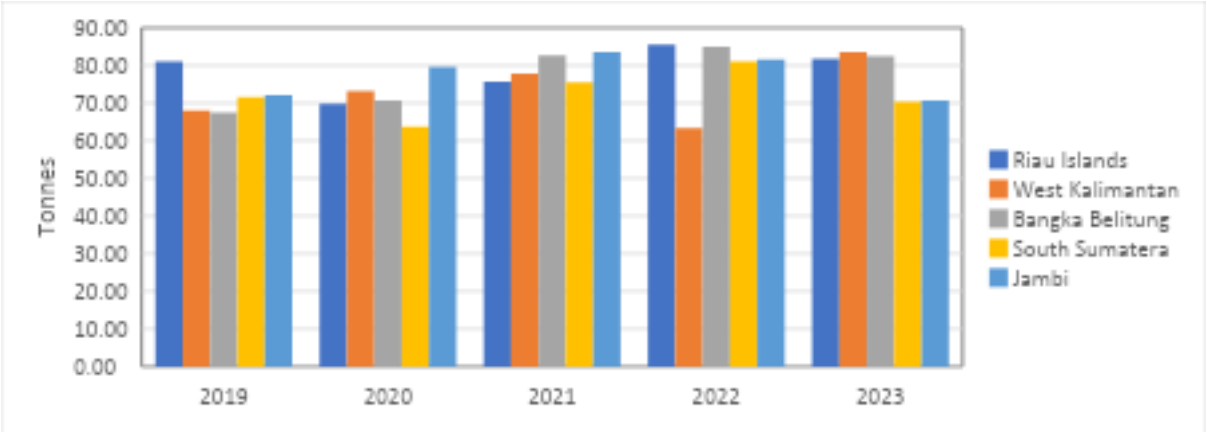

Figure 4. Volume of hazardous waste (B3) Tonnes from each of the provinces in the SCS region (source: Environment Statistics of Indonesia, 2020, 2021, 2022, 2023, 2024)

3.1.4. Domestic Liquid Waste and Solid Waste

The estimation of liquid waste was derived from calculations of the organic pollution load transported by major rivers discharging into the South China Sea (see **App. 2** for methodological details). The South China Sea (SCS), particularly the Indonesian sector, also receives discharges originating from land-based activities, specifically from Sumatra, Bangka Belitung, and West Kalimantan. The terrestrial pollution load enters the SCS through several rivers, including the Musi River (South Sumatra), the Siak River (Riau), the Batanghari River (Jambi), rivers in Bintan, and the Kapuas River (West Kalimantan). Figure 5 presents the discharge volumes of each of these rivers.

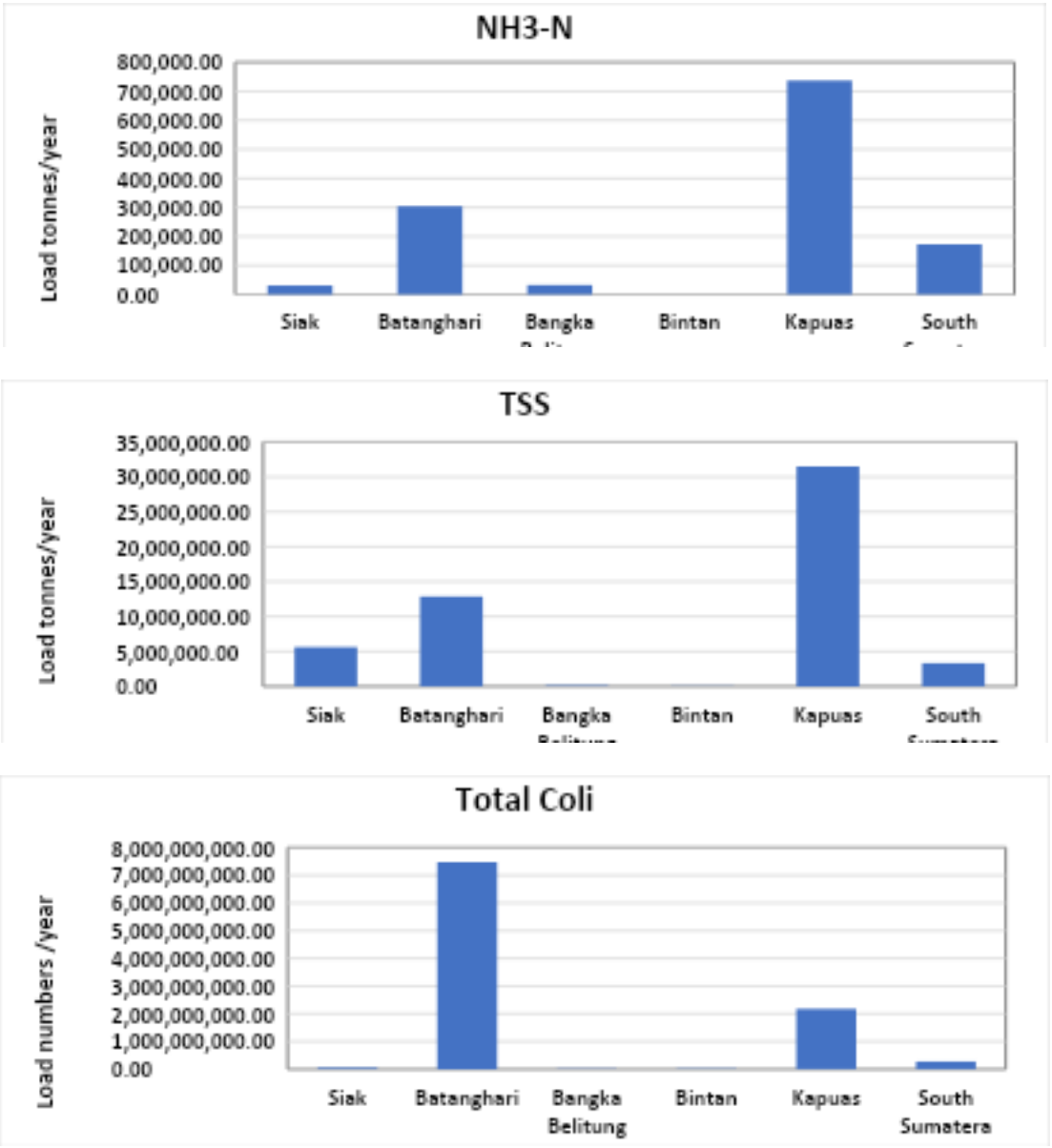

Figure 5. Annual riverine pollutant loads of NH_3-N (upper chart), TSS (middle chart) and Total Coliform (lower chart) of each river into South China Sea waters (source: data analysis 2025)

Riverine organic pollution load analysis in the South China Sea (SCS) indicates that the Kapuas River (West Kalimantan) contributes the highest NH_3-N load (~700,000 tonnes yr^{-1}), followed by the Batanghari River (Jambi, ~300,000 tonnes yr^{-1}) and South Sumatra (<200,000 tonnes yr^{-1}). The Siak and Bangka Belitung rivers show lower loads (<50,000 tonnes yr^{-1}), while Bintan records negligible levels. Similar patterns occur for TSS and coliforms, reflecting spatial variation driven by watershed scale, land-use intensity, and anthropogenic inputs across SCS river systems.

Solid waste generation across South China Sea–bordering provinces in 2022–2023 showed pronounced spatial variation. Kota Batam (Riau Islands Province) recorded the highest waste load (>400,000 tonnes yr^{-1}), followed by Kota Pontianak (West Kalimantan Province) and Musi Banyuasin (South Sumatera Province), while smaller municipalities such as Lingga,

Karimun (Riau Islands Province), and Bangka Tengah produced <50,000 tonnes yr^{-1}. Provincial totals were greatest in Riau Islands and West Kalimantan (Figure 6). Between 2022 and 2023, Batam, Pontianak, and Bangka Selatan experienced waste increases linked to urban and industrial growth, whereas Musi Banyuasin and Ogan Komering Ulu Timur showed slight declines, indicating improved collection efficiency or waste reduction efforts.

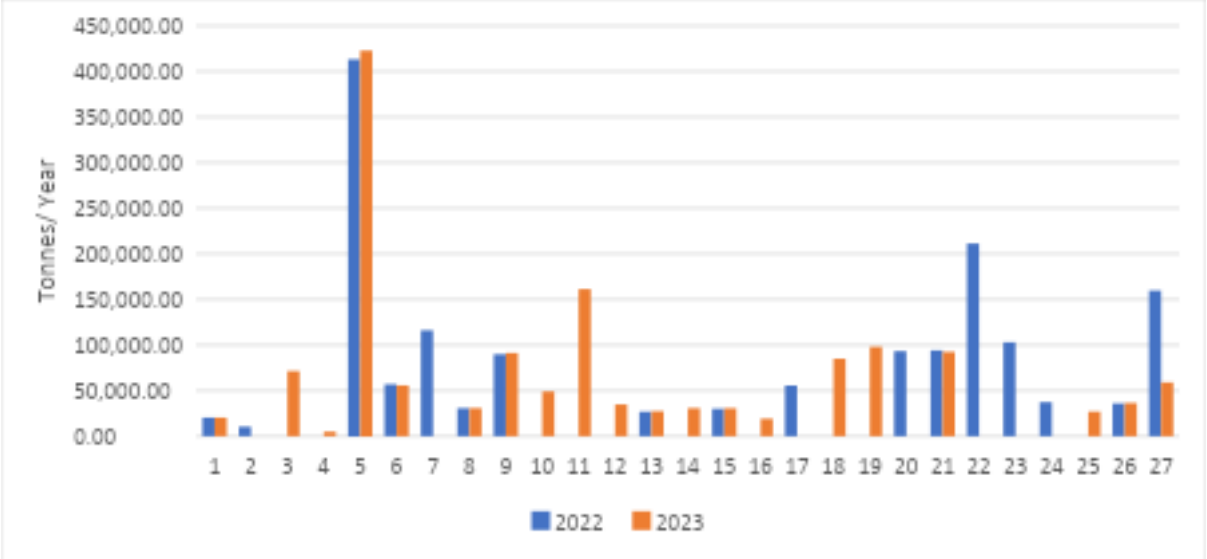

Figure 1 Annual solid waste generation based on municipality, regencies and provinces 2022-2023 (source: Environment Statistics of Indonesia, 2020, 2021, 2022, 2023, 2024).

3.1.5. Oil Pollution

A recurrent major oil pollution event identified in the study area is the stranding of oil sludge along the northern coast of Bintan Island, likely originating from ship tank-cleaning operations in adjacent international waters. These incidents consistently occur during the northeast monsoon, when prevailing currents transport pollutants southward, resulting in the accumulation of residues along Bintan's shoreline. The seasonal regularity of these events suggests strong hydrodynamic influence and highlights the need for enhanced regional monitoring and stricter enforcement of maritime waste discharge regulations. The stranding of oil sludge along the northern coast of Bintan Island has caused significant losses, particularly to marine tourism activities in the area. The recurring contamination has disrupted beach operations, reduced visitor numbers, and negatively affected the overall attractiveness and economic value of the coastal tourism sector (**Purnaweni et al., 2022**).

3.1.6. Atmospheric Pollution

Atmospheric and deposition studies across the South China Sea (SCS) region reveal distinct pollution dynamics modulated by climatic variability. Observations at Taiping Island and SCS cruises reported GEM concentrations of ~1.3–1.5 ng m^{-3}, with RGM and particulate Hg in the pg m^{-3} range (Yeh et al., 2021; Wang et al., 2019). Acid deposition and particulate matter levels increase notably during ENSO and biomass-burning periods, especially in Sumatra and West Kalimantan (Budiwati et al., 2016; Kusumaningtyas, 2013). Elevated Pb, Cd, and As levels in Natuna's coastal sediments (Rahayu et al., 2016) and persistent high

$PM_{2.5}$ concentrations over the Indonesian Maritime Continent (Napitupulu et al., 2024) highlight the combined influence of regional emissions, monsoon-driven transport, and interannual climate variability on atmospheric and coastal pollution.

3.2. Pollution Hotspots and Sensitive Areas

3.2.1 River Pollution Level

From the compilation of secondary data derived from monitoring activities conducted by the environmental agencies of each province, the following detailed data have been obtained (Environmental statistics of Indonesia, 2020-2024). The methods of the River Water Quality Index analysis is described in the **App. 3** involving water quality parameters such as pH, BOD, COD, TSS, DO, NO_3-N, total phosphate, and fecal coliform.

Figure 7 shows that the River Water Quality Index (RWQI) for six South China Sea–bordering provinces (2019–2023) ranged from poor to moderate, reflecting persistent pollution pressures. Bangka Belitung recorded the highest scores (65–70, moderate), while South Sumatra showed moderate but slightly declining quality. Jambi exhibited the poorest conditions (<50), likely due to domestic and agricultural discharges, as reflected by the high values of the total fecal coliform microbial parameter. Riau, Riau Islands, and West Kalimantan remained borderline poor–moderate (50–60), indicating continued urban and wastewater stress. A slight overall decline from 2022–2023 suggests worsening river conditions. No province achieved good status, underscoring the need for strengthened wastewater management and pollution control measures.

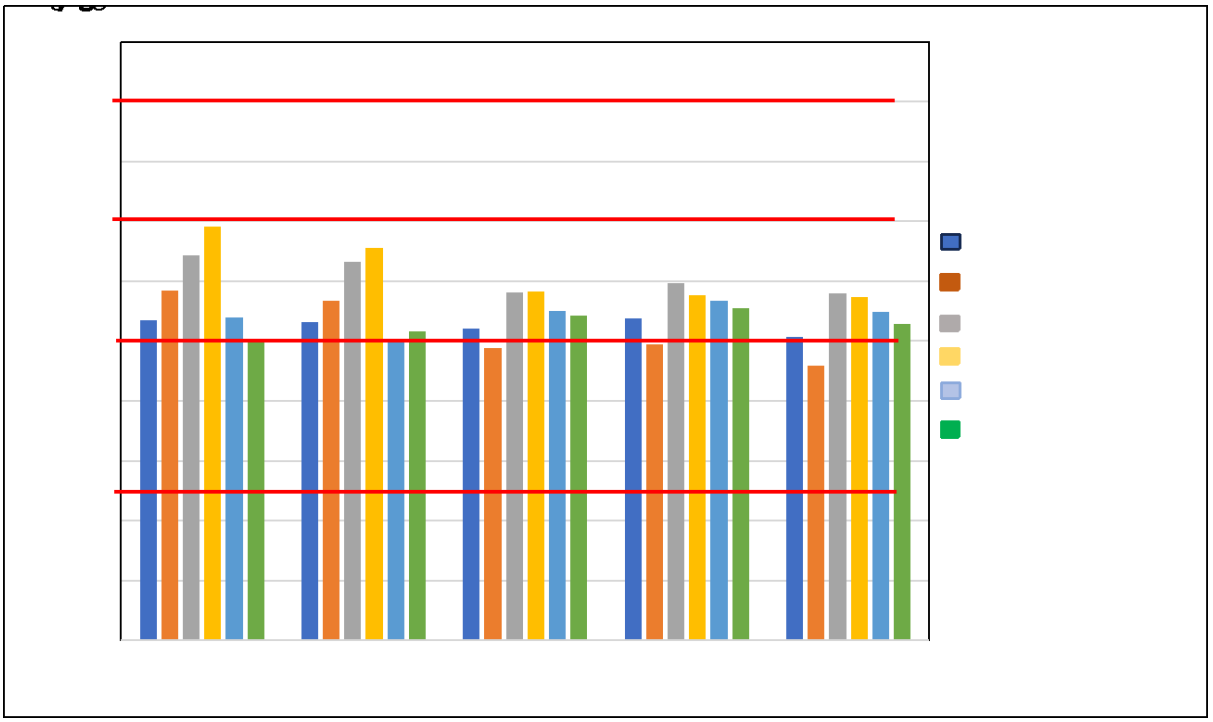

Figure 7. RWQI calculated at each province for the period between 2019-2023 (source: Environment Statistics of Indonesia, 2020, 2021, 2022, 2023, 2024)

From the assessment of other parameters, it was observed that E. coli concentrations were relatively high in several rivers within the study area, such as the Batanghari River (Jambi Province) and the Kapuas River (West Kalimantan Province) (App. 3). This finding indicates

that the rivers in the study area have been influenced by domestic sewage discharges from local communities.

3.2.2. Coastal and Sea Waters

Marine Water Quality Index (IKAL) assessments (the methods of the River Water Quality Index analysis is described in the App. 4.) across South China Sea (SCS)–bordering provinces indicate overall Moderate to Good conditions during 2019–2023 (Figure 8), with limited fluctuation. Monitoring currently emphasizes organic pollution, excluding heavy metals or hazardous substances. Kepulauan Riau consistently achieved Good status, while Jambi and South Sumatra remained Moderate. Water quality peaked in 2022, when five provinces recorded IKAL >80, before declining in 2023, particularly in Jambi and Riau. West Kalimantan the Very Good threshold (>90). The 2023 decline suggests renewed environmental stress or reduced management effectiveness, underscoring the need for enhanced wastewater control, inclusion of toxic parameters, and sustained monitoring to support long-term SCS water quality protection. In general, the seawater quality index in the provinces within the study area does not yet indicate marine pollution. This condition is presumably due to the high flushing effect in the area, which prevents the accumulation of dissolved contaminant parameters. At least, several key water quality parameters—such as Total Suspended Solids (TSS), Dissolved Oxygen (DO), Oil and Grease, Total Ammonia (NH_3-N), and Ortho-Phosphate (PO_4-P)—remain below the Indonesian marine water quality standard thresholds.

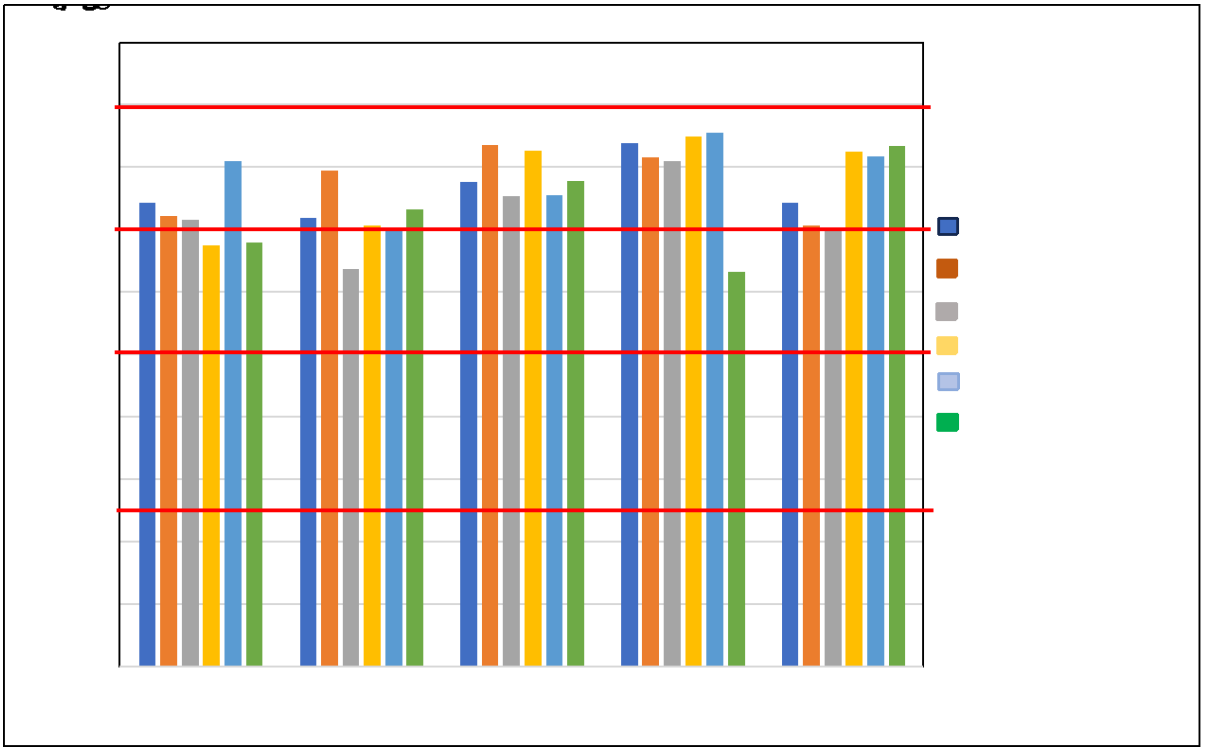

Figure 28. Distribution of marine water quality index (IKAL) values across the provinces associated with Indonesia's South China Sea (SCS) region (source: Environment Statistics of Indonesia, 2020, 2021, 2022, 2023, 2024).

4. Discussion

4.1. Priority Transboundary Pollution Issues

Transboundary pollution issue in the Indonesian part of the South China Sea primarily involves oil-related pollution, marine litter and plastic waste, and organic pollution. The distribution pattern of pollutants in the study area is related to water mass transport, strongly influenced by the hydrodynamic patterns of the region, which are governed by the monsoonal system. Water mass transport in the South China Sea (SCS) and adjacent Indonesian waters is primarily governed by monsoon variability. Figure 9 shows that during the southeast monsoon (May–September), winds drive currents from the Java Sea northward through the Karimata and Gaspar Straits, forming part of the South China Sea Throughflow (SCSTF) and transporting water, nutrients, and pollutants toward the SCS. Conversely, the northwest monsoon (November–March) reverses the flow, contributing to the Indonesian Throughflow (ITF) and enhancing freshwater input, stratification, and vertical mixing. These seasonal reversals strongly influence the spatial transport of pollutants and nutrient fluxes, southward during the southeast monsoon and northward during the northwest monsoon (**Zeng et al., 2021**). Interactions between riverine plumes, particularly from the Mekong, and monsoon-driven currents further modulate pollutant dispersion, nutrient cycling, and marine ecosystem productivity across the SCS–Indonesian region.

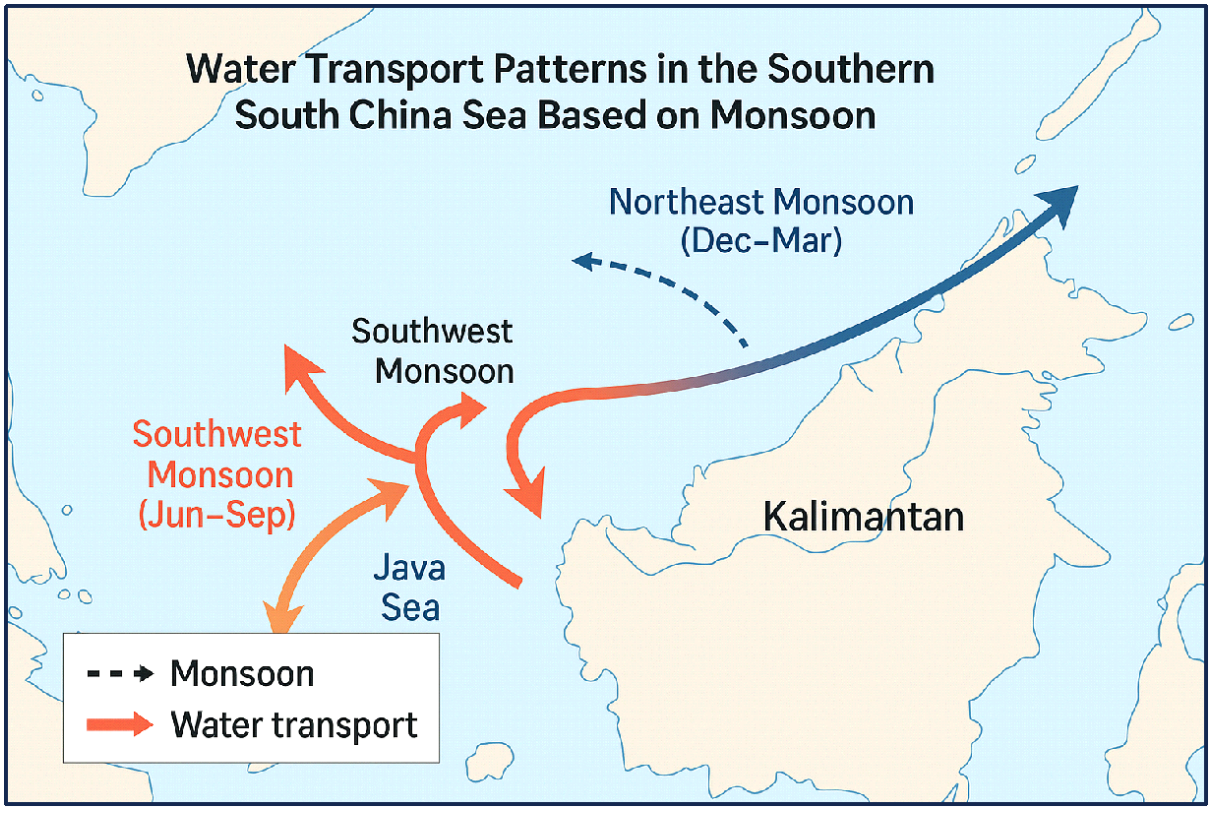

Figure 9. Hydrodynamics process in the South China Sea (above) and around Bintan Island where oil frequently stranded (source: **Wang et al., 2019; Kok et al., 2021; Nie et al., 2023**)

As shown in Figure 9, during the northeast monsoon season, which occurs between December and March, water masses flow from the Strait of Malacca and the South China Sea (SCS), reaching the northern coasts of Batam and Bintan. During this period, oil sludge stranding events occur along the northern shores of Batam and Bintan.

4.1.1. Oil-related pollution from marine transportation

Foreign vessels, frequently operate in the SCS both in the international and in the Indonesian waters around Natuna and the Riau Islands, often discharging oil, fuel, and waste. A persistent issue in the Riau Islands, particularly on the northern coasts of Bintan, is stranded oil sludge that appears during the northeast monsoon when currents move pollutants from the northern South China Sea southward. Investigations by the Ministry of Environment strongly suggest that the oil sludge originates from international vessels cleaning their tanks in the areas.

Incidents of oil spills associated with shipping activities continue to occur. For example, oil layers have been found washed ashore along the northern coasts of Batam and Bintan Islands. On Bintan Island, reported locations include Sungai Kecil Beach, Bintang Sayang Beach, Sakera Beach, and the coastal area of Lobam Island. Additional reports from local communities have identified oil pollution in Sebong Lagoi, Sebong Pereh, North Bintan, Malang Rapat, Berakit, Sri Bintan and Pengudang (**Purnaweni et al., 2022**).

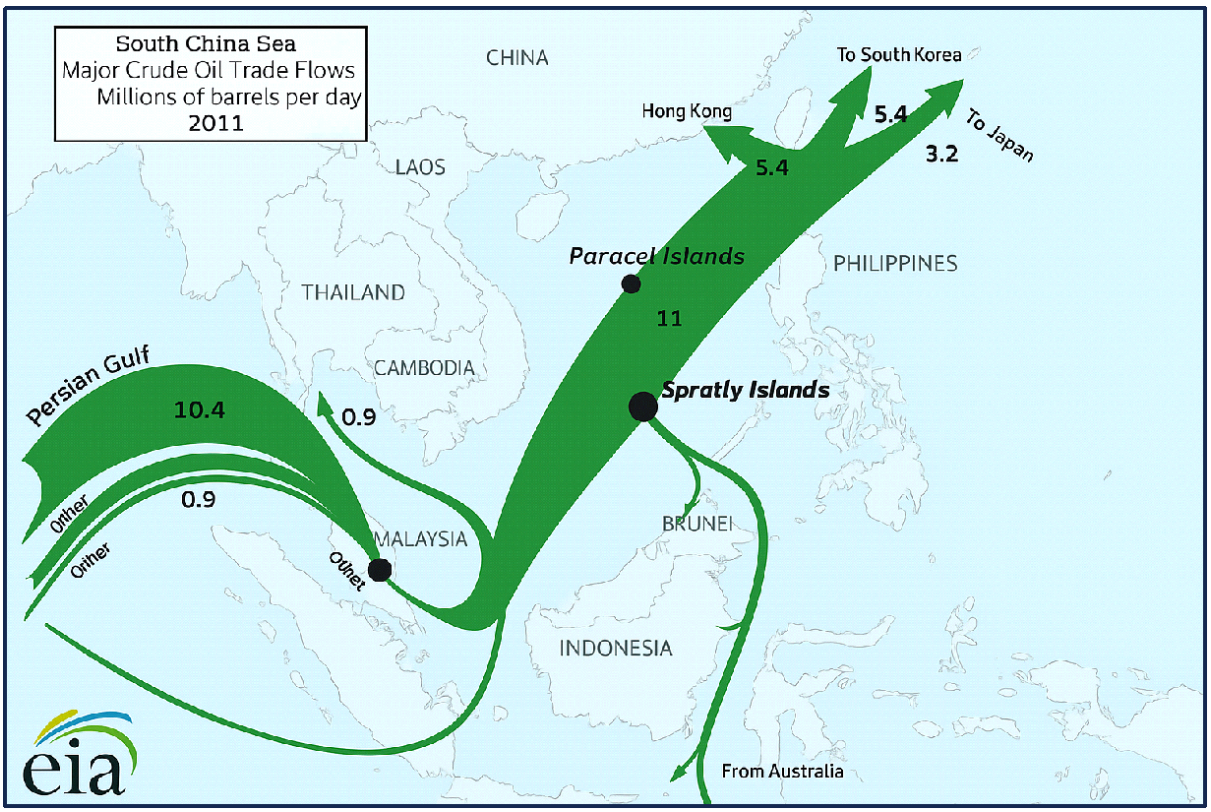

Figure 10. The South China Sea's shipping lanes connecting the Mallaca Strait and the South China Sea passing through the Indonesia's province of Riau Kepulauan (source: **ERIA, 2016**)

The western maritime transport route of Indonesia is a busy corridor connecting the Indian Ocean and the Pacific Ocean. International shipping routes pass through the Strait of Malacca, then through the narrow Singapore Strait between Batam Island and Singapore,

before entering the waters of the South China Sea (SCS) (Figure 10). In relation to this study, the Indonesian islands closest to areas affected by oil spill impacts are Batam and Bintan. These two islands are located directly along the maritime transport entrance route from the Strait of Malacca into the SCS waters.

4.1.2. Marine Litter and Plastic Pollution from Neighboring Countries and from Indonesia

Plastic waste entering the ocean varies greatly worldwide, from 1.15 to 12.7 million tonnes annually, with Indonesia contributing an estimated 0.20–1.29 million tonnes (**Jambeck et al., 2015**). Marine debris and plastic pollution are serious environmental issues in Indonesian waters, including the South China Sea (SCS), primarily originating from domestic solid waste dominated by plastics. Studies in Bintan Island show average microplastic concentrations of about 0.45 particles/m³ (≈122 particles per station), indicating low to moderate pollution levels. Polymer analyses revealed that polypropylene (PP) (54%), polyethylene (PE/LDPE), and polystyrene (PS) are the most common types, appearing as fragments, fibers, granules, and films. Surveys of Bintan's coastal areas found varying amounts of stranded plastic debris, particularly LDPE, PP, and PS, reflecting ongoing land-based and marine waste inputs that continue to impact local mangrove and coastal ecosystems (**Hidayati et al., 2023; Syakti et al., 2018**).

4.1.3. Organic Pollution from Domestic Activities

Organic pollution mainly results from domestic wastewater discharges due to the lack of adequate communal wastewater treatment systems (IPAL). Many residential areas release untreated wastewater into rivers and coastal zones, which eventually reaches the sea. Although this pollution is currently localized and not yet transboundary in scale, it highlights weaknesses in urban wastewater management.

4.2. Interactions : Impacts on Environment and Society

4.2.1.Impact of oil pollution on mangroves, coral reef and tourism

Oil strandings harm coastal tourism and damage mangrove, coral reef, and seagrass ecosystems by coating mangrove roots and smothering marine organisms. Oil sludge regularly washes ashore on the sandy beaches of northern Bintan, an area recognized as a premium tourist destination attracting both domestic and international visitors.

Reports from local communities have identified oil pollution in Sebong Lagoi, Sebong Pereh, North Bintan, Malang Rapat, Berakit, Sri Bintan and Pengudang (**Purnaweni et al., 2022**) (Figure 11).

Figure 11. Marine pollution caused by oil sludge on the Bintan Coastal, Indonesia, in 2023 (**Purnaweni et al., 2022; Thahira et al., 2023**)

4.2.2.Impact of marine debris stranded on mangroves

Hidayati et al. (2022) reported significant macro-debris and microplastic accumulation in Bintan's mangroves, affecting associated organisms such as gastropods. Microplastics (<5 mm) occur as pellets, fibers, fragments, and films, threatening fragile habitats that support biodiversity and coastal protection. **Syakti et al. (2018)** and **Ma et al. (2020)** found that microplastics enter food webs through ingestion, while **Covernton et al. (2021)** detected high concentrations in clupeid fish. **Utami et al. (2021)** noted that corals ingest microplastics, causing tissue damage and bleaching. **Mendrik et al. (2025)** observed that fibrous microplastics reduce photosynthetic activity in *Acropora* corals, highlighting serious ecological risks

4.3. Risk Assessment of Marine Pollution

Risk assessment applies a risk analysis approach using three main variables—probability, impacts, and adaptive capacity within specific pollution scenarios (**Cornelly et al., 2018;**

Ortega et al., 2014). Probability reflects the likelihood of pollution events based on pollution source intensity and is rated from 1 to 5. Impacts include water quality conditions, deviations from standards, and socio-ecological effects, also scored from 1 to 5; both are positively correlated with risk. Adaptive capacity, rated similarly, measures the ability of management units to address pollution and is negatively correlated with risk. A higher adaptive capacity reduces overall risk. Detailed methods are provided in the **App. 5** while **d**etail risk analysis results are shown at **App. 6**. Risk analysis results indicate high-risk levels for oil pollution (oil sludge) in Bintan while other pollution types showed low to moderate risks. Maximum risk for oil sludge pollution in Bintan coastal area is due to mostly its high probability and impacts and low in adaptive capacity. The high probability is evident from the relatively intense frequency of maritime transportation activities in the international waters of the region, occurring almost daily, which represents a major potential source of oily waste discharges from ship tank-cleaning operations (**Thahira et al., 2023**). In addition, the mechanism of this impact is transboundary in nature, involving cross-border pollution pathways. From an impact perspective, the recurrent stranding of oil sludge along the Bintan coastline has produced tangible environmental consequences, affecting beach cleanliness, disrupting coastal tourism, and degrading mangrove ecosystems (**Hairo et al., 2024; Purwaneni et al., 2022**).

Compared with Jakarta Bay, pollution levels in Batam, Bintan, and the wider South China Sea are relatively lower due to less intense pollution sources and impacts. In Jakarta Bay, severe contamination has led to heavy metal pollution (Hg, Pb, Cd) and toxic compounds (**Dsikowitzky et al., 2018**), eutrophication (**Damar et al., 2020**), and hypoxia (**Ladwig et al., 2016; Hayami et al., 2020**). Contaminants have also entered the food chain (**Baum et al., 2016; Kunzmann et al., 2018; Oetama et al., 2016**). Priority actions should target oil and TSS pollution, while moderate risks include marine debris, plastic waste, and E. coli contamination.

4.4. Interactions: Current Management and Institutions

Pollution management in the South China Sea (SCS) region involves coordination among multiple Indonesian institutions. At the national level, key agencies include the Ministry of Environment, Ministry of Transportation, Ministry of Home Affairs, Ministry of Foreign Affairs, and Ministry of Marine Affairs and Fisheries. At the regional level, the main authorities are the provincial governments of Riau Islands, Bangka Belitung, and West Kalimantan, supported by their respective Environmental Agencies, Marine and Fisheries Agencies, Tourism Agencies, and Regional Development Planning Agencies (Bappeda). These institutions collaborate to monitor, manage, and mitigate marine pollution across Indonesia's SCS territories. Specifically for the management of oil-sludge spills stranded along the northern coast of Bintan, coordination has been carried out under the coordination of the Ministry of Environment. Several institutions have been involved, including the Ministry of Transportation (as the national coordinator for oil-spill response), the Ministry of Foreign Affairs (due to the diplomatic engagement required with neighboring countries and ASEAN), the Provincial Government of the Riau Islands, and the Bintan Regency Government.

4.5. Gaps and Priority Challenges

The main types of pollution in the Indonesian South China Sea (SCS) region include oil sludge, plastic and marine debris, and organic and microbial contamination (e.g., *E. coli*, Total coliforms).

4.5.1. **Oil Sludge Pollution**

This transboundary issue mainly affects the northern and eastern coasts of Batam and Bintan Islands, where oil sacks and tar balls regularly wash ashore during the Northeast Monsoon (October–February). Satellite and hydrodynamic analyses trace the source to international waters between Indonesia and Singapore, likely from vessel tank-cleaning operations. The pollution damages coral reefs and coastal ecosystems, including Bintan's marine protected areas and tourist beaches (**Purnaweni et al., 2022; Thahira et al., 2023**). To address it, stronger inter-ministerial coordination (Foreign Affairs, Environment and Transportation) and regional cooperation through ASEAN are needed, supported by a special task force and tourism stakeholder association for monitoring and response. Until today, oil sludge strandings along the northern coasts of Batam and Bintan continue to occur, causing major disruptions to coastal tourism. An essential effort to address this issue is cross-border coordination involving regional and international maritime transport committees. To date, efforts have been undertaken by the Indonesian government, particularly through the Ministry of Environment, including initiatives within the regional framework of the ASEAN Working Group on Biodiversity. Direct field actions include routine clean-up operations of oil sludge stranded along the northern coasts of Batam and Bintan. Despite these efforts, oil sludge strandings on the Batam and Bintan coasts continue to occur, indicating that effective mitigation measures have yet to be achieved. Addressing this issue requires sustained efforts to prevent similar incidents from occurring in the future.

4.5.2 Plastic and Marine Debris Pollution

This type of pollution affects nearly all provinces in the SCS region, including Riau Islands, Bangka Belitung, West Kalimantan, South Sumatera and Riau. Driven by monsoonal currents, debris moves from the South China Sea toward Indonesia during the Northeast Monsoon, and in reverse during the Southeast Monsoon (**Hidayati et al., 2022; Syakti et al, 2018**). The main strategy should target waste reduction at the source, particularly from densely populated areas such as Batam, Bintan, and surrounding provinces. A notable gap remains in the efforts of the government, particularly local governments, to reduce plastic waste generation in their respective regions. Although relevant regulations are already in place, including a National Action Plan (NAP) for reducing plastic waste generation and marine plastic pollution, the main challenge lies in the effective implementation of this NAP. The NAP is outlined in the Presidential Regulation of the Republic of Indonesia Number 97 of 2017 concerning the National Policy and Strategy on Household Waste and Household-like Waste Management, and Presidential Regulation Number 83 of 2018 concerning the Handling of Marine Debris.

Although it has been mandated in national regulations, plastic pollution and marine debris continue to persist. Efforts to reduce plastic waste generation need to involve multiple relevant stakeholders, including producers of plastic packaging for food, beverages, detergents, shampoos, and other products, as well as waste management authorities responsible for handling and preventing waste from entering public waters.

4.5.3. Domestic Pollution

This type of organic and microbial pollution occurs not only in the Riau Islands but also across most provinces within the Indonesian South China Sea (SCS) region. Although currently domestic in nature and not transboundary, inadequate mitigation could increase its scale and pose public health risks. The main sources are household sanitation activities (bathing, washing, toilet use), which release wastewater containing coliform bacteria, including *E. coli*, known to cause digestive disorders such as diarrhea. Priority actions include reducing domestic wastewater contamination in rivers and coastal areas, especially in Batam, Bintan, Riau, Jambi, and Bangka Belitung. While regulations exist, stronger implementation and coordination between national and local governments are urgently needed to control pollution at its source. The main challenges include not only the provision of communal domestic wastewater treatment facilities in densely populated residential areas but also raising public awareness to encourage responsible behavior in managing household waste.

The main improvements required include not only raising public awareness to promote clean behavior but also providing infrastructure such as integrated wastewater treatment facilities in every city and settlement, establishing domestic waste collection facilities, and developing a coordinated system for managing domestic solid waste and wastewater at the community level.

4.6. Recommended Priority Actions, Emphasizing Regional Cooperation

To date, the Government of Indonesia, both at the national and sub-national levels (provincial and district/municipal), has implemented a range of actions to reduce the level of marine pollution. In principle, these efforts encompass: (1) mitigation measures aimed at reducing pollutant loads entering aquatic systems; (2) comprehensive and routine pollution monitoring; and (3) rehabilitation of contaminated ecosystems.

Mitigation efforts to reduce pollution loads have been undertaken through various approaches, including the enactment of environmental regulations concerning pollution prevention, routine budget allocations for pollution control infrastructure at both central and regional levels, and community awareness programs promoting pollution-minimizing behaviors.

Pollution monitoring activities are conducted both as an early-warning mechanism and as a means to support law enforcement in cases of suspected water pollution by specific parties. Routine monitoring of water pollution status is carried out in all provinces using evaluation instruments such as the River Water Quality Index (IKA) and the Marine Water Quality Index (IKAL). These efforts have been consistently implemented over at least the past eight years as part of an evaluation mechanism to assess the effectiveness of ongoing pollution prevention measures.

Rehabilitation efforts are directed particularly toward areas affected by acute pollution events, such as oil spills. In relation to the present study, regular cleanup operations have been conducted along the northern coast of Bintan Island and its surrounding areas to remove oil sludge. Coastal cleanup campaigns are also routinely organized by both local and central government agencies as part of broader marine environmental management initiatives. In

detail, the efforts undertaken by the Government of Indonesia to address various pollution issues, both mitigation and rehabilitation measures, are presented in **App. 7**.

However, with regard specifically to transboundary pollution issues in the South China Sea (SCS) region, further efforts are required that extend beyond the actions of the Indonesian government alone. Regional coordination within the ASEAN framework needs to be continuously strengthened, given the inherently transnational nature of the pollution occurring in this area. With regard to recommended actions for addressing the major types of pollution, several of recommend actions are presented in Table 2. In principle, transboundary pollution in the Indonesian part of the South China Sea can be managed through coordination at the regional level, namely within ASEAN, as well as at the national and local levels. The primary and urgent issue requiring immediate attention is the problem of oil sludge stranded along the Bintan coastline, which necessitates intensive coordination at the ASEAN level.

Table 1. Recommendations for reducing pollution in the Indonesian South China Sea (SCS) Region

Type of pollution	Priority Actions	Level of coordination
Oil pollution	Regional coordination on oil pollution combats due to vessel activities in international waters	ASEAN
	National coordination on the combat of oil sludge pollution	National Indonesian Government: - Ministry of Transportation - Ministry of Environment - Local Government
	Local coordination on stranded oil sludge management	- Local Government of Kepulauan Riau Province - Local Government of Bintan Regency and Batam Municipality
	Bintan Batam Tourism Association coordination on mitigating stranded oil sludge oil	- Local Government of Bintan Regency and Batam Municipality - Local tourism companies
Marine Debris and Plastic pollution	Regional cooperation and coordination on marine debris and plastic pollution combat	ASEAN
	National coordination on marine debris and plastic pollution combat	National Indonesian Government: - Ministry of Environment - Local Government
	Solid waste infrastructures	Local Government

Type of pollution	Priority Actions	Level of coordination
	Community awareness on solid waste reduction programs	Local Government
	Fishers' awareness on abandoned fishing gears waste reduction programs	Local Government
Domestic pollution	Sanitary infrastructures	Local Government
	Community awareness on hygienic living	Local Government

5. Conclusion

This study shows that pollution in the Indonesian part of the South China Sea (SCS) is combination of land and marine-based sources, with major rivers such as the Kapuas and Batanghari transporting substantial nutrient and organic loads into coastal waters. Across the provinces of Riau, Riau Islands, Bangka Belitung, South Sumatra, and West Kalimantan, five key pollution categories, agricultural runoff, aquaculture waste, hazardous waste, domestic discharges, and oil contamination, continue to influence ecosystem health. The RWQI (IKA) remains categorized as poor to moderate, in contrast to IKAL scores, which lie between moderate and good, although recent measurements indicate a decline. Oil sludge strandings along Batam and Bintan beaches pose the highest transboundary risk, disrupting tourism and damaging mangroves and coral reefs.

Oil pollution represents the most critical threat, as recurrent oil sludge strandings in Batam and Bintan create significant transboundary risks, damaging mangroves, coral reefs, and seagrass meadows while disrupting tourism and coastal livelihoods. Marine debris, including plastics and microplastics, persists across beaches and shallow habitats, highlighting chronic waste management deficiencies. Localized E. coli contamination also reflects inadequate domestic wastewater treatment in some rivers in the study area.

Risk assessment identifies oil pollution (oil sludge) as the top priority for transboundary pollution issue, followed by moderate risks from nutrient enrichment and marine debris. Fragmented institutional coordination remains a major challenge. Strengthening regional cooperation, especially through ASEAN, along with improved waste and wastewater infrastructure, stricter maritime enforcement, and enhanced public awareness is essential. An integrated transboundary governance approach is crucial to protect ecological resilience and sustain the socio-economic benefits of Indonesia's SCS waters.

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