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Ecological impacts, health risk assessment, and mitigation strategies

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Cases of oil spills in the Indonesian coastal area: Ecological impacts, health risk assessment, and mitigation strategies

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A R T I C L E I N F O

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A B S T R A C T

Oil is still the main source of energy in various sectors, such as transportation, industries, and electricity. As one of the developing countries, Indonesia has enormous activities related to oil, including drilling, transporting, and refining. This paper aimed to provide a review of the cases of oil spills in the Indonesian coastal area as an impact of oil-related activities. Most of the Indonesian oil spill cases occurred due to tanker leakage, pipe leakage, and ship accidents. Most of the well-documented and reported cases of oil spills in the Indonesian coastal area occurred in Java Region, with PT Pertamina (a government-owned oil and gas company) and its subsidiaries being the primary parties commonly involved in the accidents. The ecological impacts of the oil spill, including those on plankton, benthos, fish, birds, and vegetation, are then elaborated in detail. Additionally, health risks to humans are also intensively discussed, presenting acute and long-term exposure effects. This paper presents oil spill management strategies, focusing on the mitigations and regulations related to previous cases, in which cleanup operations and financial compensations were the most frequently implemented mitigation efforts. This paper also lists the options for technologies, including physical, chemical, and biological methods, in an effort to clean up oil spills. Monitoring the adverse effects of oil spills on human health and creating local-specific contingency plans are suggested to be conducted for future research directions.

1. Introduction

Oil is a product that is still used as the main source of energy in various sectors such as industries, transportation, and electricity (Yaqoob et al., 2021). In 2020, global demand for crude oil will reach 91 million barrels per day and is expected to increase to 104.1 million

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barrels per day in 2026 (Statista Research Department, 2023). Based on Ministry of Energy and Mineral Resources, Republic of Indonesia (2021), crude oil production in Indonesia in 2021 will reach 240.4 million barrels, and around 43.8 million barrels will be exported. This showed that Indonesia contributes around 0.13 % of the total global oil demand per day.

In general, the method of transferring oil from one place to another is based on the volume of oil transported and the location distance (Hennig et al., 2012). On the land routes, oil can be moved using rail cars, trucks, pipelines, and tankers (Vergel et al., 2022). Meanwhile, on the sea routes, marine vessels are often used to move it because they can accommodate very large amounts of oil (Huntington et al., 2015). Based on Amelia et al. (2021), the number of modes of oil transportation in Indonesia reached up to 8779 units for the land route and 1537 units for the sea route, with total capacities of around 152,000 kL and 8.6 million kL, respectively. All methods used for oil transport have the potential for oil spills (Negreiros et al., 2022). The oil spill can cause environmental pollution due to the fact that oil contains hydrocarbon compounds and heavy metals that are difficult to degrade (Singh et al., 2020a).

Coastal oil spills, which result in severe environmental harm and economic devastation, are one of the major sources of water pollution (Asif et al., 2022a). Many cases have been reported related to oil spills in coastal areas in various countries, such as Indonesia (Purnaweni et al., 2022a), India (Sivagami et al., 2019), Brazil (Azevedo et al., 2022), Korea (Yim et al., 2017), etc. The oil spill was caused by a distribution pipe leak, tanker operations (ballast water), ship repair and maintenance (docking), mid-sea loading and unloading terminals, ship scrapping, and tanker accidents (Nukapothula et al., 2021; Radović, 2021). In the last 5 years, there have been 4 major cases of oil spills that occurred in Indonesia, which are located in Balikpapan Bay, East Kalimantan Province (March 2018) (Syahrul et al., 2018), Kepulauan Seribu Coast, Jakarta Province (April 2018) (Jabbar et al., 2018), Karawang Coast, West Java Province (July 2019) (Sari et al., 2021a), and Kepulauan Riau Coast (to date) (Purnaweni et al., 2022a). The oil spill caused environmental pollution and damage to ecosystems along coastal areas, such as mangroves, river deltas, estuaries, sea grasses, and coral reefs (Andrews et al., 2021). The impacts of this pollution are that many marine biotas, such as fish, crabs, shrimp, etc., have died, and seaweed cultivation in coastal areas has been damaged (Saadoun, 2015). In addition, if not handled properly, this will have a high impact on the health of the surrounding community, causing irritation, respiratory problems, and general health problems due to consuming food and water contaminated with oil and inhaling air contaminated with oil (Ramirez et al., 2017).

Several steps have been taken by the Indonesian government to deal with oil spills on the coast, including forming an oil spill management team, conducting oil spill clean-ups, and making regulations related to oil spills (Purnaweni et al., 2022a). Several technologies have also been applied to deal with oil spills, such as in-situ burning (Bullock et al., 2019), mechanical clean-up (Tamizhdurai et al., 2022), bioremediation techniques (Imron and Titah, 2018), the use of sorbents (Aydin and Sonmez, 2015), and chemical dispersants (Adofo et al., 2022). Even though this technology has drawbacks, such as very expensive costs, quite difficult operation, and maintenance, and requires skilled human resources, it has been proven to remove oil spills with high efficiency (Adofo et al., 2022; Imron and Titah, 2018; Prendergast and Gschwend, 2014).

Although there is a lot of literature discussing cases of oil spills in the coastal area, there is still limited literature and information specifically discussing cases of oil spills on the coasts of Indonesia that focus on ecological impacts, health risk assessment, and mitigation strategies. Therefore, this review paper will discuss oil spill cases in the Indonesian coastal area more deeply, focusing on ecological impacts, health risk assessments, and mitigation strategies undertaken by the Indonesian government in tackling oil spills in coastal areas. This review paper is structured by describing oil spill issues in general, which are then focused on specific cases in the Indonesian coastal areas. The discussions are then followed by ecological impacts and health risks of oil spills in coastal areas. In-depth analysis of oil spill management and mitigation strategies in Indonesia is then presented, followed by a technological approach and author perspectives. In the future, this review paper is expected to be used by the Indonesian government as a reference in making policies related to the prevention of oil spills in Indonesia.

2. Data exploration methods

Acquisition of the data was accomplished between 1 January 2023 and 1 April 2024. All data was obtained from the Google Scholar database, while relevant information was obtained from the website in accordance with the obtained findings from Google Scholar to expand the discussion, referring to Jusoh et al. (2024). Used search keywords include “oil spill," "Indonesia," and “coastal area." In addition to that, “ecological impact," “health risk," and “mitigation strategy” were further used as additional clauses in the effort of broadening the discussion and selecting the potential papers. All authors were responsible for applying the selected criteria of publication year between 2003 and 2024, and the language used is English or Bahasa Indonesia. A total of 100 articles were selected as potential data to be used in the construction of this review after strictly applying the selection criteria.

3. Oil spill issues

An oil spill is the process of oil or other petroleum products being released into the environment from a tank, pipe, or vessel, particularly into the ocean, both intentionally and unintentionally (Cakir et al., 2021; Negreiros et al., 2022). Oil spills can also potentially harm habitats along coastlines (Corrick et al., 2021), rivers (Grmasha et al., 2023), lakes (Mouradian et al., 2023), and even land areas (Buzmakov and Khotyanovskaya, 2020).

Oil spills can originate from various oil exploration and offshore drilling operations, such as oil drilling, oil refining, and widespread and extensive oil transportation (Zhang et al., 2019; Bhattacharjee and Dutta, 2022). Inadequate or unsafe offshore oil drilling can cause oil spills (Guo et al., 2019). Improper oil refining operations can also cause oil spills (Bebeteidoh et al., 2020). Leaks during oil transportation and storage processes can occur slowly over time or result in sudden and catastrophic releases of oil (Grubesic and Nelson, 2022). Oil spills can also occur due to accidents on oil refining vessels or oil transportation vessels, such as collisions, damage, or sinking (Chen et al., 2019; Chen et al., 2020). Tankers are an example of spills that have a large impact on the ocean and coastlines (Galieriková and Materna, 2020). As reported by the International Tanker Owners Federation (ITOPF) in their Oil Tanker Spill Statistics 2022, oil transportation via tanker has led to the release of approximately 5.88 million tons of oil into marine environments from 1970 to 2022, with around 15,000 tons spilled in the ocean in 2022 (ITOPF, 2023).

Some other factors that cause oil spills include human error from not following proper safety procedures or mistreating oil equipment; damage to oil processing equipment such as pipes, valves, pumps, or storage tanks can cause oil release (Ye et al., 2020). Oil spills can also result from the sabotage of environmental activists or other intentional groups, as well as from natural disasters such as earthquakes, major storms, and tsunamis, which can damage oil equipment and cause oil spills (Zhang et al., 2019).

Oil spills on water can create thin films that spread easily due to environmental factors like waves, winds, and currents (Sundhar and Rajan, 2023). The dispersion of oil droplets in different forms can allow liquid oil to penetrate water and impact the level of hazard it poses to the marine environment (Hoshyar et al., 2023). The actions taken immediately after an oil spill are crucial, as certain clean-up efforts can worsen the harm caused by the oil, making the rehabilitation process more challenging or even impossible (Huz et al., 2019). The effectiveness of oil spill cleanup efforts is determined by multiple variables, including the kind and amount of oil spilled, its location, climate, and ocean conditions (Colvin et al., 2020). Therefore, it is important to take appropriate preventive measures and have an effective response plan to minimize damage from oil spills, that is, by preventing oil spills from occurring and properly managing them if they occur to limit their duration and impact (Crivellari et al., 2021).

4. Oil spill cases in the Indonesian coastal area

Table 1 shows various oil spill events in Indonesia on a large scale. Most of the smaller oil spill cases in Indonesia were still left unreported, and mitigation related to the small oil spill incident is very low.

Referring to Table 1, there were so many environmental challenges that needed to be faced due to the oil spills. It was documented that the majority of the oil leak incidents took place in the Java regions of Indonesia, as it is the most populated region and the place of the capital city of Indonesia. There have been numerous incidents in West Java, such as the 2019 spill in Karawang Regency and the 2021 oil escape at the ONWJ facility. Multiple incidents, including the 2021 oil escape and the 2020 pipeline failure in Jakarta, as well as the 2017 spill in Cilacap and other earlier events in Central Java.

PT Pertamina and its subsidiaries are the parties that are most frequently involved in the incidents. The most frequently referenced state-owned oil and gas company is PT Pertamina, which has been involved in a number of incidents across various locations and years. PT Pertamina's subsidiaries and operations, including PT Pertamina Hulu Energi Offshore Northwest Java (ONWJ), are also frequently implicated.

The contamination of beaches and the devastation of marine life are the most frequently reported impacts of the incidents. The mortality of fish and other marine organisms, as well as the destruction of mangrove forests, coral reefs, and seagrass beds, as referring to the case in Balikpapan City in which 34 ha of mangrove and 7000 ha of water were covered in oil. Numerous incidents resulted in health complaints from the local population and, in certain instances, fatalities. For example, the Balikpapan oil spill resulted in five fatalities as a consequence of the conflagration that ensued. Local economies, particularly those that depend on fishing and seaweed cultivation, were also impacted by the incidents. For instance, the Montara oil spill resulted in a substantial 50–85 % decrease in income for seaweed producers and fishermen.

Cleanup operations, legal and financial compensations are the most frequently reported mitigation efforts. Oil booms were implemented in numerous instances to regulate and restrict the dispersion of oil in the water. This was followed by extensive cleansing operations, which frequently required the use of both manual labor and machinery. Additionally, numerous incidents resulted in legal proceedings and requests for financial compensation. This necessitated compensating communities that were impacted and undertaking environmental restoration initiatives. For instance, the Ministry of Environment and Forestry filed a lawsuit against PT Pertamina in the wake of the Balikpapan oil disaster, resulting in a compensation request of 150–161 billion IDR for environmental restoration and ecosystem services. In some major cases, the closure of the operational site and some local government regulations were established as a response to the case and a precaution for future similar incidents.

5. Ecological impacts of oil spills in Indonesia

Depending on the location and volume of the spill, an oil spill may have substantial effects (Asif et al., 2022b). Petroleum-based oils are altered and moved by water currents, wind impacts, and biological processes when they reach a water body (Nazir et al., 2008). The high mobility and phase transition of the oil portion at sea (e.g., through evaporation or absorption) might lead to a much greater impact radius. Dispersion, evaporation, dissolution, emulsification, and sedimentation are just a few of the processes that oil spills in the water go through (National Research Council (US) Committee on Oil in the Sea: Inputs, 2003). Oil spills in the sea change quite differently from spills on land because of the impacts of wind and currents (Asif et al., 2022b). In the absence of surface cover (such as vegetation), mixing intensity brought on by wind and sea conditions leads volatile organic compounds (VOCs) to be transferred by evaporation (Tansel, 2014).

Direct and indirect effects are the two main kinds of effects of offshore oil spills. Local and regional effects are classified depending on the area of impact dispersion. Waste in the form of an oil spill specifically shows a significant negative impact on the coastal environment and marine waters, as well as a direct impact on fishing activities, including marine tourism, and an indirect impact through environmental disruption. This is especially true of direct contact with aquatic organisms. Due to high concentrations, direct impacts on organisms can have fatal consequences for marine species like fish (National Research Council (US) Committee on Oil in the Sea: Inputs, 2003). And the sublethal effect that can be precisely demonstrated by laboratory testing, including if it alters the aquatic creatures' health, including their capacity to lay eggs (Alonso-Alvarez et al., 2007). In general, oil spills affected marine plankton, benthic invertebrate, fish, birds, vegetation, and the marine ecosystem (Fig. 1).

5.1. Impact on marine plankton

Marine planktonic organisms suffer the most from the oil spill's effects, as they are incapable of moving against water currents. It was reported that the bioaccumulation of polycyclic aromatic hydrocarbons (PAHs), including pyrene, phenanthrene, and anthracene, was high in phytoplankton and zooplankton communities (Xia et al., 2022; Zhang et al., 2023). PAHs also showed acute, chronic, and sublethal toxicity that caused an increase in mortality rate and physiological activity alteration in various species and life stages of meso- and micro-zooplankton and copepods (Almeda et al., 2014). Acute toxicity, changes in feeding pattern, delayed egg formation, low hatching rates, decreasing movement speeds, and abnormal reproductions were reported by previous research (Cohen et al., 2014; Hansen et al., 2015; Singh et al., 2020b).

5.2. Impact on benthos

Benthos is often referred to as a varied community of animals living on the ocean floor close to deep-sea deposits. Even though these communities have low vulnerability to the toxicological effects of oil in the offshore, they might still be affected by the high concentration of hydrocarbons during the oil spill (de la Huz et al., 2005). Previous research reported abnormalities in carbohydrate metabolism that affect small invertebrates such as amphipods. Increasing death rates, impairment in reproductive capability, changing hormonal cycles, and alteration of transcriptomes were also reported (Hook et al., 2014). The oil spill also caused significant changes in the macrofauna population, such as isopods, amphipods, and polychaetes, as well as the decreasing mobility of subtidal benthos (Junoy et al., 2005). The bioaugmentation phenomenon also occurred due to the consumption of plankton by some benthic organisms.

5.3. Impact on fish

As the most economically valuable element of the marine ecosystem and a major source of food (Kurniawan et al., 2021), marine fish are also severely affected by oil spills, with the highest effect mostly visible to humans being fish deaths after incidents (Wibowo, 2018). At a low concentration (0.5 g/L), PAHs in oil affected the embryo's development, causing cardiac dysfunction, morphological impairment, abnormal organ development, death of neural cells, and cardiotoxicities (Incardona et al., 2013, 2004). Adult fish that are exposed to high oil concentrations may have slower swimming speeds, decreased aeration capacity, heart failures, a decline in cardiovascular output, and acute

Table 1
Oil spill cases in Indonesia.

No.	City, Province	Date	Case	Involved parties	Losses	Damage	Mitigation	Reference
1	Untung Island, Kepulauan Seribu, Jakarta	25 April, 2021	PT Pertamina Hulu Energi Offshore Northwest Java (ONWJ) pipe leakage in YYA−1 well	PT Pertamina Hulu Energi Offshore Northwest Java (ONWJ)	Uncounted	Coastal damage and sand contamination.	Cleaning by Pertamina's ship. Technical recommendation from the Ministry of Environmental and Forestry.	(Seneque, 2021)
2	Pari Island, Kepulauan Seribu, Jakarta	12 August 2020	Pipeline Zuluu facility oil spill spot	PT Pertamina Hulu Energi Offshore Northwest Java (ONWJ)	Uncounted	2 kilometers of coastal contamination, with dead fish and damaged seaweed cultivation.	Cleaning using a fish cone. Coordinate with the Pulau Panggang and Pulau Pramuka peoples. Shut production down.	(National Transportation Safety Committee, 2023)
3	Monpera Beach	8 March 2020	Oil spill contamination Monpera Beach	Unidentified tanker unloading process	Uncounted	Coastal contamination and sand contamination	Investigation by police.	(Suriyatman, 2020)
4	Kuala Idi, East Aceh Regency, Aceh	2020	Oil spill in Kuala Idi Beach H−4 Langsa Offshore well	PT Pertamina	Uncounted	Sea ecosystem damage (mangrove, coastal, and seagrass) and fishing activity disturbance.	Investigation, oil spill modelling, and inspection used helicopters and 13 ships.	(Directorate General of Marine Space Management, 2021)
5	Karawang Regency, West Java	12 July 2019	Oil spill in Java Sea caused by leaking well and pressure imbalance in the well bore (well kick) in the YYA−1 Block Offshore Northwest Java (ONWJ)	PT Pertamina Offshore Northwest Java (ONWJ)	3000 barrels of oil	Effect on an 84 kilometers-wide spreading sea area. This oil spill polluted three provinces, 7 districts, 22 districts, and 57 villages	Closure of the YYA−1 well using a relief well. PHE ONWJ's efforts to localize the oil by operating a static and movable oil boom and sucking up spilled oil. Deployed 30 boats, a 3500-meter offshore oil boom, a 3000-meter shoreline oil boom, a 700-meter fishing net, and a lift-up and sent more than 5,53 million sacks of oil-contaminated sand to a legal waste management operator.	(Friana, 2019; Sari et al., 2021b)
6	Banjarmasin, South Kalimantan	25 May 2018	The burning of the SPOB Srikandi 511 vessel at Pertamina's Jetty III BBM Terminal	PT Pertamina	138.290 barrels of oil	The length of the fire that burned the seven ships was about 300 m from the location, and pollution of the surrounding environment due to the spilled oil	Oil booms are installed around the jetty to stem the oil spills.	(National Transportation Safety Committee, 2023)
7	Balikpapan City, East Kalimantan	31 March 2018	Balikpapan oil spill was caused by a cracked pipeline linked to Pertamina Refinery in Balikpapan. MV. Ever Judger's anchor hit and stacked on Pertamina's oil pipe, causing the pipe rupture.	PT Pertamina (Persero)	18.000 barrels and 5 peoples were killed since catch fire	34 ha of mangrove forest are contaminated, causing health complaints, deaths, and endangered dolphins. There are also 7000 ha of water contamination. Spreading area of 13000 acres in Balikpapan Bay.	The Ministry of Environment and Forestry sued in court, and PT Pertamina was requested to pay compensation of $10–15 billion for ecosystem services, environmental restoration, and environmental dispute settlement.	(Ahyadi et al., 2021; Chow, 2018; Kahfi, 2018)
8	Bayur Coast, West Sumatra	29 September 2017	Pipe leakage	PT Wira Innomas	50 tons of palm oil	1 hectare of air surface contamination, 500 m of coastal bleaching	Unreported	(BBC Indonesia, 2017)
9	Cilacap Offshore, Central Java	20 May 2015	MT Martha Petrol Leakage	PT Pertamina UP IV Cilacap	24.000 kiloliters of Middle Fuel Oil (MFO) 180 and 5.000 kiloliters of Middle Fuel Oil (MFO) 380	Unrecorded	Unreported	(Wibowo, 2018)

(continued on next page)

Table 1 (*continued*)

No.	City, Province	Date	Case	Involved parties	Losses	Damage	Mitigation	Reference
10	Southern coast of Kota Ternate, North Maluku	30 July 2013	MT Ptriot Andalan Tanker Sank	PT Pertamina Terminal facility (TBBM)	4000 tons of solar and 1400 tons of premium oil fuel	Several oil well blowouts have occurred off the coasts of Balikpapan and Madura. Spread until 500 m.	The response to the incident was handled by the terminal staff and the local Indonesian Coast Guard.	(National Transportation Safety Committee, 2023)
11	Timor Sea	21 August 2009	Montara oil rig in the Atlas Block of Northwest Timor spillage	PTT Exploration and Production Public Company	More than 2500 barrels of oil loss	A total of 90.000 square kilometers of the Timor Sea were polluted, crossing about 13 regencies and cities in Nusa Tenggara Timur. The destruction of tens of thousands of hectares of coral reefs. The income of seaweed farmers and fishermen decreased between 50 percent and 85 percent.	Observation and sampling in the Timor Sea with the results the total distribution of oil spills in the Timor Sea based on satellite imagery monitoring from August 30 to October 3, 2009, covering an area of 16,420 km. The government formed Montara Task Force that still work until now. Pursue compensation to the company by an Australian court where the company exists for A $34,000 in damages (still going).	(Ambarwati, 2021; Indonesia Water Portal, 2022)
12	Cilacap Regency, Central Java	4 April 2008	Sipat Island Tanker leakage	Local parties	18.500 kiloliters middle fuel oil (MFO)	Coastal damage 0–3 miles from an area with dead fish, dead birds, sand contamination reported	Unreported	(Wibowo, 2018)
13	Balongan, Indramayu Regency, West Barat	27 January 2008	MT Pendopo ship fire and pipe hose leak	Director of Sea Relations	Uncounted	Naphtha and crude oil pollution	Unreported	(National Transportation Safety Committee, 2023)
14	Kotok Island, Jakarta	June 2007	Oil spill	PT Pertamina, BP MIGAS, PT. CNOOC SES Ltd, BP West-Java	Uncounted	Tar ball lumps 4–5 cm thick form 1–2 kilometers of stretch around Kotok Island. The oil spill polluted the waters of several islands, from Kotok Besar Island, 20 miles north of Ancol, North Jakarta, to Harapan Island, 10 miles northeast of Kotok Island. Oil plumes pollute the beaches of tourist areas and settlements on 20 islands in the region.	Unreported	(Tempo, 2007)
15	Bintan Regency, Riau	2 January 2005	Tanker collision	Collision between oil tanker Al-Yarmouk and bulk carrier Sinar Kapuas	$\pm$ 33.000 barrels of Madura crude oil	11 nautical miles northeast of Pedra Branca, spreading of oil from Singapura to Bintan Island	Unreported	(National Transportation Safety Committee, 2023)
16	Penyu Coast, Cilacap Regency, Central Java	10 September 2004	Lucky Lady Tanker spillage	PT Pertamina UP IV Cilacap	5.300 m^3 crude oil	Coastal damage miles from area and sand contamination	Unreported	(Wibowo, 2018)
17	Kepulauan Seribu, Jakarta	28 December 2003	Oil spill incidents originated from ship accidents in Tanjung Priok Harbor and the ALKI I	PT Pertamina, BP MIGAS, PT CNOOC SES Ltd., BP West-Java	Uncounted	The oil spill polluted 78 of the 87 islands that are included in the National Park area.	Unreported	(Suhery et al., 2017)

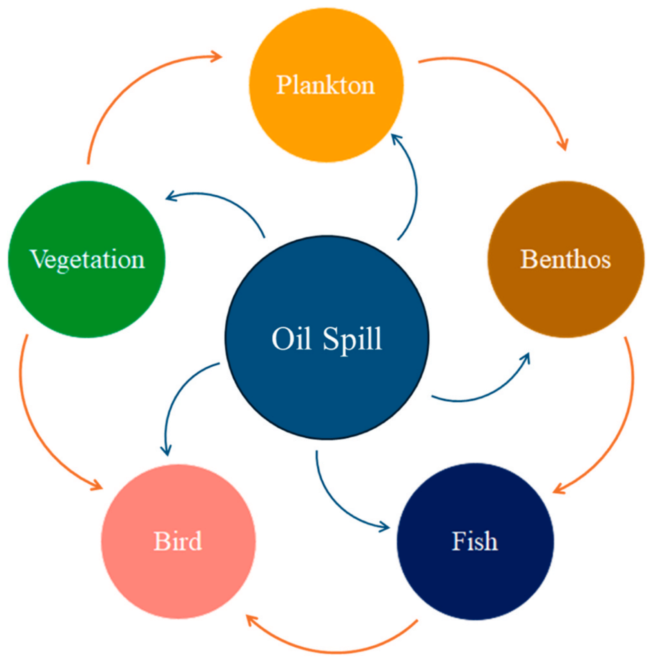

Fig. 1. Ecological impact of oil spills.

cardiotoxicity. The sub-lethal effects of PAHs have been demonstrated by previous research, including fish eggs and larval mortality, reduced development and feeding rates, genetic damage, increased vulnerability to starvation, and an inability to escape predators (Hicken et al., 2011; Langangen et al., 2017; Meier et al., 2010). Consumption of benthos by fish may also lead to the bioaugmentation of pollutants in the food web.

5.4. Impact on birds

Birds, such as shorebirds and seabirds, are particularly sensitive to and at risk from oil spills due to the potential for inhalation, ingestion, and contact with oily substances. Direct contact with oil caused birds to lose some functional feather capability, resulting in drowning and hypothermia (Tran et al., 2014). The presence of oil in a bird's feather causes an alteration of insulation and buoyancy capabilities, affecting their ability to navigate and fly and reducing their body heat, which may then lead to death, which is mostly visible after the incidents (Wibowo, 2018). Inhalation and ingestion of PAHs cause chronic effects, including anaemia, immunotoxicity, and pathological abnormalities of the thyroid, lungs, kidneys, liver, and glands (Troisi et al., 2016). Carnivore birds consuming oil-exposed fish may also lead to further accumulation via bioaugmentation mechanisms.

5.5. Impact on marine vegetation ecosystem

Dissolved crude oil had negative impacts on corals, including smothering, coating, decreasing growth rate, decreasing lipid level, morphological alteration, bleaching, and decolouration (Meyer et al., 2016). Another reported effect of oil on corals was leaf wilting and loss, root deformation, and root pneumatophores, which were caused by the decreasing oxygen flow in mangrove ecosystems (Duke, 2016; Lewis et al., 2011; Naidoo et al., 2010). The change in underwater vegetation have impacts on the surrounding micro- and microorganism species. The impact of oil spills on inland vegetation may also affect organisms' living habitat, especially birds and mammals. Oil spills also caused vegetation stress in coastal areas, especially for seaweed species. It was reported that seaweed cultivations are severely damaged in Pari Island, Kepulauan Seribu, Jakarta (National Transportation Safety Committee, 2023), while farmers are also reporting a decrease in revenue of up to 85 % after the Montara oil spill incident in the Timor Sea (Ambarwati, 2021; Indonesia Water Portal, 2022).

6. Health risk of oil spills

In addition to impacting the environment, oil spills also pose health risks to humans. Previous studies addressed the short-term health impacts of exposure to oil spills on cleaning personnel and local inhabitants, while studies on long-term effects focused on the workers (summed in Fig. 2).

Concentrated on symptoms reported by people who had been exposed and that were obtained through the use of standardized questionnaires, while the unexposed controls were included in five of the investigations. The following symptoms, listed in decreasing frequency (Levy and Nassetta, 2011), are reported to have occurred in some oil spill cases, including:

1. Respiratory symptoms such as runny nose, coughing, shortness of breath, painful throat, and other throat problems,
2. Eye problems, such as irritated eyes and painful, itchy, and/or reddened eyes,
3. Migraine,
4. Skin lesions and symptoms such as redness, itching, irritation, and dermatitis,
5. Nauseas,
6. Dizziness,
7. Feeling weary or exhausted.

According to previous research, those who were exposed more intensely and/or for a longer length of time, such as cleaning workers and community members, tended to experience symptoms more frequently (Laffon et al., 2016). Thousands of studies on the chronic (as well as acute) health effects caused by oil's constituents, such as benzene and other organic solvents and PAHs, have been published in the medical and scientific literature. However, there have been relatively few studies on the effects of exposure to major oil spills on chronic health. D'Andrea and Reddy (2018) reported the correlation of long-term oil exposure to the development of chronic rhinosinusitis and reactive airway dysfunction, as well as pulmonary and cardiac function abnormalities.

7. Oil spill management strategy in Indonesia

Oil spills that have occurred repeatedly in Indonesia have posed a threat and had a negative impact on sustainable development in Indonesia's coastal areas. In the context of policy, the state and/or government have an important role to play in ensuring the realization of sustainable development through policy (Olawuyi, 2012). The existence of a policy regarding the regulation of oil spills in Indonesia aims to prevent, reduce, and control pollution (Purnaweni et al., 2022b). Constitutionally, as stipulated in the 1945 Constitution Article 33 Paragraphs 2 and 3, as well as clarified by the Law of the Republic of Indonesia Number 22 of 2001 concerning oil and natural gas, it is explained that oil resources are one part of the production of non-renewable strategic natural resources. dominate the lives of many people and are controlled and used by the state as much as possible for the prosperity and welfare of the people because it is a vital commodity that has an important role in the national economy. So that the state is one that must act as the biggest responsibility in carrying out the public interest.

Most of the oil spill cases in Indonesia do not only originate from an imbalance in domestic shipping activities, such as the rampant disposal of liquid waste and oil waste from port activities, as well as offshore exploration and exploitation of petroleum, but also originate from ships. international ships sailing through Indonesian waters (Purnaweni et al., 2022b; Zacharias et al., 2021), which resulted in a high intensity of oil

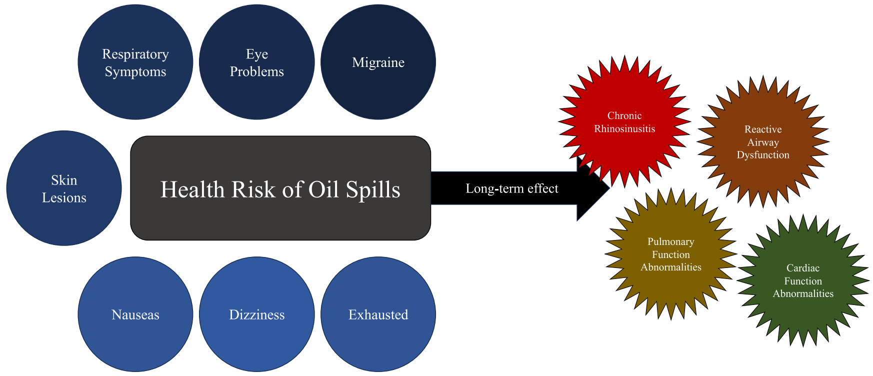

Fig. 2. Health risk of oil spills to humans.

spills that occurred in Indonesia. In fact, Law Number 17 of 2008 concerning Shipping has regulated shipping activities based on safety, security, and protection of the maritime area, including the sea along with archipelagic waters and Indonesian inland waters.

The strategy for handling oil spills in Indonesia is regulated in Law No. 32 of 2009 concerning environmental management. In addition to this law, the handling of the oil spill case has also been emphasized through Presidential Regulation Number 109 of 2006 concerning the management of oil spill emergencies at sea by instructing the Ministry of Maritime Affairs and Fisheries (KKP) as a member of the team involved in tackling pollution caused by oil spills at sea. Based on Presidential Regulation Number 109 of 2006, the Ministry of Maritime Affairs and Fisheries issued a Decree of the Minister of Maritime Affairs and Fisheries Number 54/KEPMEN-KP/2016 concerning the Team for Mitigating the Impact of an Oil Spill on Marine Resources and Fisheries, where one of the important points in the regulation is to provide directives to the regional government to form a Regional Team for Emergency Management of Oil Spills at Sea, which functions to facilitate monitoring and coordination between the Regional Teams and the National Team for cases of oil spills that occur.

The Presidential Decree Number 109 of 2006 contains the importance of the existence of a National Team for Emergency Response to Oil Spills at Sea, which consists of 13 ministries and government agencies, chaired by the Minister of Transportation and the Ministry of Transportation as the person in charge of the National Oil Spill Coordination Center (Anggraeni, 2019). The government's efforts to deal with oil spill cases nationally are strengthened by several regulatory discretions at the ministry level, as above, which cover the Decree of the Minister of Maritime Affairs and Fisheries No. 54/KEPMEN-KP/2016 concerning the Team for Mitigating the Impact of Oil Spills on Marine Resources and Fisheries and Regulations Minister of Environment Number 7 of 2014 concerning Environmental Losses Due to Pollution and/or Environmental Damage. The three components of costs that must be paid by polluters to handle oil spills are divided into:

a. Operational costs for responding to an oil spill emergency,
b. Operational costs for countermeasures due to environmental impacts, community losses, and restoration of environmental damage, as well as reimbursement for countermeasures costs,
c. Rehabilitation costs, including long-term monitoring costs and loss of fishery resources.

In general, in efforts to deal with oil spills that occur, the government tends to use prevention, response, and recovery methods and strategies. However, so far, efforts related to the formation of regulations regarding the handling of oil spill cases by the government have focused more on restoring the environment from piles of waste, both oil spills and other chemicals. Government regulations related to oil spill response strategies in Indonesia are summarized in Table 2.

Table 2
Indonesian government regulations pertaining to oil spill response strategies.

No	Government regulations	The impact on oil spill response strategies
1.	Presidential Regulation Number 109 of 2006 concerning the Management of Oil Spill Emergencies at Sea	Every company, unit, or person is responsible for dealing with emergencies involving oil leaks at sea as a result of their business and/or activities.
2.	Law Number 27 of 2007 concerning the Management of Coastal Areas and Small Islands	Prohibition of oil mining, which has an impact on environmental damage
3.	Law Number 32 of 2009 concerning Environmental Protection and Management	Anyone who causes pollution or damage to the environment is responsible for cleaning up the mess and restoring the function of the environment.
4.	Regulation of the Minister of Transportation Number 58 of 2013 concerning the Prevention of Pollution in Waters and Ports	Each company must have oil storage facilities in the waters, and port activities must meet pollution prevention standards, including personnel procedures and equipment.
5.	Regulation of the Minister of the Environment Number 7 of 2014 concerning Environmental Losses Due to Pollution and Environmental Damage	Determine and calculate environmental losses.
6.	Decree of the Minister of Maritime Affairs and Fisheries Number: 54/KEPMEN-KP/2016	Establish national and local teams to handle oil spill cases.
7.	Decree of the Minister of Transportation Number 263 of 2020	Budgeting for the cost of handling an oil spill is under the authority of the local government.
8.	Presidential Regulation Number 76 of 2022 concerning the International Convention Regarding Preparedness, Countermeasures, and Cooperation Related to Oil Pollution, 1990	Fulfillment of human rights and constitutional rights of citizens in accordance with 1945 Constitution Article 28 H and increasing the protection of maritime areas, especially against the threat of oil spills at sea.

Considering that the impact of an oil spill can have long-term implications for the environment, it is necessary to establish national, regional, and international policies, for example, in granting compensation rights to the aggrieved party (Albert et al., 2018; Olawuyi, 2012). Therefore, in order to implement the 1945 Constitution Article 28 H, on April 28, 2022, the President of the Republic of Indonesia issued Presidential Regulation Number 76 of 2022, which aims to fulfill the human rights and constitutional rights of citizens and increase protection in the maritime environment, in particular against the threat of oil spills at sea. Therefore, the role of communication between the government, private industry, volunteers, and local communities is considered one of the important pioneers in dealing with oil spill cases (Chun et al., 2020).

8. Technological approach on oil spill issues

8.1. Choosing the appropriate oil spill treatment method

Every incident of an oil spill in the sea provided a challenge to keep learning and preparing better treatment technologies for the future. Oil spills generally occur in two stages, namely the initial and final stages. The initial stages were characterized by the dispersion, evaporation, and emulsification of the oil in the environment. The final stages were characterized by sedimentation, oxidation, and biodegradation. Knowledge related to the oil spill stages could be one of the basics in selecting a treatment method. Factors that could be considered in the selection of oil spill treatment technology were as follows: understanding of oil characteristics, changes in properties over time, and influence of oil characteristics to the effectiveness of technology (Ivshina et al., 2015); Characteristics of the contaminated marine environment, such as temperature, wind conditions, seabed properties, waves, currents, and weather (John et al., 2016); the location of the oil spill (surface or deep-sea spill and proximity to the coastline) (John et al., 2016); the toxic effects of technology to the environment (Marti et al., 2014); type of oil spill (early and late stages); spilled oil volume; and cost-effectiveness (Singh et al., 2021).

Types of oil spill treatment technologies were as follows: physical (booms, skimmers, and adsorbents), chemical (dispersants), and biological (microorganisms, biosurfactants) (Fig. 3). However, many people think that cleaning up oil spills in the seawater still leaves oil residues that could easily spread and pollute the seawater. Therefore, a combination of several types of technologies and local jurisdictional methods (fines based on spilled oil residue after processing) continued to be developed to increase the effectiveness of processing results (Tuan Hoang et al., 2018).

8.2. Oil spill treatment technologies

8.2.1. Physical technologies

Physical technology is aimed at controlling and inhibiting the spread of oil spills in seawater. The physical method does not change the physical and chemical characteristics of oil spills (Tuan Hoang et al., 2018). Some of the physical treatment technologies, including booms, skimmers, and adsorbents, are detailed in the paragraphs below.

Booms: Booms were used to prevent the spread of oil spills in the seawater. Boom effectiveness was influenced by boom designs, types, velocity characteristics, wind directions, and wave characteristics (speed and height) (Tuan Hoang et al., 2018). There were three types of booms: fence booms, curtain booms, and fire-resistant booms. Fence booms were lightweight and corrosion-resistant, with floating structures. Curtain booms were made of polyurethane, polystyrene, and bubble wrap, with a structure of circular chambers and full foam to keep them afloat. However, curtain booms were more difficult to clean up and store than fence booms because they were heavier and taller. The fire-resistant booms were constructed of fire-resistant materials to prevent possible explosions and fires from oil spills. Fire-resistant booms were heavier to pull than curtain booms.

Skimmers: Skimmers were used to retrieve and collect oil spills in the seawater after the spill area was limited by boom treatment. The physical and chemical characteristics of the oil spill were not changed so that the oil could be reused. The effectiveness of the skimmers was affected by weather conditions, the thickness of the floating oil spill, velocities, waves, and wind. The advantages of skimmers compared to booms were that they were self-propelled and were towed and operated by ships from the shore. The types of skimmers were: oleophilic, weir, elevating, submersion, suction/vacuum, and vortex/centrifugal. The oleophilic and submersion skimmer types had greater effectiveness and speed of oil removal than the other types, respectively 75–95 %, 0.2–5 m^3/h, and 70–95 %, 0.5–80 m^3/h (Tuan Hoang et al., 2018).

Adsorbent materials: Adsorbent materials were used to absorb the remaining oil spills in the seawater after booms and skimmers. Adsorbent materials had a high rate of absorbing oil and repelling water. They changed the liquid oil into a semisolid material. The adsorbent materials were usually squeezed to remove the absorbed oil so that it could be reused or safely disposed of. The effectiveness of the adsorbent was influenced by its recyclability, absorption rate, and capacity. The use of adsorbent materials in oil spill preparation was the most effective and inexpensive physical technology compared to others. There were three types of adsorbents: inorganic adsorbents, natural organic absorbents, and synthetic organic materials (Tuan Hoang et al., 2018).

The use of natural organic adsorbents was considered the most environmentally friendly technology, so many developments had been carried out to increase the effectiveness of oil removal. Oil spill treatment using low-cost natural adsorbents is one of the most important challenges in the world. Carbonized peat moss (250 °C) modified with acetic acid increased the absorption capacity from 8 to 15.7 g/g (Olga et al., 2014). Modified palm fibers had an adsorption capacity of 35.71 g diesel oil/g adsorbent (Abdelwahab et al., 2017). Expanded perlite and natural zeolite were used as oil spill adsorbents with respective adsorption capacities of 3.50 g/g and 2.21 g/g (Danehpash et al., 2018). The adsorption capacity of expanded perlite with high surface area and high porosity showed good results when compared to natural zeolite. Based on these studies, it could be interpreted that the various ways to increase the active surface area could increase oil adsorption. In addition, the natural sorbents were cheap and abundantly available (Zamparas et al., 2020).

Additionally, there is another method to clean up the oil spill, which is in-situ open burning. Despite its cheap and easy operation, this method is highly not recommended due to the formation of toxic hazardous gases as byproducts of burning (Adofo et al., 2022). The physical technology of an oil spill could clean up oil quickly and with high effectiveness. However, the limitations of this technology were that it was flammable, expensive, must be used with other technologies, complicated, and generated new waste in aquatic environments (Galblaub et al., 2016; Tuan Hoang et al., 2018).

8.2.2. Chemical technologies

Chemical technologies for oil spill treatment aim to control and

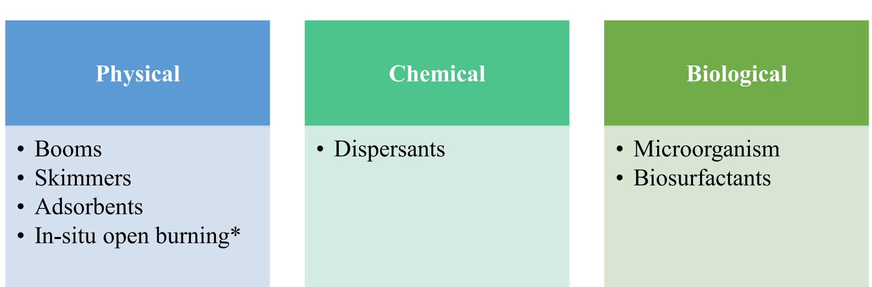

Fig. 3. Oil spills treatment technologies (*Not recommended).

remove oil spills by changing their physical and chemical characteristics. Generally, chemical technologies were carried out after the physical technologies in oil spill cleanup. This technology was fast, easy to apply, and inexpensive. However, the limitation of this technology was the presence of new waste from chemicals added to the environment (Leslie et al., 2021).

Dispersants were one type of chemical technology in oil spill treatment that was widely used and continued to be developed. Dispersant formulations are mixtures of surfactants that dissolve in one or more solvents. Dispersants contained two functional groups, namely hydrophilic (binding water) and lipophilic (binding oil). Surfactants contained active compounds that could reduce the surface tension of the oil film and increase the dispersion of oil in the water (Adofo et al., 2022; Leslie et al., 2021).

An amphipathic property of surfactants, dispersants, was used in oil spills to disperse the oil-water contact. Additionally, the hydrophilic phase of the surfactant molecule dissolved in the water, while the lipophilic phase of the molecule adhered to the oil. As a result, there was less surface tension between the two substances. The waves' agitation may cause the oil molecules to separate into individual droplets (oil drops) that float in the 5–10 m water column below the surface and range in size from 1–70 m (Tuan Hoang et al., 2018; Zheng et al., 2022). The created droplets were then diluted in the water column and stabilized by adsorption surfactant molecules. Furthermore, marine bacteria in the sea degraded the oil droplets. (Farahani and Zheng, 2022).

The highest efficiency of oil spill removal in saline conditions was 48.19 % using Tween-80 (Leslie et al., 2021). A mixture of surfactant (Brij-58) and solvent (1,2-dimethylbenzene) could remove 93 % of oil spills, while surfactant alone (Brij-58) could remove 67.65 % of oil in 4 hours. The use of a mixture of surfactants and solvents could increase the efficiency of oil spill removal compared to surfactants alone. This was because the administration of solvents was synergistic and acted as a catalyst in the solubilization, extraction, and desorption of pollutants (Gao et al., 2021).

8.2.3. Biological technologies

Biological technologies (biodegradation) for cleaning up oil spills were carried out by using microorganisms (bacteria, fungi, yeast), biosurfactants, and plant-based biosurfactants to break the bonds of complex and toxic compounds in oil into simple and less toxic compounds in their metabolic processes (as food substances) (Rahmati et al., 2022).

Microorganisms: Biodegradation of oil spills could use indigenous microorganisms or add hydrocarbon-degrading microorganisms. The microorganisms used had the ability to degrade hydrocarbons and petroleum compounds in oil spills. The duration of biodegradation was influenced by the complexity of the compounds contained in the oil. The more complex the compound, the longer the biodegradation process will take. Factors affecting biodegradation were nutrient bioavailability, concentration and volume of oil spills, and temperature. Biological methods were suitable for various weather conditions, were relatively low-cost, and the final products (CO_2 and H_2O) were environmentally friendly (Rahmati et al., 2022). Microorganisms that had the ability to remove oil spills were *Pseudomonas aeruginosa*, *Aspergillus niger*, *Alcanivorax*, *Marinobacter*, *Prosthecochloris*, and others (Indah Sutiknowati, 2011; Ojewumi and Ejemen, 2018). The bacterial strains *Alcanivorax*, *Marinobacter*, and *Prosthecochloris* were known to have the highest efficiency in total petroleum hydrocarbon (TPH) removal (90–99 %) and could survive up to 90 days in the oil spill treatment process on Pari Island (Indah Sutiknowati, 2011). The combination of *Pseudomonas aeruginosa* and *Aspergillus niger* could reduce TPH in the ex-situ oil spill treatment process with an efficiency of 98 % (Ojewumi and Ejemen, 2018). A mixture of several microorganisms was known to increase the efficiency of oil spill removal compared to one type of microorganism (Tanzadeh and Ghasemi, 2016; Zahari et al., 2022).

Biosurfactants: Biosurfactants are environmentally friendly amphiphilic molecules produced by microorganisms. They significantly decreased the hydrophobicity and increased the rate of total petroleum hydrocarbon (TPH) biodegradation. However, developing the use of biosurfactants for oil spill treatment required high costs, specific environmental conditions, and a long process. Therefore, its use was usually combined with other solvents. Some examples of biosurfactants were rhamnolipids (produced by *P. aeruginosa*), emulsan glycolipopeptide (produced by *Acinetobacter calcoaceticus*), surfactin (produced by *B. subtilis*), and others (Rahmati et al., 2022). Another group of microorganisms that produce biosurfactants are *Pseudomonas poae* BA1, *Acinetobacter bouvetii* BP18, *Bacillus thuringiensis* BG3, and *Stenotrophomonas rhizophila* BG32 (Ali Khan et al., 2017). The highest hydrocarbon degradation was 96.07 % by biosurfactants from *Pseudomonas poae* BA1 (Ali Khan et al., 2017).

9. Concluding remarks, author perspectives, and future research directions

The recorded oil spill cases in Indonesia were mostly still related to big incidents, while some other smaller cases were left unreported, or maybe even unmitigated. Tanker leakage, pipe leakage, and ship accidents are the major causes of oil spills in Indonesia, involving PT Pertamina as one of the most responsible parties. Reports of Indonesian oil spill cases are mostly still related to the visible impacts, such as oil contamination in seawater and sand and the deaths of fish and birds, while non-visible parameters, such as hydrocarbon concentration and possible air pollution, are still left unanalysed. Oil spill mitigation in Indonesia focused on the rapid clean-up of oil spills, regulation related to the responsible parties, and action to prevent worse incidents in the future. Establishing regulations related to the long-term clean-up of residual oil after an incident is highly suggested, not only to benefit the environment but also to prevent unwanted health risks to nearby communities. For future research directions, it is crucial to monitor the adverse effects on human health, particularly in low-income regions that rely on marine resources for food security. Urgent action is required to create local contingency plans that are customized to the specific requirements of each coastal ecosystem and region in order to prepare for the potential occurrence of future oil disasters. In order to mitigate the consequences of any future accidents, these strategies should emphasize the importance of prompt and effective responses.

CRediT authorship contribution statement

Ali Roziqin: Writing – original draft. **Muhammad Fauzul Imron:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition. **Dwi Sasmita Aji Pambudi:** Writing – original draft. **Rizkiy Amaliyah Barakwan:** Writing – original draft. **Hafizan Juahir:** Writing – review & editing. **Setyo Budi Kurniawan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Funding acquisition, Data curation. **Hajjar Hartini Wan Jusoh:** Writing – review & editing. **Mahasin Maulana Ahmad:** Writing – original draft. **Benedicta Dian Alfanda:** Writing – original draft. **Rizka Andriani Mahmudah:** Writing – original draft. **Fatmalia Khoirunnisa:** Writing – original draft.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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