JCRECO
Journal of Critical Ecology
JCRECO 2(2): 143–159
ISSN 3048-4200

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Ecological impacts of marine oil spill pollution: An integrative assessment of ecosystem damages and conservation strategies

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Received Date: May 30, 2025 Revised Date: July 19, 2025 Accepted Date: August 30, 2025

ABSTRACT

Background: Indonesia, as a maritime nation with 40% of global maritime trade passing through its waters, faces high risks of marine oil pollution. Balikpapan Bay, located in East Kalimantan, has suffered recurring oil spill disasters, notably the large-scale spill in 2018. These spills have severely impacted the marine ecosystem, local biodiversity, and the socio-economic conditions of coastal communities. **Methods:** This study employed a qualitative descriptive approach through case study analysis. Primary data were collected from government documents, field reports, and previous academic studies, particularly focusing on ecological damage assessments conducted by the Ministry of Environment and Forestry, NGOs, and local communities. Spatial data from satellite monitoring were used to assess the extent of the oil spill. The data analysis included categorization of ecological impacts on key ecosystems such as mangroves, coral reefs, seagrasses, marine fauna, and bird species. **Findings:** The oil spill in Balikpapan Bay contaminated nearly 13,000 hectares of marine waters and 60 km of coastline, causing substantial damage to 34 hectares of mangrove forest, 4 coral reef areas, 5 seagrass beds, and seaweed cultivation zones. It led to mass deaths of crabs, plankton, and endangered marine mammals. Bird populations were also severely affected due to loss of insulation and ingestion of toxic substances. The spill had a cascading effect on the local marine food web, reduced biodiversity, and caused economic losses for traditional fishing communities. **Conclusion:** The Balikpapan Bay oil spill has led to a multidimensional ecological crisis. This study underscores the urgent need for proactive oil spill prevention and ecosystem protection strategies. Conservation zoning, enforcement of environmental regulations, and community-based monitoring are essential to prevent future disasters. **Novelty/Originality of this article:** This study presents a comprehensive ecological assessment of the Balikpapan Bay oil spill by combining field data, satellite imagery, and governmental reports.

KEYWORDS: biodiversity degradation; ecological impact; oil spill pollution.

1. Introduction

Geographically, Indonesia is an archipelagic nation, with approximately two-thirds of its territory comprising ocean, making its maritime area significantly larger than its landmass. Beyond its vast marine potential, Indonesia is also recognized for its strategic maritime position, which plays a vital role in global shipping routes. According to the Ministry of Transportation of the Republic of Indonesia, 40% of the world's maritime trade passes through Indonesian waters. In response, the Indonesian government seeks to enhance the competitiveness of its maritime industry, in part by optimizing national

Cite This Article:
Wakito, R. F. M., & Ridlani, I. A. (2025). Ecological impacts of marine oil spill pollution: An integrative assessment of ecosystem damages and conservation strategies. *Journal of Critical Ecology, 2*(2), 143-159. https://doi.org/10.61511/jcreco.v2i2.2197

shipping routes as corridors for oil transportation, given that oil refineries are often located in bays to facilitate distribution (Lestari et al., 2023).

To accommodate larger volumes of oil, Indonesia utilizes marine vessels in its oil transportation activities and currently operates 1,537 units for maritime routes, with a total capacity of 8.6 million kiloliters. However, this mode of transportation carries a high risk of oil spills (Adofo et al., 2022; Agustin et al., 2024). Such incidents can lead to environmental pollution, as oil contains hydrocarbon compounds and heavy metals that are difficult to degrade (Kurniawan et al., 2024).

Although petroleum has played a crucial role in global energy development—contributing to 50% of the world's energy supply since 2018—its impact on ecosystems poses significant risks to both society and the environment. Among the consequences of petroleum use are offshore oil exploration, transportation, and maritime accidents, which often result in oil spills that become pollutants in aquatic environments (Bhattacharjee & Dutta, 2022; Thakur & Koul, 2022). Such maritime incidents have detrimental effects on marine ecosystems, tourism, and local economies. Suspended particles can adsorb oil and settle on the seafloor, potentially altering the habitat conditions of tropical marine ecosystems.

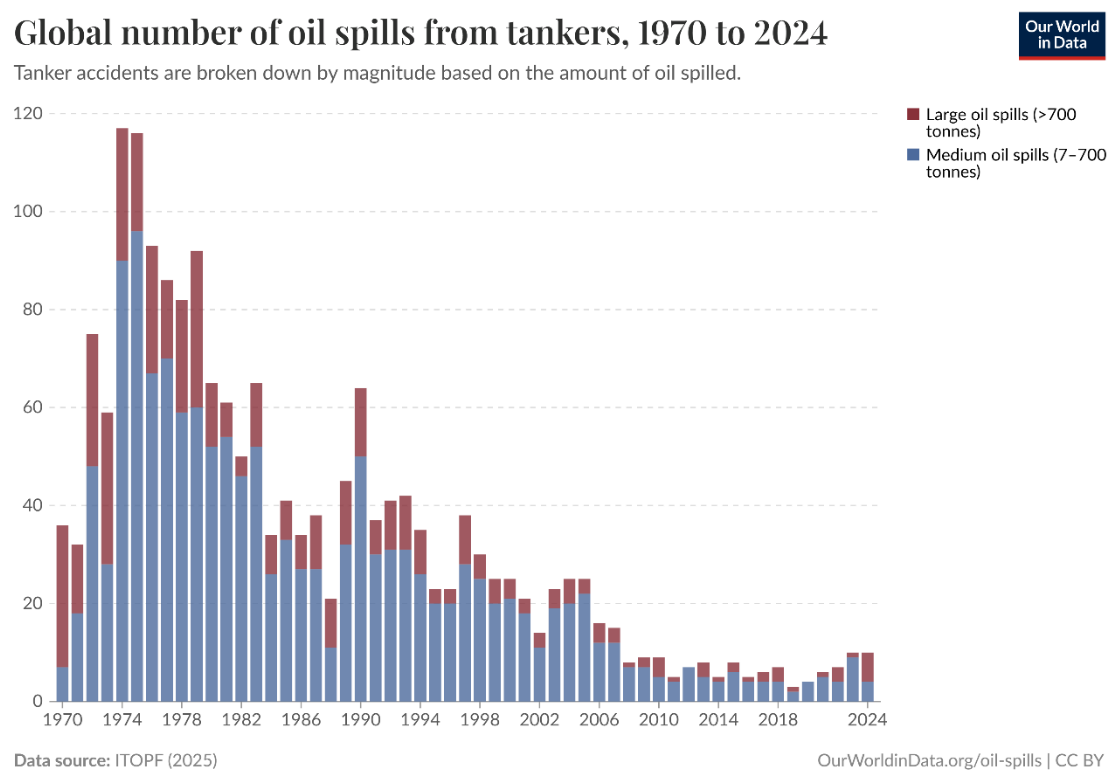

Fig. 1. Global numbers of oil spills from tankers, 1970 to 2023 (Ritchie et al., 2025)

Numerous reports have documented oil spill incidents in coastal areas across various countries, including Indonesia, India, Brazil, South Korea, and others. Coastal oil spills may result from distribution pipeline leaks, tanker operations, ship maintenance and repair (docking), offshore loading and unloading, shipping activities, and tanker accidents. Over the past five years, four oil spill incidents have occurred in Indonesia, specifically in Balikpapan Bay, East Kalimantan Province; the coastal area of the Thousand Islands, West Java Province; and the coastal area of the Riau Archipelago.

The primary negative impact of oil pollution is ecosystem damage and a decline in biodiversity, largely caused by soil layer degradation. In addition to affecting the surrounding biotic and abiotic environment, oil can also poison algae, disrupt the feeding cycles of aquatic organisms, and reduce the production of edible crustaceans. Birds exposed to contamination may experience impaired flight ability and weakened feather strength, increasing their vulnerability to cold temperatures. Oil spills also adversely affect sea turtles, which are frequently found injured or dead due to oil contamination, with an estimated more than 2,000 cases reported over the past 60 years (de Souza Dias da Silva et al., 2024). In aquatic environments, oil contamination poses significant threats to microbial communities, plant assemblages, and a wide range of marine fauna. The degree of damage is largely influenced by the chemical characteristics and toxicity of the spilled oil, which can enter organisms through multiple exposure pathways and subsequently destabilize ecosystem functions and food-web dynamics (Hettihanthri et al.,2024). Globally, oil spills in populated areas spread rapidly, contaminating soil and groundwater, damaging crops, and reducing water quality. Kalimantan is recognized as one of Indonesia's major oil-producing islands. The island hosts numerous oil refineries and other mining activities both onshore and offshore. One of the regions with the highest oil drilling activity is Balikpapan Bay, which has relatively narrow upstream and downstream sections and is part of the open sea of the Makassar Strait. The upstream area of Balikpapan Bay contains many drilling sites that have significant impacts on the surrounding waters.

Oil pollution has long been recognized as one of the most persistent and destructive threats to coastal and marine environments, particularly in regions where industrial extraction activities intersect with ecological and human systems (Thiagarajan, C., & Devarajan, 2025; Zhang et al., 2024). Marine oil spills constitute some of the most critical environmentak disturbances impacting aquatic ecosystems, with profound consequences for marine biodiversity, ecological stability and the socioeconomic resilience of coastal populations (Hettithanthri et al., 2024). Activities associated with the extraction, transport, and processing of petroleum particulary offshore drilling, marine shipping, and pipeline distribution continue to pose persistent risks of accidental hydrocarbon release into ocean environments. From 1970 to 2023, an estimated 629 documented spill events accounted for the discharge of approximately 1.522.000 tonnes of oil, with tanker-related incidents representing nearly 45% of global marine oil spills (ITOPF, 2023; Jayarathna et al., 2024). Catastrophic events such as the Exxon Valdez spill in Alaska (1989), the Deepwater Horizon blowout in the Gulf of Mexico (2010), and the Hebei Sprit spill in Korea (2007) highlight the critical importance of advancing scientific understanding of spill-induced ecological impacts and strengthening conversation and mitigation frameworks (Barron et al., 2020). As global energy demands continue to rise, oil-producing regions such as Indonesia face increasing pressure from extraction, transportation, and refining activities. These pressures heighten the likelihood of accidental spills, operational leaks, and chronic contamination that can destabilize the delicate balance of coastal ecosystems. Understanding these impacts requires not only ecological assessment but also a holistic consideration of human–environment interactions, socio-economic vulnerabilities, and policy contexts.

In Indonesia, the ecological risks posed by oil pollution intersect closely with issues of environmental justice and sustainable development. Many affected communities depend heavily on coastal resources for food security, cultural identity, and economic livelihoods (Hanazakit et al., 2013). When spills degrade habitats, reduce fisheries productivity, or contaminate water sources, marginalized groups often bear the greatest burden (Ningsih, 2024). This disparity underscores the need for inclusive ecological discourse that amplifies community perspectives and integrates interdisciplinary insights from ecology, economics, politics, and ethics. Such an approach is vital for ensuring that environmental management strategies are both scientifically sound and socially equitable.

Balikpapan Bay represents a critical case where industrial expansion and ecological vulnerability converge. Its strategic location along the Makassar Strait has made it a focal point for Indonesia's petroleum industry, resulting in dense clusters of offshore and onshore extraction sites. However, the same characteristics that make the bay economically valuable also increase its ecological sensitivity. The narrow channel system restricts water flow, allowing pollutants to accumulate and spread rapidly across interconnected habitats. This highlights the importance of using empirical data, spatial analysis, and interdisciplinary frameworks to understand how environmental degradation unfolds within complex socio-ecological systems.

Given these intersecting ecological and socio-economic dimensions, addressing oil pollution in regions like Balikpapan Bay requires collaborative engagement across scientific, governmental, and community-based actors. Strengthening regulation, improving monitoring systems, and integrating local knowledge are essential steps toward resilient ecosystem management. Moreover, situating these efforts within broader discussions on sustainability and environmental justice can help catalyze systemic change toward a more equitable and ecologically stable future. Such considerations align with the journal's aim to foster interdisciplinary collaborations, generate innovative ecological thought, and promote practical solutions that benefit both people and the planet.

Balikpapan Bay has experienced large-scale oil spill incidents since 2014, which have caused significant damage to the surrounding environment (Widiawan, 2021). Major pollution events in Balikpapan Bay have occurred multiple times rather than just once or twice. It is evident that oil spill pollution in Balikpapan has had a substantial impact on the environment, particularly concerning the local ecology. Therefore, in this paper aims to further analyze the pollution conditions in Balikpapan Bay and its ecological impacts on the surrounding area.

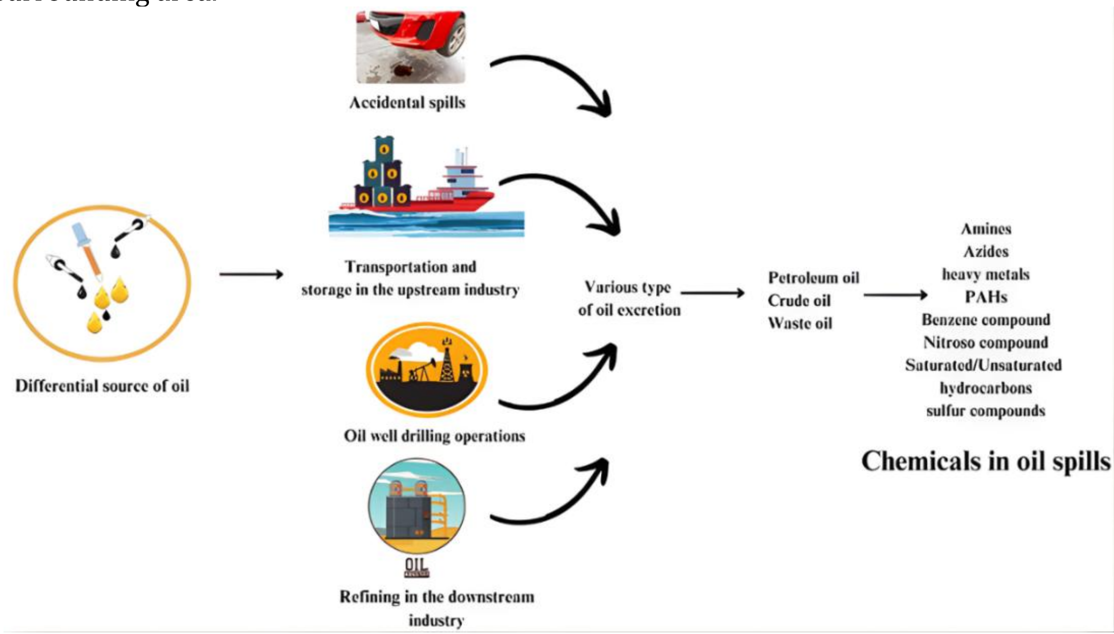

Fig. 2. Chemical exposure from various sources of oil spills
(Sharma et al, 2024)

Indonesia is an archipelagic country, with two-thirds of its territory consisting of ocean. Of all global maritime transportation routes, 40% of the world's maritime trade passes through Indonesia. One of the largest uses of sea transport is for oil logistics. However, maritime oil transportation carries a high risk of oil spills into the ocean. Balikpapan Bay is one of the bays that has experienced large-scale oil spills causing significant damage. Oil spills in Balikpapan Bay have resulted in various impacts, including economic, social, environmental, and ecological effects. Therefore, this paper aims to analyze in greater depth the ecosystem conditions in Balikpapan Bay, the state of the bay following oil spills, and the impacts on the surrounding ecology.

2. Methods

This study adopts a qualitative case study approach to examine the ecological impacts of marine oil spill pollution in Balikpapan Bay, Indonesia. Data were obtained from multiple secondary sources, including reports from the Ministry of Environment and Forestry, scientific literature, environmental NGOs, and satellite data from national space agencies.

The choice of Balikpapan Bay as the study location was based on the area's historical frequency of oil spills and its ecological significance as a marine biodiversity hotspot.

The primary focus was on the 2018 oil spill caused by a ruptured crude oil pipeline owned by PT Pertamina RU V Balikpapan. Satellite imagery and spatial analysis were used to determine the extent of oil spread, while impact assessments on mangroves, coral reefs, seagrasses, marine fauna, and bird species were drawn from field surveys and ecological monitoring reports. The method of analysis in this study involved several integrated stages. First, data collection was conducted by compiling satellite imagery, relevant policy documents, and environmental impact assessments from governmental and non-governmental sources. These data were then categorized based on ecosystem types, such as mangrove forests, coral reefs, seagrass beds, and avifauna, to identify the specific areas affected by the oil spill. A thematic analysis was subsequently employed to interpret patterns related to environmental degradation and biodiversity loss within the affected zones. Finally, a policy analysis was carried out to assess the effectiveness of government responses, imposed sanctions, and the implementation of environmental rehabilitation programs, providing a comprehensive view of institutional accountability and ecological recovery efforts.

3. Results and Discussion

3.1 Seawater pollution theory

Environmental Science is the study of human interactions with the world, aiming to understand how life on Earth sustains and develops, comprehend the relationship between humans and the environment, and find solutions to environmental problems and sustainability (Miller et al., 2016). Aquatic environments are ecosystems characterized by complex reciprocal relationships among plant and animal species and their habitats. Habitat degradation causes damage to one or more species within the food chain, which can subsequently impact other species at the sea surface.

According to Miller, water pollution refers to changes in water quality that harm living organisms or render water unsuitable for human use, including irrigation, drinking, and recreation. Pollution can originate from point sources or non-point sources. Coastal areas, coral reefs, and wetlands are the most affected regions by pollutants. Approximately 40% of the global population lives in coastal zones, with coastal populations expected to double by 2050. This indicates that 80% of marine pollution originates from land-based sources. Marine pollution should not be viewed solely as a problem of the ocean; rather, oceans and land constitute an inseparable ecosystem that mutually affect each other. All activities conducted on land, whether intentionally or unintentionally, significantly impact marine ecosystems (Miller et al., 2016).

3.2 Balikpapan Bay

Balikpapan Bay is a landscape encompassing a watershed area of approximately 211,456 hectares and waters covering 16,000 hectares, with extensive mangrove ecosystem coverage of around 16,800 hectares (Ahmadi, 2016). This ecosystem serves as an important habitat for protected terrestrial and aquatic wildlife in Indonesia. Currently, Balikpapan Bay serves as a key environmental hub for East Kalimantan, spanning three administrative regions: Penajam Paser Utara (PPU), Kutai Kartanegara, and the City of Balikpapan. Due to its strategic location, Balikpapan Bay plays a significant role in transportation for the surrounding communities. Moreover, the upcoming development of the Nusantara Capital City in Penajam Paser Utara Regency further increases the bay’s strategic importance (Willard et al., 2022).

The current management of the mangrove ecosystem in Balikpapan Bay does not yet fully reflect the implementation and compliance with Presidential Regulation (Perpres) No. 73 of 2012 concerning the National Strategy for Mangrove Ecosystem Management

(SNPEM), specifically Articles 1, paragraphs (1) and (2), which has been established as a government effort at the regional level to manage mangrove ecosystems. Protection of the Balikpapan Bay area is also stipulated in the East Kalimantan Governor's Decree No. 522.5/K.672/2020 regarding the Designation of Indicative Maps of Essential Ecosystems. This regulation indicates efforts to protect the extensive area of the Essential Ecosystem Area (KEE) in Balikpapan Bay, covering approximately 65,000 hectares (DIKPLH, 2019). In addition, East Kalimantan Province Regulation No. 2 of 2021 concerning the Coastal Zone and Small Islands Spatial Plan (RZWP3K) regulates the zoning map for conservation areas, small islands, maritime waters, and marine nature parks. Balikpapan Bay—located in Penajam Paser Utara Regency—is designated within the Coastal and Small Islands Conservation Area (KKP3K) with zoning codes KKP3K-06 to KKP3K-07 (DIKPLH, 2019).

Balikpapan Bay has long been recognized as one of the representative mangrove ecosystems in Indonesia. The mangrove forests within the area of the new capital city (IKN) are located along the coast of Penajam Paser Utara and parts of Balikpapan Bay. In 2018, the mangrove coverage in Balikpapan Bay reached approximately 16,800 hectares. The mangrove forests in Balikpapan Bay play a crucial role in protecting the coastline from abrasion, disaster mitigation, and serving as fish spawning grounds (Alvin, 2023).

The waters of Balikpapan Bay constitute a relatively enclosed water system. Since there are no major rivers flowing from upstream, most of the bay's water currents do not flow out to the Makassar Strait but instead move back and forth between upstream and downstream with the tides. This means that nearly all sediment entering Balikpapan Bay remains within the bay. Similarly, any waste discharged from the land will accumulate in the bay's waters, potentially causing an ecological crisis if protective measures are not implemented.

3.3 Chronology of the marine oil spill in Balikpapan Bay

On March 30, 2019, an oil spill disaster occurred in Balikpapan Bay. This incident was caused by a rupture in a 20-inch diameter underwater crude oil distribution pipeline located between the Lawe-Lawe Terminal and the Balikpapan Terminal owned by PT Pertamina RU V Balikpapan. The break occurred at coordinates S 01°14'42.1'' and E 116°47'16.2'', approximately 500 meters from Lawe-Lawe Terminal toward Penajam (DIKPLH, 2019).

During the investigation of the oil spill, authorities reported that there was inconsistent information regarding the anchoring process, resulting in procedural errors. The anchoring location was incorrect, causing the anchor to hit Pertamina's pipeline used for crude oil transport, leading to a leak that contaminated the seabed with spilled oil. Pertamina Refinery Unit V Balikpapan acknowledged that the oil spill originated from the ruptured pipeline in the waters near Lawe-Lawe, Penajam Paser Utara (Arif, 2018).

The crude oil spill significantly impacted the ecosystem and marine biota in Balikpapan Bay. The spill affected approximately 12,145 m^3 of Balikpapan Bay waters and 30,156 m^3 in the Penajam Paser Utara Regency, with shoreline contamination extending about 60 km. Field surveys found that about 29.52 hectares of mangrove forests were damaged due to the spill, representing 80% of the total mangroves in Jenebora Village being contaminated (Oktawati et al., 2022).

The Ministry of Environment and Forestry imposed administrative sanctions on PT Pertamina (Persero) RU V Balikpapan based on the Ministerial Decree No. SK 2631/Menlhk-PHLHK/PPSA/GKM.0/4/2018 dated April 30, 2018, regarding the Enforcement of Administrative Coercive Sanctions. The sanctions outlined seven mandatory actions to be completed within 180 days, including the obligation to restore the environment affected by the oil spill in Balikpapan Bay, particularly along the coastal areas of Balikpapan City. This includes rehabilitating 29.52 hectares or 4.34% of the total 2,537.16 hectares of mangrove forest in Balikpapan City.

Following the sanctions, PT Pertamina RU V Balikpapan approved the Environmental Function Recovery Plan for Balikpapan Bay in accordance with the Ministry of Environment's letter No. S.1385/MenLHK-PSLB3/PKTDLB3/PLB4/12/2018 dated

December 3, 2018. The recovery methods for the contaminated mangrove areas include: a) land cleaning before rehabilitation using microbial treatments; and b) mangrove rehabilitation to replace damaged plants. Additionally, the Ministry of Environment and Forestry filed a lawsuit against PT Pertamina demanding compensation ranging from IDR 150 to 161 billion for restoration and ecosystem services (DIKPLH, 2019).

3.4 Ecosystem condition in Balikpapan Bay

Balikpapan Bay, located in Kalimantan, is an area with a rich ecosystem characterized by high biodiversity (Kreb et al., 2020). The bay encompasses a watershed area (Daerah Aliran Sungai, DAS) of approximately 211,456 hectares and a water area of 16,000 hectares. There are 54 sub-watersheds draining into this bay, including the Sei Wain watershed, which is a protected forest known as the Wain River Protected Forest. The bay is also dotted with 31 small islands.

Balikpapan Bay holds significant importance for the surrounding communities. Along its coastline lie traditional fishing villages such as Gersik, Jenebor, Pantai Lango, Maridan, and Mentawir. The livelihoods of thousands of traditional fishermen depend heavily on the natural wealth of Balikpapan Bay. Degradation of the ecosystem has resulted in a decline in income for these fishermen (Ahmadi, 2016). From a conservation perspective, Balikpapan Bay exhibits high biodiversity. The area comprises primary tropical rainforest, secondary tropical rainforest regeneration, mangrove forests, swamps, rocky terrain, coral reefs, seagrass beds, and shallow marine waters. The secondary forest connecting forest fragments to other significant forests includes the Bukit Soeharto conservation area to the northeast and Mount Meratus to the southwest. Its aquatic ecosystems connect to the Makassar Strait to the east (Kristiningrum et al., 2020).

Balikpapan Bay is a habitat for the proboscis monkey (*Nasalis larvatus*). It supports the largest population of proboscis monkeys in the world, estimated at 1,400 individuals, representing five percent of the global total, which is approximately 20,000 to 25,000 individuals. The bay is also home to over 100 other species, including the Bornean orangutan (*Pongo pygmaeus*), Müller's gibbon (*Hylobates muelleri*), Irrawaddy dolphin (*Orcaella brevirostris*), dugong (*Dugong dugon*), and the sun bear (*Helarctos malayanus*). Additionally, more than 300 bird species inhabit the area, such as the Bornean ground cuckoo (*Carpococcyx radiceus radiceus*) and Storm's stork (*Ciconia stormi*) (Boonratana et al., 2021).

From a broader perspective, Balikpapan Bay represents a large ecosystem that benefits not only the city of Balikpapan but also Penajam Regency. The Wain River plays a significant role as a source of clean water. This river serves as the main water supply for oil companies and vital industries in Balikpapan. Other rivers such as Semoi, Lawe-lawe, Riko, and Tempadung are also anticipated to be important future water sources. The forests along Balikpapan Bay function as flood controllers and play a crucial role in regulating the local climate. The potential for sustainable economic development through the utilization of Balikpapan Bay's natural resources is substantial but remains underdeveloped (Ahmadi, 2016).

Based on research conducted by Latifa (2020), the Lawalata team in 2017 it was stated that the locations of marine and terrestrial mammals such as the Irrawaddy dolphin (*Pesut*), *dugong* (sea cow), proboscis monkey (*bekantan*), turtles, and crocodiles are identified. The IUCN Marine Mammal Protected Area Taskforce has recognized Balikpapan Bay as a critical habitat for endangered aquatic mammals. Furthermore, the IUCN notes that the upper regions of the bay and the Riko and Kariangau rivers are important permanent habitats (year-round) for the Irrawaddy dolphin in Balikpapan Bay. The estuaries of Kariangau, Berenga River, and Kwangan Island serve as habitats for dugongs and feeding grounds for other marine mammals (Willard et al., 2022).

The oil spill in Balikpapan Bay has generated a profound and multidimensional ecological crisis, demonstrating how intensive maritime activities can threaten the integrity of coastal ecosystems. The contamination of nearly 13,000 hectares of marine waters and

60 kilometers of coastline resulted in substantial degradation of key ecological zones, including 34 hectares of mangrove forests, coral reefs, seagrass beds, and seaweed cultivation areas. The destruction of these interconnected habitats signifies the loss of critical ecological functions such as shoreline protection, nutrient cycling, fish spawning grounds, and overall ecosystem productivity (Elisha & Felix, 2021; Ogwu et al., 2025). These findings emphasize the urgent importance of biodiversity conservation and ecosystem dynamics within vulnerable coastal environments.

Beyond the immediate destruction of habitats, the spill caused severe disruptions to the broader socio-ecological system (Malakar et al., 2023; Subramaniam et al., 2023). Mass mortality of crabs, plankton, endangered marine mammals, and the decline of bird populations—affected by toxic exposure and loss of feather insulation—illustrate cascading impacts on the marine food web and long-term ecological resilience. These disruptions highlight the necessity of interdisciplinary approaches that integrate ecology, climate adaptation, and human-environment interactions, especially in regions where ecological health underpins social stability and economic livelihoods.

The ecological degradation also produced significant social consequences for coastal communities, particularly traditional fishing groups whose livelihoods depend directly on healthy marine ecosystems (Danquah et al., 2021). Declining fish stocks and damaged coastal habitats exacerbated economic inequalities and disproportionately impacted communities that are often underrepresented in environmental policymaking. This underscores the importance of environmental justice frameworks, ensuring that marginalized voices are integrated into ecological research, governance, and conservation strategies. The study's comprehensive integration of field assessments, satellite imagery, and governmental reports provides a robust foundation for advancing practical, evidence-based ecological solutions. Its findings support the need for strengthened environmental regulation, proactive oil spill prevention mechanisms, and community-based monitoring systems that empower local stakeholders.

3.5 Conditions in Balikpapan Bay after the oil spill

According to satellite data from Indeso KKP, oil pollution in Balikpapan Bay occurred between 2014 and 2017. The cause of seawater pollution prior to 2018 remains unknown. However, the oil spill in April 2018 was confirmed to originate from a broken pipeline owned by PT Pertamina. Satellite monitoring on April 1, 2018, indicated that the oil spill covered nearly 13,000 hectares. The oil spill in Balikpapan Bay has spread to the Makassar Strait. Until now, there has been no government agency routinely monitoring and mitigating oil pollution at sea. As a result, actions taken have been mostly reactive, occurring only after incidents happen (Arif, 2018). Satellite radar imagery monitoring on Sunday, April 1, 2018, revealed that the oil spill in Balikpapan Bay caused various impacts, one of which was damage to the ecosystem. The Oil Spill Response Team reported that the affected areas included 12,145 cubic meters of water in Balikpapan Bay, 30,156 cubic meters in Penajam Paser Utara Regency, and approximately 60 kilometers of coastal shoreline (KLHK Response Team, 2018).

Following the oil spill incident, residents complained of nausea and dizziness due to the strong smell of oil lasting for several days, especially in areas where settlements were still exposed to the oil spill. Additionally, oil layers were still found in the waters, on poles, and under houses affected by tidal changes in Margasari, Kampung Baru Hulu, Kampung Baru Hilir, and Kariangau RT 01 and RT 02 villages in West Balikpapan District. The estimated impacted area due to the oil spill was approximately 7,000 hectares, with a shoreline affected along Balikpapan City and Penajam Paser Utara Regency reaching about 60 kilometers (Balikpapan Bay Civil Society Coalition, 2020).

Balikpapan Bay is vital for the surrounding communities. Along the coastline, there are traditional fishing villages such as Gersik, Jenebor, Pantai Lango, Maridan, and Mentawir. The livelihoods of thousands of traditional fishermen depend on the natural resources of

Balikpapan Bay. Degradation of the ecosystem has caused these fishermen to lose their sources of income (Gusmawati et al., 2020).

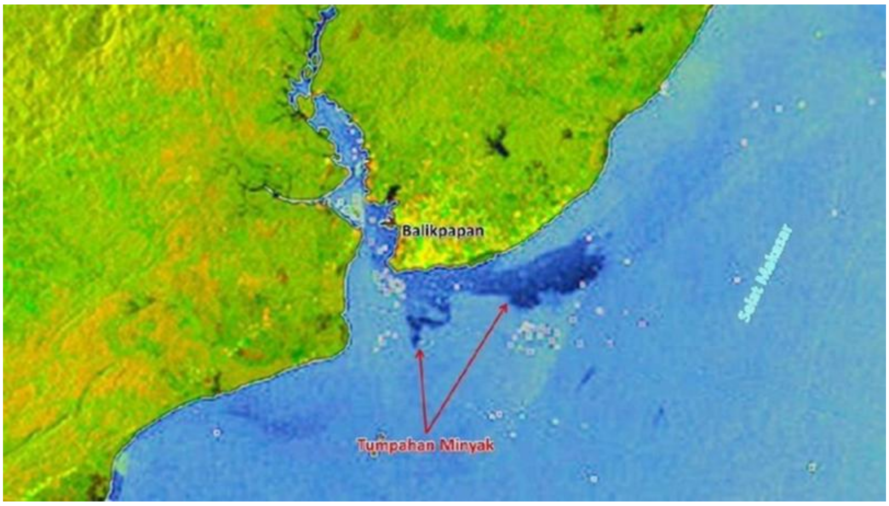

Fig. 3. Satellite image of oil pollution in Balikpapan Bay
(X/Twitter: Sutopo/@Sutopo_PN)

The ecosystem of Balikpapan Bay, including mangroves, seagrass beds, coral reefs, and the wildlife within, serves as a guardian of ecological balance. There are at least six interconnected and essential elements played by this ecosystem: environmental carrying capacity and support, natural service functions, climate change, disaster mitigation, essential ecosystems, and sustainable energy and economy (Balikpapan Bay Civil Society Coalition, 2020).

Fig. 4. Oil pollution in Balikpapan Bay
(Alvin, 2023)

The oil spill caused damage to mangrove plants covering an estimated area of 34 hectares in Kariangau Village RT 1 and 2, and 22 hectares of mangroves in Jenebora Village. According to survey results, 80% of the total mangroves in Jenebora Village were contaminated by the oil spill (Oktawati et al., 2022). Field observations found impacted ecosystems including approximately 34 hectares of mangroves in Kariangau Village RT 01 and RT 02, 6,000 mangrove plants in Kampung Atas Air Margasari, and 2,000 mangrove seedlings belonging to residents of Kampung Atas Air Margasari (KLHK Response Team, 2018).

3.6 Impacts on marine organisms and ecosystems

Coral reef ecosystems are also highly vulnerable to damage from oil spills floating on the water surface, which disrupt the organisms living there, increase water temperatures, block sunlight penetration, and interfere with gas exchange from the atmosphere (Ramadhan et al., 2017). Oil can harm coral reefs due to exposure and the level of toxicity concentration of the oil (Suhery et al., 2017). Chronic oil toxicity can affect coral reproduction, growth, behavior, and development, thereby diminishing the coral reefs' function as a buffer for coastal and marine life and their role in protecting shores from erosion caused by currents, wind, and waves (Ramadhan et al., 2017).

The waters of Balikpapan Bay are home to a diverse range of marine life, including algae, fish, coral reefs, and many other species. The oil spill incident has caused significant environmental problems in and around Balikpapan Bay, affecting the biotic environment within it. The spill has led to increased mortality of aquatic fauna, damage to four coral reef areas, destruction of seaweed cultivation, and harm to five seagrass beds. Additionally, crab populations have died off at Banua Patra Beach (Alvin, 2023).

Seabirds represent one of the taxa most suspectible to oil spill impacts due to their distinctive behavioral patterns and physiological traits. Oil contamination compromises the structural integrity of feathers, impairing their waterproofing and insulation functions, which can result in hypothermia, reduced buoyancy, and subsequent drowning (NOAA, 2023). Druing preening, seabirds ingest adhered hydrocarbons, leading to gastrointestinal disruption, diarrhea, hepatic, and renal injury, and hemolysis (NOAA, 2023). In addition, volatile fractions of wathered oil can be inhaled, causing respiratory distres. Vulnerability assessments conducted in the northern Gulf of Mexico highlight substantial knowledge gaps and underscore the need for enhanced demographic data, improved tracking of seabird movement patterns, and more accurate estimates of residency duration to reduce uncertainty in exposure and impact evaluations (Michael et al., 2022). Oil coating their feathers causes the loss of waterproofing and insulation properties, leading to hypothermia. Additionally, when birds preen themselves, they ingest the oil, which causes internal injuries and often results in death. Oil spills also contaminate the birds' food sources, exacerbating the problem (Sharma et al., 2024).

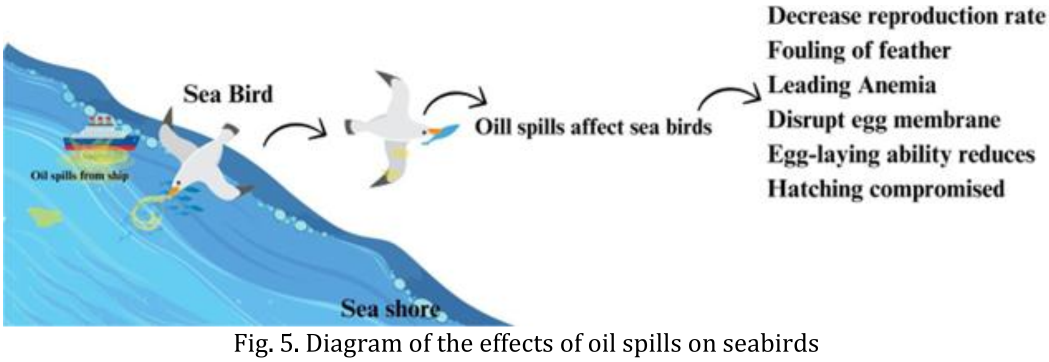

Fig. 5. Diagram of the effects of oil spills on seabirds
(Sharma et al, 2024)

Marine plankton are among the organisms most affected by oil spills due to their limited ability to move against water currents. Research has shown that bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) is high in both phytoplankton and zooplankton (Xia et al., 2023). PAHs cause acute and chronic toxicity, leading to increased mortality rates, altered feeding behaviors and egg cell formation, reduced productivity, and decreased mobility (Cohen et al., 2024).

The ecological responses to oil contamination arise from a combination of direct toxicological effects and indirect processes such as nutrient enrichment. Surface oil layers impede light penetration into the water column, thereby distrupting photosynthetic activity and damaging primary producers (Hettihanthri et al., 2024). At the same time, the biodegradation of petroleum compounds by microbial assemblages depletes dissolved oxygen and releases nutrients, which under certain environmental conditions may promote phytoplankton proliferation. The use of chemical dispersants during spill mitigation efforts adds further complexity by modifying the spatial distribution and bioavailability of hydrocarbons. Although dispersants are intended to enhance degradation processes, their ecological implications remain contested, as studies report divergen findings regarding their toxicity and broader environmental effects (Asif et al., 2022).

3.7 Conservation and remediation strategies

The most effective means of reducing ecological harm from oil spills lies in preventive measures, including stringent safety standards, routine maintenance of operational equipment, and through risk assessments. Although recent technological innovations have contributed to a gradual decline in the frequency of spill events, expanding maritime transport and the intensification of petroleum extraction in remote regions and challenging environmental conditions continue to elevate overall risk levels (ITOPF, 2023; Jayarathna et al., 2024).

Mechanical recovery remains the predominant strategy for responding to marine oil spills and typically involves the deployment of containtment booms, skimmers, and sorbent materials. Booms act as floating barriers that corral and concentrate surface oil, thereby facilitating more efficient removal by skimming devices. Despite their widespread use, mechanical recovery techniques are constrained by several operational limitations, including high costs associated with large scale deployment, reduced efficiency when dealing with thinly spread oil, and significant performance declunes under rough sea conditions (Jayarathna et al., 2024).

Sorbent technologies have advanced substantially, with contemporary research emphasizing both synthetic and bio-based materials capable of selectively absorbing hydrocarbons while repelling water. These include natural sorbents such as peat moss and agricultural by-products, as well as synthetic options like polypropylene and polyurethane foams. Emerging innovations encompass superhydrophobic and oleophilic materials, magnetically responsive sorbents that simplify post-use retrieval, and aerogels with exceptionally high sorption capacities (Jayarathna et al. 2024; Hettithanthri et al., 2024).

Chemical dispersants remain one of the more debated oil spill response tools. Their primary function is to reduce oil droplet size, thereby increasing the oil-water interfacial area and facilitating dispersion throughout the water column. Contemporary formulations such as Corexit EC9500A and Finasol OSR 52 contain less toxic chemical components in an effort to mitigate ecological risks (Asif et al., 2022). Nonetheless, the overall efficacy and environmental consequences of dispersant use continue to be scrutinized. Although dispersants can reduce shoreline contamination by keeping oil offshore, their application introduces additional chemical stressors into marine environments, posing toxicity risks to planktonic organisms, fish larvae, and other sensitive taxa. Research findings remain inconsistent on whether dispersants inhibit or enhance biodegradation, with some studies suggesting reduced microbial activity and others indicating increased hydrocarbon removal as a result of higher oil bioavailability (Asif et al., 2022; Jayarathna et al., 2024). Emerging works seeks to develop biosurfactant-based dispersants that are environmentally compatible and effective across diverse environmental settings, including polar regions (Farooq et al., 2024).

Bioremediation strategies typically follow two pathways : biostimulation, which enhances the activity of indigenous oil-degrading microorganisms through nutrient supplementation, and bioaugmentation, which introduces specific microbial strains or consortia into contaminated environments (Navarro & Caipang, 2024). Biostimulation played a major role during the Exxon Valdez response, where nitrogen-rich fertilizers were applied to enhance biodegradation rates (Atlas&Hazen, 2011). Recent advancements in bioremediation research include the development of synergistic microbial consortia that pair biosurfactant-producing bacteria with hydrocarbon-degrading specices, as well as systems incorporating microalgae and fungsi to support microbial proliferation and enhance degradation efficiency (Navarro & Caipang, 2024). High-throughput sequencing has facilitated the discovery of novel microbial candidates possessing biodegradation or biosurfactant-producing capabilities. Additional studies show that marine macroalgae such as *Caulerpa prolifera* can degrade diesel when supported by hydrocarbon-degrading bacteria inhabiting their surfaces. Innovative approaches such as nano-enhanced bioremediation employ nanoparticles as magnetic sorbents or emulsifiers to increase hydrocarbon bioavailabillity by providing abundant surfaces for microbial attachment and growth (Pete et al., 2021).

4. Conclusions

Balikpapan Bay covers a watershed area of approximately 211,456 hectares and a water surface area of 16,000 hectares. It is a vital region for the surrounding communities, with thousands of fishermen relying on its natural wealth for their livelihoods. The Wain River serves as the main source of clean water, alongside 29 other rivers that flow into the bay. Balikpapan Bay boasts high biodiversity, including primary tropical rainforests, secondary rainforest regeneration, mangrove forests, swamps, rocky lands, coral reefs, seagrass beds, and shallow marine waters. The forests along the bay play crucial roles in flood control and local climate regulation. Furthermore, Balikpapan Bay is home to over 1,400 proboscis monkeys (*bekantan*), more than 300 bird species, and over 100 other wildlife species such as the Bornean orangutan, Bornean gibbon, and sun bear. The IUCN Marine Mammal Protected Area Taskforce has recognized Balikpapan Bay as a critical habitat for endangered aquatic mammals.

Following the oil spill caused by a leak in PT Pertamina's pipeline on April 1, 2018, the affected area spread to nearly 13,000 hectares and extended along 60 kilometers of coastline, even reaching the Makassar Strait. The spill caused significant damage to the ecosystem, including the destruction of 34 hectares of mangrove forests, four coral reef areas, seaweed farms, five seagrass beds, and a massive die-off of marine life, particularly crab species.

Based on these conclusions and considering the critical importance of the Teluk Balikpapan aquatic ecosystem, several recommendations for preventing and mitigating oil spills are proposed: First, the entire northern area of Teluk Balikpapan—from the Pulau Balang Bridge toward Sepaku—should be designated as a National Park, including all waters, mangroves, and a sufficiently wide buffer zone of coastal forest along the mangrove edges. Second, all bekantan habitats (mangrove forests and buffer zones on land), including the southern part of Pulau Balang, should be classified as essential ecosystem areas. Third, all seagrass beds and coral reefs should be designated as marine conservation areas under the Ministry of Marine Affairs and Fisheries/*Kementerian Kelautan dan Perikanan* (KKP) and strictly protected from disturbance or pollution. Fourth, Balikpapan Bay must be preserved as a wildlife corridor connecting the three forest areas, Wain River, Soeharto Hill, and Meratus Mount, meaning protected area boundaries must encompass all forest corridors leading to these regions. Fifth, natural green belt rehabilitation along riverbanks and affected areas is urgently needed. Sixth, coordination among all stakeholders is crucial to ensure that oil spills or other types of pollution do not recur. Prevention efforts should take priority over reactive measures due to the severe damage caused, including the tragic loss of five lives, not to mention other environmental impacts. Seventh, strict monitoring of activities that could cause pollution to water, air, or soil within the Balikpapan Bay area must be enforced to prevent unwanted incidents. Finally, the government should take the lead in properly managing and accommodating the Balikpapan Bay ecosystem to avoid further ecological disasters in Indonesia, especially in areas close to this vital ecosystem.

Acknowledgement
We would like to express my sincere gratitude to Dr. Drs. Suyud Warno Utomo, M.Si., for his invaluable guidance, constructive feedback, and continuous support throughout the development of this article.

Author Contribution
All authors contributed equally to the conception, analysis, writing, and revision of this article.

Funding
This research received no external funding.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
Not available.

Conflicts of Interest
The authors declare no conflict of interest.

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