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Artificial Intelligence for Detecting Oil Spills in Strategic Areas: A Strategic Study and Implementation Review in the Natuna Sea

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ABSTRACT
Oil spills in the strategic area of Natuna have continued to increase in recent years, causing significant ecological, economic, and geopolitical impacts. However, Indonesia's marine pollution detection system still relies on conventional methods that are limited spatially, temporally, and operationally. This study aims to analyze the potential implementation of Artificial Intelligence, especially the Convolutional Neural Network (CNN) model based on satellite imagery, to improve the effectiveness of oil spill monitoring and strengthen national Maritime Situational Awareness (MSA). The research uses a qualitative approach through literature studies, strategic analysis, and Natuna case studies. Secondary data were collected from scientific articles, reports from national institutions, international platforms such as EMSA and Copernicus, and data on Natuna pollution incidents for the 2019–2023 period. The analysis was carried out through thematic analysis, comparative analysis, strategic analysis, and case-based reasoning. The results show that CNN has high accuracy in detecting oil spill patterns from Sentinel-1 and Sentinel-2 imagery and has the potential to provide valid digital documentation for rapid response and legal proceedings. Further analysis revealed that AI integration is technically feasible for application in the TNI Pusinformar system, although it requires strengthening infrastructure, human resources, SOPs, and data security. The discussion emphasizes that AI application can improve data-based diplomacy, environmental law enforcement, and Indonesia's maritime surveillance capacity; thus, a national roadmap and supporting policies are needed for operational implementation.

INTRODUCTION

Globally, oil spills represent a critical environmental and economic threat. According to the International Maritime Organization (IMO), approximately 1,000 to 1,500 oil spill incidents occur annually worldwide, resulting in economic losses exceeding USD 5 billion per year (IMO, 2022). International frameworks such as the United Nations Convention on the Law of the Sea (UNCLOS) and the International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) have established obligations for coastal states to develop robust monitoring and response mechanisms. Despite these global initiatives, many developing nations, including Indonesia, continue to struggle with inadequate detection infrastructure and delayed response capabilities (Aisyah et al., 2022).

Indonesia, as an archipelagic country, has a vast maritime area of strategic value in terms of economy, environment, and geopolitics. One such area occupying a crucial position is the Natuna Waters, located in international shipping lanes and containing large energy reserves and potential fishery resources (Marliani, 2024). This region is of major concern due to its position directly adjacent to the South China Sea, a disputed territory among various countries and the center of global trade routes (Isak et al., 2020). In addition to being a meeting point of economic interests, Natuna also symbolizes Indonesian sovereignty amid complex regional dynamics (Iswardhana, 2024). Thus, surveillance and protection of this area are integral to national resilience (Qurbani et al., 2024).

The potential of natural resources in Natuna is immense. In the fisheries sector, this area produces pelagic fish such as cod, mackerel, and small tuna, with an estimated catch potential of more than 500,000 tons per year (Juanita and Setiani, 2022). In addition, the Natuna area is rich in oil and gas reserves, making it one of the locations with the largest energy potential in Southeast Asia (Zubaidi and Wiyana, 2024). However, this wealth also attracts foreign vessels to exploit resources illegally, both through fish theft (illegal fishing) and illegal drilling (Purnaweni et al., 2022).

The area also holds high ecological risks. Offshore oil and gas exploration and exploitation activities, international tanker traffic, and illegal waste disposal have increased incidents of marine pollution, especially oil spills (Sodik, 2020). Data show that the number of oil spill cases in Natuna waters increased from 4 cases in 2020 to 7 cases in 2022, with the area of impact rising from 15 km^2 in 2019 to 47 km^2 in 2022 (Muthmainnah and Suwardi, 2023; KLHK, 2021). The concentration of Total Petroleum Hydrocarbons (TPH) at some points has even exceeded the quality standards set by the government for clean seas (Ministry of Environment and Forestry, 2021), indicating the urgency of addressing marine pollution in this region.

Pollution due to oil spills has a wide impact on Natuna's tropical marine ecosystem. Toxic polycyclic aromatic hydrocarbon compounds (PAHs) accumulate in fish tissues, with concentrations increasing from 2.1 mg/kg in 2020 to 3.8 mg/kg in 2023 (Falahudin, 2023). These substances are known to be carcinogenic and can interfere with the nerve tissue and immune systems of marine life (Bacosa et al., 2025). The resulting ecological disturbances include damage to coral reefs, seagrass meadows, and a decline in the quality of fishery habitats, clearly reflected in the destruction of nursery and feeding grounds (Hamzah et al., 2023).

In the long term, such pollution is not only ecologically harmful but also economically damaging to coastal communities and Indonesia's credibility in international maritime environmental diplomacy (Purnaweni et al., 2022). In fact, this impact triggers the potential for new conflicts, especially in border waters involving foreign vessels, as noted in several incidents with Chinese vessels around Natuna (Storey, 2020). When Indonesia's documentation system remains weak, proving violations by foreign parties legally within the framework of international law becomes difficult (Wahyuni, 2022).

Until now, Indonesia's oil spill detection system has relied on conventional methods such as visual reports from patrol boats and local fishermen (LIPI, 2020). This makes early detection and rapid response difficult, especially in remote areas or during adverse weather conditions. Many incidents are only identified after impacts have reached the coastline (Putri, 2021). In addition, manual reports often lack adequate visual documentation, and many are unverified or without legally valid evidence (Setyawati, 2020).

According to the WALHI report (2022), only a small portion of marine pollution cases have been successfully pursued legally due to weak documentation and a lack of environmental forensic systems. Technical limitations also include uneven marine surveillance infrastructure, especially in remote areas such as Natuna. During extreme weather or nighttime surveillance, visual-based systems become completely unreliable (Harahap and Simanjuntak, 2022). This underscores the urgency of implementing satellite-based or radar detection technology, as seen in several neighboring countries (Gautama, 2017).

The absence of a real-time detection system for monitoring oil spills in Indonesia slows the initial response to marine pollution incidents. According to LIPI (2021), delayed detection leads to broader ecosystem destruction and reduces the possibility of compensation claims against polluters. While developed countries such as Norway and Canada have adopted automated monitoring systems based on satellite imagery and artificial intelligence (AI), Indonesia still relies on conventional, reactive, and inefficient surveillance (EMSA, 2022).

In this context, artificial intelligence (AI) technology offers great opportunities for modernizing maritime surveillance. AI enables rapid and precise processing of satellite imagery to identify visual patterns indicating oil spills (Rahman et al., 2021). Deep learning-based approaches such as Convolutional Neural Networks (CNNs) have proven capable of distinguishing normal from polluted sea surfaces in seconds with high accuracy (Wijaya and Fauzan, 2023). This technology can also be adapted to tropical water conditions such as those in Natuna, which feature complex waves and sea surface temperatures.

AI-based systems have been effectively implemented by the European Maritime Safety Agency (EMSA) through a combination of Sentinel-1 radar and Sentinel-2 optical imagery, enabling detection across various times and weather conditions (Brekke and Solberg, 2005). Indonesia, as an archipelagic country with significant geographical challenges, has the potential to adopt a similar system, especially for vulnerable areas such as Natuna and the Strait of Malacca (Iswardhana, 2024). While existing studies have demonstrated the technical feasibility of CNN-based oil spill detection (Al-Ruzouq et al., 2020; Li et al., 2021) and explored regional maritime security challenges (Marliani, 2024; Storey, 2020), a critical gap remains in understanding how these technologies can be operationalized within Indonesia's existing defense infrastructure. This research addresses this gap by examining the integration of AI systems with the TNI Pusinformar command structure, analyzing legal and diplomatic frameworks for using AI-generated evidence in maritime law enforcement, and proposing a contextualized implementation roadmap that accounts for Indonesia's unique institutional, geographical, and geopolitical conditions. Unlike previous studies that focus on either technical detection capabilities or strategic security concerns in isolation, this research bridges both domains by showing how AI-based detection systems can simultaneously enhance environmental monitoring, strengthen legal enforcement mechanisms, and support evidence-based maritime diplomacy in the contested waters of the South China Sea.

Beyond environmental monitoring, integrating this technology holds strategic value for defense policy and maritime diplomacy. According to Laksmi (2023), AI and geospatial data can enhance maritime situational awareness (MSA), which is vital for national security decision-making. Strengthening AI-based maritime intelligence systems can also improve Indonesia's position in regional forums such as the ASEAN Maritime Forum and bolster its influence in South China Sea governance (Storey, 2020). However, adoption requires institutional and infrastructure readiness, particularly integration with TNI command and control systems such as Pusinformar.

This research is guided by the following four main problem formulations: How can an AI-based oil spill detection system be developed? How accurate is the AI model in detecting oil spills through satellite imagery? How compatible is the AI system with integration into the TNI Pusinformar's data and information processing system? What are the strategic implications of AI system integration for improving national maritime situational awareness (MSA) capabilities?

This article aims to present a conceptual and strategic analysis of the potential application of AI technology—especially satellite-based CNN models—in detecting oil spills in Natuna's strategic waters. Specific objectives include reviewing the technical approaches to developing an AI-based oil spill detection system; evaluating the performance and accuracy of AI models in automatically detecting spill areas; analyzing the potential integration of the system into the TNI Pusinformar's maritime information mechanisms; and explaining the strategic implications for strengthening Indonesia's situational awareness and maritime security systems.

The contribution of this article is to provide a conceptual basis for policy development, technological roadmaps, and strengthening the national marine surveillance system through the integration of smart technologies and data-driven approaches.

METHOD

This study employed a descriptive qualitative approach with literature study methods and strategic analysis. This method was chosen because the purpose of this article was to evaluate the potential use of artificial intelligence (AI) for oil spill detection and analyze its implications for Indonesia's maritime situational awareness (MSA) system.

This research comprised a literature study (library research) enriched with strategic analysis of Indonesia's institutional readiness, technology, and policy framework. This approach was suitable for conceptual topics lacking primary operational data.

This research utilized secondary data obtained from various credible sources, both national and international. Primary sources included scientific articles discussing convolutional neural networks (CNNs), satellite imagery, and oil spill detection methods, which formed the technical basis for the discussion. In addition, the research drew on official reports from national institutions such as the Ministry of Maritime Affairs and Fisheries (KKP), the Ministry of Environment and Forestry (KLHK), the National Research and Innovation Agency (BRIN), the Indonesian National Army Navy (TNI AL), and the Hydro-Oceanography Service (Dishidros), which provided data on environmental conditions, maritime policies, and marine surveillance infrastructure. To enrich the global perspective, the study also referred to international reports from the European Maritime Safety Agency (EMSA), the National Oceanic and Atmospheric Administration (NOAA), and the Copernicus platform, which supplied satellite imagery data.

Technical data in the form of public imagery from Sentinel-1, Sentinel-2, and MODIS were also used to understand relevant visual characteristics in the context of oil spill detection. In addition, various case studies on oil pollution incidents in the Natuna area during the 2019–

2023 period served as important references to illustrate empirical dynamics in the field. Literature on maritime policy and regional security complemented the research's understanding of the strategic and geopolitical aspects behind the importance of implementing AI technology in Indonesia. All sources were selected based on relevance, credibility, and a relatively up-to-date publication range, the majority of which were published between 2019 and 2025, ensuring that the research results reflected the latest conditions and developments.

Data collection in this study was carried out through several complementary stages. First, systematic literature searches were conducted through scientific databases such as Scopus, Google Scholar, IEEE Xplore, and ScienceDirect to obtain academic articles relevant to artificial intelligence, convolutional neural networks (CNNs), and satellite imagery-based oil spill detection. The next stage involved searching policy reports and official documents published by government agencies, including KKP, KLHK, BRIN, TNI AL, and Dishidros, to gather information on operational conditions, environmental policies, and maritime surveillance data in Indonesia.

In addition, the study examined technical data from satellite imagery accessed through the Copernicus repository, particularly Sentinel-1, Sentinel-2, and MODIS, to understand visual characteristics and observation parameters relevant to oil spills. Data collection also included extracting numerical data on total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), and records of oil pollution incidents in Natuna waters from various scientific reports and official documents. The entire process was conducted systematically to ensure that the data used were comprehensive, valid, and supportive of the research's analytical objectives.

Data analysis in this study was conducted through several complementary qualitative approaches. First, thematic analysis was applied to identify main patterns in the literature, particularly related to oil spill detection technology development, CNN model accuracy levels, and operational aspects of satellite imagery use. This approach enabled the capture of core themes such as model reliability, challenges in tropical marine environments, and supporting infrastructure needs. In addition, comparative analysis was used to evaluate AI applications in marine monitoring across various countries, highlighting differences in approaches, technological readiness levels, and relevance to the Indonesian context. This was combined with strategic analysis, including SWOT and gap analyses, to assess national readiness from institutional, technological, and policy perspectives. Finally, case-based reasoning was employed to examine oil spill incidents in Natuna, interpreting them as an empirical basis for assessing the urgency and potential implementation of AI systems in Indonesia.

RESULT AND DISCUSSION

This section presents the results of research findings obtained through literature analysis, empirical data on oil pollution in Natuna, and evaluation of technological and institutional readiness in the context of the implementation of AI detection systems.

Oil Pollution Data in Natuna (2019–2023)

The Natuna region experienced a significant increase in the number and extent of oil spill incidents between 2019 and 2023. Based on a report by the Ministry of Maritime Affairs and

Fisheries (KKP) and the results of a study by Muthmainnah and Suwardi (2023), there were 13 oil spill incidents, with pollution coverage increasing from 15 km² in 2019 to 47 km² in 2022. In addition, the concentration of Total Petroleum Hydrocarbons (TPH) at several marine observation points has exceeded the national clean sea threshold set by the Ministry of Environment and Forestry (MoEF, 2021).

Its ecological impact is also seen in trophic tissues. In a study by Lubis and Hidayat (2022), it was found that the content of Polycyclic Aromatic Hydrocarbons (PAHs) in fish tissue increased from 2.1 mg/kg in 2020 to 3.8 mg/kg in 2023. This is an indicator that oil pollution has had a direct impact on marine life and has the potential to endanger human health through the consumption of polluted marine products.

However, not all incidents have been successfully identified as sources. WALHI (2022) noted that the low quality of visual documentation and weak environmental forensic systems make most pollution incidents legally unactionable. The lack of accurate spatial and temporal data makes it difficult to conclusively verify the source and timing of oil spills.

Natuna waters as a strategic area also face diplomatic risks. Several oil spill incidents are suspected to have originated from foreign tankers crossing the Indonesian Archipelago Sea Channel I (ALKI I). However, as explained by Azhari and Saeri (2024), legal proof of these allegations is very difficult to do due to weak documentation and time-of-incident verification, even though this area is under the supervision of Indonesia's maritime sovereignty.

Conventional vs. Conventional Detection Systems AI System

Conventional detection systems in Indonesia still rely heavily on visual observations from patrol boats, fishermen's reports, and direct observation by maritime authorities. As explained by Setiawan and Prasetyo (2021), this method has spatial and temporal limitations because it only covers a limited area and is very vulnerable to bad weather and the availability of fleets and personnel.

In contrast, artificial intelligence (AI)-based systems offer much higher efficiency in terms of coverage and detection time. The finding that CNN models processing Sentinel-1 data can detect oil spills in less than 10 minutes after data reception (Al-Sudani & Al-Suhail, 2024) strongly supports this study's argument about AI superiority over conventional methods. This rapid detection capability represents a dramatic improvement over the 6-12 hour delay typical of conventional reporting systems. This is in stark contrast to conventional methods which generally take between 6 to 12 hours for field reports to be received and processed administratively.

However, Kim et al.'s (2023) study provides an important cautionary note regarding CNN performance in tropical dynamic ocean conditions. Their research demonstrates that CNN accuracy can decrease by 15-20% in waters characterized by high wave activity, variable sea surface temperature, and complex optical properties—conditions that closely match those found in Natuna waters. This finding suggests that while AI systems offer significant advantages, their implementation in Indonesia's tropical maritime environment requires careful model adaptation and validation to ensure reliability under local oceanographic conditions.

One of the main advantages of AI systems is its ability to generate digital documentation based on visual evidence, which can be used in legal proceedings as well as international diplomacy. According to Anderson et al., (2020), the digital forensic value of satellite images processed by AI makes this system an important tool in marine pollution investigations that have been difficult to do with conventional approaches.

However, AI adoption in Indonesia still faces a number of challenges. Maritime digital infrastructure support and adaptive operational policies are needed so that the data generated by automated detection systems can be immediately translated into real actions on the ground by law enforcement officials and environmental agencies.

AI System Workflow Simulation

Conceptually, an AI-based oil spill detection system consists of five main stages. First, data was collected from Sentinel-1 (which uses Synthetic Aperture Radar/SAR) and Sentinel-2 (which provides multispectral optical imagery). According to Al-Ruzouq et al. (2020), the use of these two types of imagery allows monitoring of the ocean in all weather and weather conditions, as well as improving the accuracy of the model in recognizing spill patterns.

Second, the raw image needs to go through radiometric and geometric correction. This process is followed by preprocessing such as speckle filtering to remove noise in the SAR imagery, which is crucial for sea surface features to be properly recognized by the system (Zeng and Wang, 2020).

Third, the cleaned images are then fed into a CNN (Convolutional Neural Network) system that has been trained using an oil spill dataset. The CNN model will extract spatial features such as texture, shape, and contrast levels from sea level to differentiate between polluted and unpolluted areas (Al-Ruzouq et al., 2020). The model is also able to recognize typical patterns of oil spills based on pre-trained models.

Fourth, the results of the classification are visualized in the form of digital maps such as GeoTIFF or GeoJSON. This information is exported to a real-time monitoring dashboard system, which allows integration with automatic notifications to maritime command centers if significant spill patterns are detected (Zeng and Wang, 2020).

Fifth, the detection results can be re-verified semi-automatically by human operators in a process called human-in-the-loop validation. According to Wang et al. (2021), this approach combines the sophistication of AI processing with human intuition and strategic judgment, making the system more adaptive and accountable in an operational context.

Analysis of AI Compatibility with the TNI Pusinformar System

The TNI Pusinformar is currently a maritime information integration center that receives data from coastal radar, AIS, as well as manual reports from ships and bases. However, there is no real-time integration with AI-based satellite image processing systems (Dishidros TNI AL, 2021).

AI integration allows Pusinformar to expand its function from just a data aggregator to an analytical command center that can interpret ocean dynamics automatically. This is in line with the modern doctrine of network-centric warfare that places information as a strategic advantage (Storey, 2020).

Nevertheless, interoperability is a major challenge. AI systems need to be adapted to the data formats and protocols used by the TNI C4ISR system. This includes geospatial file compatibility, network communication protocols, as well as access authorization (Awal et al., 2025).

The application of AI also requires new SOPs in decision-making based on system outcomes, including the scenario of who is authorized to act on incidents based on automated data. This has not been fully regulated in the current operational command system.

Technology Infrastructure: IT, Satellites, and Networks

The implementation of AI systems requires an integrated maritime ICT infrastructure, including GPU processing servers, cloud storage for big data images, as well as secure communication networks (Wang et al., 2021). Indonesia currently has limited satellite processing capacity at BRIN and Dishidros, but it does not yet support continuous tactical operations.

The main data sources are Sentinel-1 and Sentinel-2 which can be accessed for free through the Copernicus platform. However, the speed of acquisition and download is still a barrier in remote areas like Natuna. Solutions such as military VSATs or fiber networks to nearby bases need to be considered.

It is also important to ensure that the AI system has network redundancy and offline inference capabilities, where the system can still run if the internet connection is lost. This becomes an absolute requirement for systems in border regions (Wang et al., 2021).

Human Resources Readiness and Institutional SOPs

The availability of human resources is a critical component in the adoption of AI technology. Currently, only a small percentage of TNI and BRIN personnel have expertise in satellite image processing and machine learning (Ambarwati et al., 2023). Technical training and the establishment of a special AI unit within the Pusinformar structure need to be a priority.

Current institutional SOPs do not cover scenarios for the use of AI systems in the detection and decision-making process. Adjustments to the command structure, access rights, and reporting flows must be prepared by involving various agencies including Bakamla, Dishidros, and KKP (Yuliana et al., 2022).

Cross-sectoral needs also demand collaborative protocols between institutions. Data from AI needs to be regulated in its confidentiality status, classification, and who has the right to publish it—for example in the context of diplomacy or pollution litigation.

SOP reform should also include regular training and AI-based pollution response simulations, to improve cross-functional operational readiness.

Data Security and Interoperability

The issue of data security is very important considering that AI will access strategic imagery and generate sensitive information. The system needs to be equipped with end-to-end encryption, two-factor authentication, and audit log recording to avoid strategic data leakage (Laksmi, 2023).

Interoperability includes compatibility with national defense systems, such as mil-C2 and military geospatial protocols. The system must be able to convert the detected data into an interoperable format such as MIL-STD-2525 or NATO ADatP-3 for the purpose of joint operations (Awal et al., 2025).

The legal aspect needs to be strengthened by the rules for the use of AI in maritime surveillance, as well as the legal framework for the use of satellite data as legal evidence in the law enforcement process and international diplomacy.

This section discusses the strategic significance of the research results, interprets technical and institutional findings, and relates them to the context of maritime security and national policies

The Effect of AI Integration on Maritime Situational Awareness (MSA)

The integration of artificial intelligence (AI) in Indonesia's maritime surveillance system has significantly improved the quality of Maritime Situational Awareness (MSA), which is the ability to understand, monitor, and predict maritime conditions in real-time. AI systems that utilize satellite imagery and deep learning algorithms enable continuous and consistent collection and interpretation of spatial data without reliance on manual patrols.

With early detection of oil spills, the presence of unknown vessels, or illegal activities, AI supports early warning functions that are crucial in safeguarding strategic areas such as Natuna. As noted by Al-Ruzouq et al. (2020), CNN-based systems are capable of detecting oil spills with high accuracy even in complex marine conditions.

In addition to detection, AI also strengthens the predictive element of MSA through analysis of historical patterns and projections of pollution movements. This predictive ability is important in quick decision-making by the Indonesian Navy and other maritime agencies, in order to prevent the spread of environmental impacts and regional conflicts.

AI integration also extends MSA's reach to exclusive economic zones (EEZs) and ALKIs, areas that are often difficult for conventional patrol vessels to reach. This allows for cross-border detection of illegal tanker activity or deliberate pollution.

Furthermore, AI-enhanced MSAs have a strategic function in international diplomacy. Satellite-based detection data can be used as evidence-based diplomacy to prove violations of maritime law by foreign ships (Azhari and Saeri, 2024).

AI has the potential to make Indonesia a formidable maritime domain awareness owner in Southeast Asia, with more autonomous information control and not dependent on foreign partners as before.

Indonesia's Readiness in Regional and International Contexts

In the regional framework, Indonesia's readiness still faces challenges in terms of data infrastructure, system interoperability, and human resource training. This is in contrast to Singapore which has successfully applied multi-sensor tracking technology and predictive analytics for port and high seas security in an integrative manner (Raska, 2024). Meanwhile, Indonesia's system still relies on manual report-based detection and visual observation, showing a gap in the adoption of smart maritime technology (Margaretha and Syuzairi, 2024).

Nevertheless, several initiatives have been initiated. The National Research and Innovation Agency (BRIN) and the Indonesian Navy's Hydro-Oceanography Service are developing a national platform for AI-based satellite image processing, which will integrate Sentinel and MODIS data directly (Yusdian et al., 2023). This initiative is the first step in building national capabilities in high-technology-based monitoring of marine areas.

At the ASEAN level, Indonesia participates in regional cooperation for AI-based marine surveillance. This activity includes satellite data collaboration and the preparation of maritime interoperability protocols with ASEAN countries (Chua et al., 2025). However, according to the latest analysis, Indonesia's position is still not dominant in terms of technology and digital maritime policy (Zhao, 2025), so AI adoption needs to be accelerated so that Indonesia does not lag behind in regional strategic competition.

Legal readiness is also an important issue. Until now, there is no national regulation that explicitly regulates the use of AI data and satellite imagery as legal evidence in the context of law enforcement, especially in the environment and defense sectors (Putro et al., 2023). This legal vacuum has the potential to weaken Indonesia's position in international forums, especially in maritime security diplomacy.

From the defense side, the TNI Navy Maritime Information Center (Pusinformar) has great potential as a pioneer in the integration of AI into military C4ISR systems, as long as cybersecurity protocols and military-civilian system integration are carefully designed (Pandjaitan, 2024).

Indonesia has a strategic geographical position along the Indonesian Archipelago Sea Channel (ALKI), which opens up great opportunities to become a regional maritime data center. However, this potential will only be achieved if it is accompanied by serious investment in technology and strengthening digital diplomacy (Fita, 2025).

Finally, national readiness to adopt AI is largely determined by political will and cross-agency coordination. Without strong institutional integration, AI technology will only be an administrative tool, not a catalyst for systemic transformation (Saleh and Supriyadi, 2025).

Data-Based and Environmental Diplomacy

Conventional maritime diplomacy tends to rely on verbal claims, bilateral communication, and manual reporting. However, in the context of cross-border oil spills and illegal exploitation, data-driven diplomacy is becoming a new, more robust and objective approach. AI integration allows Indonesia to produce evidence-based on images and authentic time-of-events. This can be used in multilateral forums to pressure polluting countries that cross the EEZ without permission. Fita (2025) emphasized that digital documentation and satellite data are increasingly crucial in building legitimacy in international litigation and increasing national resilience through maritime diplomacy.

Environmental diplomacy with satellite-based evidence can also encourage cross-border surveillance cooperation agreements, such as joint patrols in the Natuna Sea and ALKI areas. This strengthens Indonesia's position as a protector of regional biodiversity. Al Hafiz and Al Badi'ah (2025) note that the integration of AI in real-time ship tracking and UNCLOS-based data transparency opens up opportunities for more efficient and reliable preventive diplomacy.

Furthermore, verified AI data allows Indonesia to provide early notification to neighboring countries if pollution is detected sourced from abroad. This strengthens Indonesia's position as a cooperative and proactive country. Awal, Sumadinata, and Yani (2025) also highlight that satellite-based maritime monitoring promotes the effectiveness of regional mitigation against marine pollution through international cooperation.

Indonesia could also propose an AI-based regional satellite data exchange forum, similar to the Information Fusion Centre in Singapore, but focused on the issue of pollution and maritime climate change. Supriyadi, Prakoso, and Suwarno (2025) assess that automated monitoring systems and regional leadership are very important in building sustainable and cooperative maritime security strategies. The use of this data can also be incorporated into national climate change reports and used for international funding negotiations or a sea-based energy transition.

Finally, data-driven diplomacy also pressures countries that violate the laws of the sea to be more careful because all their activities are now recorded and accessible to the public. This is in line with the trend of global transparency and open monitoring technologies. Goodman, Baudu, and Fleishman (2023) call this approach a form of science diplomacy that combines technology, supervision, and international governance. It also expands the arena of diplomacy from the military and economic realms to collective security-based environmental diplomacy. A more constructive and pro-ecosystem approach.

Potential Deterrent Effects and Law Enforcement Based on Digital Evidence

So far, law enforcement against oil spills in Indonesia has often been hampered by the difficulty of proving in court. The lack of documentation, the loss of traces of the time of the incident, and the absence of confirmation of the perpetrator's position have made many cases not continue legally (WALHI, 2022).

With an AI system based on satellite imagery, each incident can be recorded with complete metadata: time, GPS position, type of pollution, and visual evidence. This makes the system a legitimate digital forensic evidence tool to be used in investigations and litigation.

The deterrent effect arises when the perpetrators—both national and foreign ships—realize that their activities can be recorded and acted upon legally. Even before it was acted upon, the publication of AI detection data in the media also put pressure on reputation.

In the context of technology-based law enforcement, changes in marine environmental regulations are needed to recognize the legality of digital data as primary evidence. Currently, satellite imagery data is only used as supporting information.

If designed with a robust legal framework, AI can accelerate the transformation of environmental law enforcement systems from reactive to proactive, with powerful prevention and early warning functions.

CONCLUSION

This study conceptually addressed its four key problem formulations: developing AI-based oil spill detection using proven Sentinel imagery and CNN models; confirming CNNs' high accuracy in classifying pollution even in complex marine conditions; enabling integration with TNI Pusinformar via protocol interoperability and HR training; and highlighting strategic benefits for enhancing maritime situational awareness (MSA), environmental diplomacy, and data-driven law enforcement. AI surpasses manual systems by rapidly processing Sentinel-1 data to generate pollution maps, provide predictive early warnings based on historical patterns, and supply robust digital evidence for operations and diplomacy, while recommended steps include investing in GPU infrastructure at BRIN and Dishidros, specialized training for Pusinformar and Bakamla personnel with new SOPs, and national policies affirming AI evidence legality. Limitations include reliance on prior studies without direct CNN testing, numerical performance metrics (e.g., confusion matrices), or primary satellite processing, focusing instead on conceptual-strategic analysis. For future research, empirical validation through field experiments—testing custom CNN models on Natuna-specific Sentinel data with ground-truth verification—would strengthen technical claims and enable prototype development for TNI integration.

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