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Integrated maritime surveillance model based on artificial intelligence and blockchain for detecting illegal ship-to-ship activities

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ABSTRACT

Background: Illegal ship-to-ship (STS) activities pose a serious threat to Indonesia's maritime security, particularly in the Riau Islands region, which is located along the strategic Malacca Strait, while conventional surveillance systems continue to face limitations due to weak data integration and the practice of Automatic Identification System (AIS) signal deactivation. This study aims to develop Maritime Guard Intelligence (MGI) as an integrated maritime surveillance system based on intelligent technology. **Methods**: This study employed the Research and Development (R&D) method through the stages of needs analysis, system design, concept testing, and validation of implementation potential. **Findings:** The proposed system integrates Isolation Forest and Convolutional Neural Network (CNN) algorithms for anomaly detection and satellite image analysis, while blockchain technology is utilized to ensure data transparency, integrity, and traceability in maritime surveillance. **Conclusion:** This study suggest that MGI has the potential to become an effective, participatory, and sustainable digital maritime surveillance model. **Novelty/Originality of this article:** The novelty of this study lies in the integration of Artificial Intelligence (AI)-based anomaly detection, satellite image analysis, and blockchain-based data verification within a single integrated maritime surveillance system.

KEYWORDS: machine learning; maritime security; ship-to-ship illegal.

1. Introduction

Indonesia is an archipelagic country with abundant marine resource potential, which is susceptible to exploitation and creates vulnerabilities to transnational crime (Aprilia et al., 2023). In particular, the Riau Islands region constitutes a strategic international shipping route directly connected to the Malacca Strait, one of the busiest maritime corridors in the world (Wulandari et al., 2023). This geographical position makes the region both a center of economic activity and an area vulnerable to various forms of sovereignty violations, including illegal fishing, illegal ship-to-ship (STS) transfers, fuel smuggling, and unauthorized navigation (Nguyen, 2023; Kurniawan et al., 2025). In the Society 5.0 era, digital technologies such as artificial intelligence (AI) and blockchain offer significant opportunities to strengthen intelligent, transparent, and collaborative maritime surveillance systems (Alotaibi & Alshehri, 2023; Islam, 2024).

Illegal fishing and illegal STS activities remain major threats to Indonesia's maritime security and marine resource sustainability. The number of foreign vessels involved in

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illegal fishing activities continues to increase, particularly in border areas such as the Riau Islands (Bila et al., 2023). Globally, fisheries-related crimes are still underreported, with fewer than 2% of countries consistently reporting illegal fishing incidents (Mackay et al., 2020). These activities have caused substantial economic losses, estimated at approximately IDR 3 trillion annually in the Riau Islands region alone (Ardhani, 2021). Consequently, maritime security has evolved into a multidimensional issue that requires integrated governance, institutional strengthening, and cross-border cooperation (Siregar et al., 2025).

A major challenge in maritime surveillance is that many vessels intentionally deactivate their Automatic Identification System (AIS) signals or manipulate vessel identities to avoid detection (Huang et al., 2024). As a result, conventional surveillance approaches that rely heavily on manual patrols often fail to identify suspicious maritime activities effectively (Pandey, 2023). Furthermore, the lack of real-time data integration among maritime institutions limits the capability to detect illegal STS activities in strategic waters such as the Riau Archipelago (Liu et al., 2021). Although Indonesia has established maritime governance policies through Presidential Regulation Number 16 of 2017 concerning Indonesia's Maritime Policy and Law Number 32 of 2014 concerning Maritime Affairs, no specific regulation currently governs the utilization of AI and blockchain technologies in maritime surveillance systems (Priyanta, 2021).

Previous studies have demonstrated the effectiveness of AI in improving maritime surveillance, anomaly detection, and operational efficiency (Ma et al., 2023). However, most studies focus on AIS data analysis or satellite imagery independently, while only limited research has integrated blockchain technology to ensure data authenticity and integrity (Alsharabi et al., 2024). Existing approaches also lack decentralized verification mechanisms that can improve transparency and trust among stakeholders involved in maritime monitoring activities (Simau et al., 2023). This research gap highlights the need for an integrated surveillance framework capable of simultaneously detecting suspicious maritime activities and ensuring the reliability of surveillance data.

To address these challenges, this study proposes Maritime Guard Intelligence (MGI), an integrated maritime surveillance system that combines machine learning and blockchain technology to detect illegal STS transfer activities in real time. The system utilizes the Isolation Forest algorithm to identify anomalous vessel movement patterns from AIS data and Convolutional Neural Networks (CNN) to analyze satellite imagery for visual verification. Detection results are subsequently validated and recorded using a blockchain-based Proof-of-Authority (PoA) mechanism to ensure transparency, traceability, and data integrity. Therefore, this study aims to develop an innovative maritime surveillance model that enhances the detection of illegal STS activities while supporting transparent, secure, and collaborative maritime security governance. Furthermore, the proposed system contributes to the achievement of Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water), SDG 16 (Peace, Justice and Strong Institutions), and SDG 9 (Industry, Innovation and Infrastructure).

2. Methods

This study employs a Research and Development (R&D) method with an integrated technology system development design based on Artificial Intelligence (AI) and Blockchain. This method was selected because the research not only analyzes phenomena but also produces an innovative product in the form of the MGI system that can be practically implemented for monitoring illegal STS activities. The study was conducted in the waters of the Riau Islands. This area was selected because it is a densely trafficked international shipping route with a high potential for illegal STS activities. The research was carried out over 11 months, starting from the system design stage to testing. The research data were obtained from several sources. First, AIS data containing information on vessel position, speed, direction, and stopping duration. Second, Sentinel and Landsat satellite imagery used to visually observe vessel activities at sea. Third, reports from fishermen through the application as a form of community participation. Secondary data from maritime agencies were also used as comparative and validation materials.

The research stages were conducted sequentially, beginning with System Requirements Analysis, which involved identifying problems in monitoring illegal STS activities and determining appropriate technological solutions. This was followed by Data Processing and Analysis, where AIS data were cleaned from errors and duplication, then analyzed using the Isolation Forest method to detect anomalous vessel movement patterns. Meanwhile, satellite imagery was analyzed using Convolutional Neural Networks (CNN) to detect two vessels in close proximity within a certain period, indicating potential STS activities. The next stage was Blockchain Integration, where AI detection results were recorded in the blockchain system using the Proof of Authority (PoA) mechanism. The objective was to ensure data immutability and enhance monitoring transparency. The final stage consisted of conceptual validation and system feasibility assessment based on historical maritime data, literature evidence, and stakeholder requirements.

The selection of Isolation Forest as the primary anomaly detection algorithm for AIS-derived behavioral data was driven by its capacity to isolate outliers in high-dimensional, unlabeled datasets without requiring a predefined model of normal vessel behavior, an essential characteristic considering that confirmed cases of illegal STS transfer in the Riau Islands are scarce and rarely documented with reliable ground-truth labels. Unlike distance-based or density-based methods such as DBSCAN, which depend heavily on parameter tuning and struggle with the variable density of vessel traffic in congested shipping lanes, Isolation Forest isolates anomalies through recursive partitioning, which keeps computational cost low and makes the algorithm suitable for near-real-time processing of large-scale AIS streams. Convolutional Neural Network (CNN) was selected for satellite image analysis because of its proven capability to automatically extract spatial features such as vessel silhouette, size ratio, and relative proximity directly from raw pixel data without manual feature engineering, an advantage that is particularly valuable given the variability of vessel types and weather conditions encountered in the Riau Archipelago.

The selection of detection parameters was guided by operational characteristics commonly associated with illegal STS transfer activities, as documented in prior maritime anomaly detection research (Liu et al., 2021; Wolsing et al., 2022). Four primary parameters were embedded into the Isolation Forest feature space: (1) relative vessel speed, where a sudden reduction to near-zero knots outside designated anchorage zones is treated as a behavioral indicator; (2) inter-vessel distance, calculated from paired AIS coordinates, with proximity below a defined threshold considered indicative of physical contact between vessels; (3) duration of proximity, since legitimate passing maneuvers are typically brief whereas STS transfer operations require sustained contact time; and (4) route deviation, measured as the angular and spatial divergence from a vessel's historical or declared trajectory. These four parameters were not treated in isolation but combined into a composite anomaly score, allowing the model to capture compound behavioral signatures rather than relying on any single indicator, which helps mitigate the risk of misclassifying legitimate activities such as bunkering or pilot transfer as illegal STS transfer.

Model validation was conducted using standard classification performance metrics, namely accuracy, precision, recall, and F1-score, each carrying distinct operational significance for maritime law enforcement. Accuracy reflects the overall proportion of correctly classified vessel activities, while precision indicates the proportion of flagged anomalies that are genuinely illegal STS events, which is critical for avoiding the unnecessary deployment of patrol assets. Recall measures the system's capacity to correctly identify actual illegal STS occurrences, a metric of particular importance given the severe consequences of failing to detect genuine violations.

This study also considers legal and public policy aspects. Currently, there are no specific regulations governing the use of AI and blockchain in maritime monitoring systems based on community participation. Therefore, government support is essential in formulating appropriate regulations. Through the MGI approach, the system is expected not only to be technically effective in detecting illegal STS activities but also to possess academic legitimacy and policy relevance in supporting national maritime security governance.

To ensure the reliability and effectiveness of the MGI system, a multi-layer validation approach was incorporated throughout the development process. At the technical level, the anomaly detection model based on AIS data was evaluated using historical vessel movement records to determine its ability to identify suspicious patterns associated with illegal STS activities. Several indicators, including vessel speed, distance between vessels, duration of proximity, and unexpected route deviations, were used as parameters in the detection process. The performance of the model was assessed through accuracy, precision, recall, and F1-score measurements to ensure that the system could minimize both false-positive and false-negative detections.

For satellite image analysis, the Convolutional Neural Network (CNN) model was trained using annotated datasets containing images of vessel encounters and non-encounter situations. The model was designed to recognize visual characteristics indicating potential ship-to-ship transfer activities, such as the presence of two vessels operating in close proximity for an extended period. Data augmentation techniques were applied to improve model robustness under varying weather conditions, sea states, and image resolutions. This approach was expected to enhance the system’s capability to detect suspicious maritime activities even in challenging environmental conditions.

The Proof of Authority (PoA) consensus mechanism was deliberately selected over alternative blockchain protocols such as Proof of Work (PoW) and Proof of Stake (PoS) due to its suitability for permissioned, institution-based surveillance networks. PoW requires substantial computational power and energy expenditure to validate transactions, rendering it impractical for resource-constrained maritime monitoring infrastructure operating in remote archipelagic regions with limited electricity access. PoS, while more energy-efficient than PoW, ties validation rights to capital stake, a model poorly suited to a public-interest maritime security application in which validation authority should instead be granted to accountable institutional actors rather than the holders of digital assets. PoA addresses these limitations by assigning validation rights to a predetermined and identifiable set of trusted nodes comprising academic supervisors, fishermen cooperative representatives, and maritime authority personnel whose identities and reputations are directly tied to the legitimacy of recorded data.

This design substantially reduces energy consumption and transaction latency while preserving institutional accountability, an essential property for evidentiary use in law enforcement contexts where the chain of custody of digital evidence must be traceable to identifiable validators (Bhumichai et al., 2024; Kim et al., 2024). Moreover, because PoA does not require token-based incentive structures, it avoids the financial and regulatory complications associated with cryptocurrency-based consensus mechanisms, making it more compatible with Indonesia’s existing public-sector governance and procurement frameworks. The integration of Artificial Intelligence and Blockchain represents one of the key innovations of this research. While AI functions as the analytical engine capable of identifying potential illegal STS activities in real time, blockchain serves as a trusted infrastructure for data storage and verification. Every detection result generated by the AI module is automatically converted into a digital record and stored within the blockchain network. Through the implementation of the Proof of Authority (PoA) consensus mechanism, only authorized institutions can validate and confirm data entries, thereby ensuring data authenticity, security, and accountability. This mechanism also reduces the possibility of data manipulation and strengthens inter-agency trust in the monitoring process.

Community participation constitutes another important component of the MGI system. Fishermen and coastal communities often possess valuable local knowledge regarding unusual vessel activities occurring in surrounding waters. Therefore, the proposed application provides a reporting feature that allows users to submit observations, photographs, geographic coordinates, and descriptions of suspected illegal STS activities. These reports are then integrated with AIS and satellite data to support cross-validation and improve detection accuracy. By combining advanced technologies with community-based monitoring, the system promotes a more inclusive and participatory approach to maritime governance.

Furthermore, the research adopts a user-centered development perspective by considering the needs of relevant stakeholders, including maritime security agencies, local governments, fisheries authorities, and coastal communities. Stakeholder requirements were identified through literature analysis and policy reviews to ensure that the developed system aligns with operational needs and existing governance frameworks. This approach is expected to facilitate future implementation and increase the practicality of the proposed innovation.

Ultimately, the MGI system is designed not only as a technological solution but also as a governance innovation that supports transparency, accountability, and collaborative maritime monitoring. By integrating AI-based analytics, blockchain-enabled data security, and community participation mechanisms, the system offers a comprehensive framework for addressing illegal STS activities in Indonesian waters. The findings of this research are expected to contribute to the development of smarter maritime surveillance systems and provide policy recommendations for strengthening national maritime security and sustainable ocean governance.

3. Results and Discussion

3.1 Innovation concept and framework

Illegal ship-to-ship (STS) transfer activities constitute a tangible threat to Indonesia's maritime security, particularly in the waters of the Riau Islands, which directly border the strategically significant international shipping lane of the Malacca Strait. According to (Boşilcă et al., 2022), Illegal ship-to-ship transfer activities have become a major concern because they are frequently exploited for smuggling and illicit trade activities (Cai et al., 2026). These illegal activities result in economic losses amounting to hundreds of billions of rupiah and disrupt marine ecosystems that serve as a primary source of livelihood for local fishermen (Dao et al., 2025). Therefore, the authors initiated the development of the MGI system, an innovation integrating machine learning and blockchain technology to detect illegal STS transfer activities in real time by involving local fishermen as participatory observers.

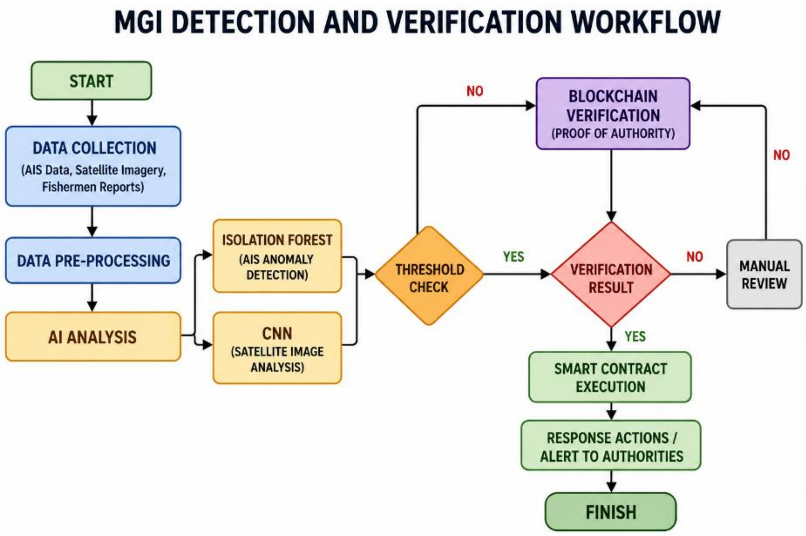

Fig. 1. MGI detection and verivication workflow

The primary objective of MGI is to establish an integrated early detection system capable of identifying and verifying suspicious vessel activities based on AIS data, satellite imagery, and visual reports from fishermen. These data are analyzed using an Isolation Forest-based machine learning model to detect anomalous vessel movement patterns, and a CNN model to identify illegal STS transfer activities from satellite imagery. Once anomalies are detected, the Proof of Authority (PoA) blockchain mechanism is employed to verify data authenticity and sources in a decentralized manner through trusted nodes, namely students, fishermen, and maritime authorities. All analytical outputs are permanently recorded in a decentralized blockchain ledger, ensuring that vessel activities are documented transparently, securely, and immutably. The MGI workflow begins with data collection, followed by AI analysis, blockchain verification, and notification delivery to maritime authorities, thereby creating an intelligent, efficient, and integrated system.

The operational workflow of MGI, beginning with data acquisition from AIS, satellite imagery, and fishermen reports. The collected data are processed using AI-based anomaly detection models and subsequently verified through blockchain mechanisms. Verified information is then forwarded to maritime authorities for rapid response, ensuring transparent, secure, and real-time monitoring of illegal ship-to-ship activities. In its implementation, MGI emphasizes synergy between technological innovation, students, and coastal communities. Fishermen are trained as co-observers who actively report vessel activities through a lightweight Android-based application. The system is designed using lightweight AI architecture to maintain offline-first functionality with automatic synchronization when network connectivity becomes available, thereby accommodating the conditions of remote maritime areas.

Following the pilot testing phase, the system will be implemented through collaboration among UMRAH (Raja Ali Haji Maritime University), local government authorities, and digital fishermen cooperatives to ensure operational sustainability. This approach not only strengthens maritime security but also creates new employment opportunities for fishermen as part of the digital maritime surveillance ecosystem. In the future, MGI development will focus on integrating marine Internet of Things (IoT) sensors, predictive deep learning models, and blue economy analytics to support secure, intelligent, and sustainable maritime management in Indonesia.

Further development of MGI is also directed toward enhancing system interoperability with existing maritime surveillance platforms. This is essential to ensure that MGI does not operate as a standalone system, but rather becomes an integral component of the national maritime surveillance ecosystem. Through interoperability, data generated by MGI can be accessed and utilized simultaneously by multiple relevant agencies, thereby accelerating coordination processes and decision-making in responding to illegal maritime activities.

In practical terms, interoperability between MGI and existing national maritime surveillance infrastructure particularly Indonesian Maritime Information Center/IMIC (*Bakamla*) and the Ministry of Marine Affairs and Fisheries (*KKP*) vessel monitoring system would require the establishment of standardized data exchange protocols, such as application programming interfaces (APIs) capable of translating MGI blockchain-verified detection records into formats compatible with existing institutional databases. Without such standardization, MGI risks operating as an isolated pilot project rather than a scalable component of national maritime governance. Establishing application-level interoperability would also allow MGI community-sourced fishermen reports to supplement, rather than duplicate, the radar and satellite feeds already managed by *Bakamla*, thereby creating a layered surveillance architecture in which formal institutional sensors and grassroots observation operate complementarily. Achieving this level of integration nonetheless depends on inter-agency data sharing agreements and a shared technical governance framework, areas in which Indonesia’s maritime regulatory environment currently remains underdeveloped (Priyanta, 2021; Siregar et al., 2025).

In addition, algorithmic performance optimization constitutes a major focus of system development. The currently effective Isolation Forest and CNN models can be further enhanced through continuous learning processes utilizing the latest field-acquired data. Consequently, the system is not static but adaptive to emerging patterns of increasingly complex and dynamic illegal STS activities. This adaptive capability represents a significant advantage in addressing evolving maritime crime strategies.

Compared to conventional surveillance approaches that rely solely on AIS monitoring or manual patrol operations, the integration of AI and blockchain within MGI offers several substantive advantages. AIS-only monitoring is inherently vulnerable to circumvention, since vessels engaged in illegal STS transfer routinely deactivate or spoof their AIS transponders to evade detection (Huang et al., 2024), leaving a critical surveillance gap that purely AIS-dependent systems cannot resolve. Manual patrol operations, meanwhile, are constrained by limited vessel availability, high operational costs, and the vast geographic extent of the Riau Archipelago, which makes continuous physical coverage practically unattainable.

By contrast, MGI's dual-algorithm architecture allows the system to maintain surveillance continuity even when AIS signals are deliberately switched off, since CNN-based satellite image analysis operates independently of AIS transmission and can detect physical vessel proximity directly from imagery. Furthermore, whereas conventional systems generally store detection records in centralized institutional databases vulnerable to single-point failure or undisclosed alteration, the blockchain layer in MGI ensures that once an anomaly is verified, the corresponding record becomes immutable and auditable by all authorized nodes, a property that conventional AIS-based or patrol-based recording mechanisms structurally lack (Elmay et al., 2022; Li & Sun, 2025). This combination positions MGI not merely as an incremental improvement over existing tools but as a structurally different surveillance paradigm that closes both the detection gap and the data-integrity gap simultaneously.

From an operational perspective, MGI is also designed to incorporate a priority-based alert handling mechanism. Since not all anomalous activities carry the same level of risk, a probability score-based classification system is required to determine response urgency. This enables maritime authorities to focus on activities with higher violation potential, thereby ensuring more efficient and targeted allocation of patrol resources. Furthermore, the development of the user interface is a crucial aspect to ensure usability for various stakeholders, including fishermen and maritime agency operators. An informative and real-time dashboard enables users to monitor vessel movements, anomaly statuses, and data verification results quickly and accurately. A system design that is both simple and functional is essential to enhancing operational effectiveness, particularly under technically constrained field conditions.

In the context of system validation, real-case simulation testing is necessary to ensure that MGI performs optimally under diverse operational conditions. These tests include variations in weather conditions, vessel traffic density, and signal disruptions commonly encountered in open sea environments. The outcomes of this validation process will serve as the basis for system refinement prior to broader implementation. Subsequently, system sustainability also represents a key concern in MGI development. Beyond technological support, an operational management model is required to ensure long-term functionality. This includes system maintenance mechanisms, software updates, and periodic user capacity-building through regular training. With a clear sustainability strategy, MGI is expected to evolve beyond a short-term innovation into a long-term system capable of continuously meeting maritime surveillance needs.

With these developments, MGI functions not merely as a detection tool but also as a decision support system capable of providing strategic information for maritime authorities. The information generated is not only descriptive but also analytical, thereby supporting the formulation of more effective and data-driven maritime surveillance policies. From a broader governance perspective, the integration of AI and blockchain within MGI reflects an emerging global pattern in which digital technologies are increasingly positioned as instruments of marine governance rather than purely technical tools. By embedding verifiability into the surveillance pipeline itself, MGI shifts maritime monitoring from a model in which transparency is asserted by reporting institutions after the fact to one in which transparency is structurally enforced through the immutability of the blockchain ledger. This distinction is analytically significant because it relocates the basis of public trust away from institutional reputation alone and toward verifiable, tamper-evident data, a shift consistent with broader global discussions on the role of blockchain in strengthening institutional accountability (Li & Sun, 2025). At the same time, this technical assurance of data integrity does not by itself guarantee responsive governance; without corresponding institutional commitment to act upon verified detection records, the transparency afforded by MGI risks becoming a passive archive rather than an active enforcement tool, reinforcing the importance of the regulatory and institutional support discussed in the Policy and Governance Implications section below.

3.2 Conceptual framework

MGI functions to monitor and detect illegal STS transfer activities in the waters of the Riau Islands through the integration of marine sensors, radar, satellite imagery, and AIS data. Data from multiple sources are transmitted to a processing center to be cleaned and standardized prior to analysis. This stage ensures data accuracy, enabling the system to identify suspicious vessel movements in real time with a high level of reliability.

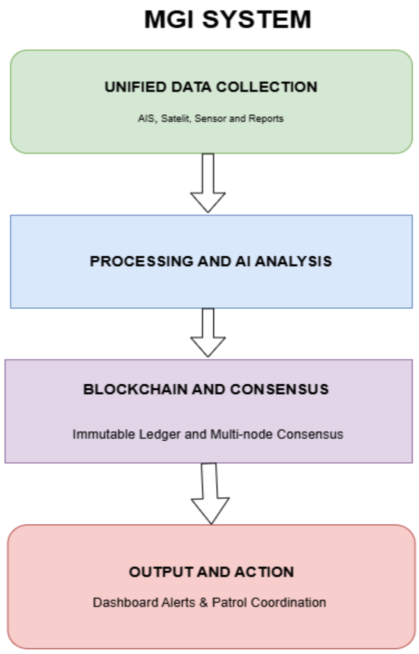

Fig. 2. Maritime Guard Intelligence (MGI) system architecture

The data acquisition layer collects information from AIS, radar, marine sensors, satellite imagery, and fishermen reports. The AI processing layer utilizes CNN and Isolation Forest algorithms to identify suspicious vessel behavior. Subsequently, the blockchain layer validates and stores detection results through a Proof-of-Authority mechanism. Finally, the decision-support layer delivers alerts and recommendations to maritime authorities for operational response. The analysis is conducted using artificial intelligence through two primary algorithms. CNN processes satellite imagery to identify abnormal vessel activities, while Isolation Forest analyzes AIS data to detect anomalies such as signal loss or sudden directional changes. If the probability of suspicious activity reaches a predefined threshold, the system designates the area as a high-risk zone and activates automated alerts for further monitoring.

The AI detection results are subsequently verified through smart contracts within a blockchain network. The PoA model ensures that incoming data are validated by trusted nodes consisting of students, fishermen, and maritime authorities. Once validated, the system automatically executes commands, such as transmitting warning signals, activating additional radar systems, or forwarding target coordinates to patrol vessels. This process ensures data security and transparency without human intervention. The final stage involves adaptive learning to continuously improve system accuracy. Each detection and verification result is stored for retraining the AI models. In this manner, MGI becomes increasingly capable of recognizing emerging patterns and strengthening its predictive capabilities. The combination of marine sensors, artificial intelligence, blockchain, and continuous feedback establishes MGI as an efficient and transparent maritime surveillance system capable of strengthening Indonesia's maritime sovereignty.

Further enhancement of MGI system performance is directed toward improving detection accuracy through the simultaneous integration of multisource data. By combining AIS data, satellite imagery, radar, and marine sensor inputs, the system does not rely on a single information source but performs cross-validation to minimize detection errors, including both false positives and false negatives. This approach enables the system to compare vessel movement patterns with real-time visual field conditions, resulting in more comprehensive and accurate analyses.

In addition, MGI is designed with Geographic Information System (GIS)-based spatial mapping capabilities that enable dynamic visualization of areas vulnerable to illegal activities. Through this mapping, the system can identify hotspots of illegal STS activities based on historical data and incident frequency. This information is critical for maritime authorities in determining surveillance strategies, including patrol fleet deployment and security prioritization. Consequently, surveillance shifts from a reactive approach to one based on measurable risk analysis. From an operational efficiency perspective, MGI adopts an automation-based approach in information processing and distribution. Each system-generated alert is classified according to urgency level and directly forwarded to relevant stakeholders through dashboards and digital notifications. This reduces dependence on manual processes that are often time-consuming and susceptible to delayed responses. Through automation, response times to potential violations can be significantly reduced.

Table 1. SWOT analysis

Strength	Weakness	Opportunities	Threats
The integration of machine learning and blockchain technology enables real-time and accurate detection of illegal ship-to-ship transfer activities.	High initial costs for equipment and infrastructure.	Potential to serve as a national model for digital maritime surveillance.	Potential cyberattacks targeting blockchain networks.
The decentralized system ensures data security and transparency.	Limited technological proficiency among coastal human resources.	Opportunities for collaboration with national and international institutions.	Policy changes may hinder implementation.
Collaboration among students, fishers, and maritime authorities is effective in field implementation.	Dependence on AIS and satellite data, which are sensitive to weather conditions.	Supports blue economy and smart maritime policies.	Risk of sensor damage due to extreme marine conditions.
Lightweight AI remains functional in low-connectivity areas.	Regular training is required for fishers as system users.	Potential for technology export to ASEAN countries.	Monitoring gaps due to delays in data synchronization.

Furthermore, to ensure reliability under various conditions, MGI is designed with a flexible and scalable architecture. The system can adjust data-processing capacity according to incoming data volume, ensuring optimal performance even during surges in vessel activity within specific regions. This flexibility also supports future system development, including the addition of new analytical modules or integration with other technologies without requiring a complete structural redesign. Another critical aspect is the strengthening of audit mechanisms and data traceability within the blockchain system. Every activity recorded in the system can be chronologically traced, from the detection process to the actions taken. This not only enhances transparency but also provides a strong foundation for law enforcement processes, as each digital record possesses high validity and accountability.

Moreover, MGI presents opportunities for the development of collaborative regional systems, particularly within Southeast Asia, where interconnected maritime characteristics prevail. Through cross-border interoperability, the system has the potential to support secure and integrated maritime data exchange, enabling broader and more effective monitoring of illegal activities. This is particularly relevant given that many illegal STS activities involve transnational jurisdictions.

With these enhancements, MGI functions not only as a detection and monitoring tool but also as a strategic platform for data-driven decision-making. The system provides a comprehensive real-time overview of maritime security conditions while delivering analytical insights for long-term planning. Therefore, MGI holds significant potential to serve as a foundational framework for the development of modern, adaptive, and sustainable maritime surveillance systems in Indonesia.

3.3 Stakeholder analysis

Based on the Pentahelix model (Figure 3), there are five classifications: academia, business, government, media, and communication. These five stakeholders play a highly significant role in the development of MGI (Istyanto et al., 2024). Specifically, the roles of these five classifications are as follows (Table 2).

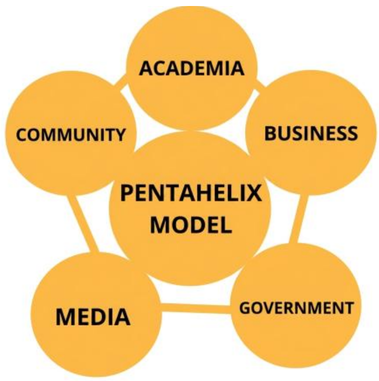

Fig. 3. Pentahelix model

The implementation of the MGI innovation primarily targets the enhancement of roles, collaboration, and positive impacts for various stakeholders within the maritime ecosystem. This program is expected to strengthen the capacity of coastal communities, encourage student involvement in applied research, improve monitoring effectiveness by maritime authorities, and support data-driven policymaking by local governments. Overall, the implementation of MGI is directed toward creating an adaptive, collaborative, and sustainable marine surveillance system. The integration of AI and blockchain is expected to strengthen the monitoring system through faster, more accurate, and more transparent mechanisms. The detailed targets and success indicators are presented in the following Table 3.

The implementation of MGI is also expected to generate significant social, economic, and governance benefits for coastal regions, particularly in the Riau Islands. From a social perspective, the system encourages active community participation in maritime surveillance through a digital reporting mechanism. Coastal communities and fishermen are positioned not merely as beneficiaries but also as strategic partners in monitoring activities. This participatory approach can strengthen public awareness regarding maritime security issues while fostering a sense of collective responsibility for protecting marine resources and territorial waters. Increased community engagement is expected to improve the early detection of suspicious maritime activities that may otherwise go unnoticed by conventional monitoring systems.

Table 2. Pentahelix model analysis

No	Classification	Institution/ Stakeholder name	Main activities/ Contribution
1	Academia	Raja Ali Haji Maritime University (UMRAH), Supervising Lecturers, Research Students	Designing and developing the AI–Blockchain system (Isolation Forest, CNN, PoA), conducting field testing, and providing digital fisheries training.
2	Government	Indonesian Maritime Security Agency (Bakamla RI), Ministry of Transportation, Riau Islands Marine and Fisheries Agency, Local Government	Providing operational permits, regulatory support, system integration with national maritime data, and supervision of field implementation.
3	Business/ Industry	Technology Partners (Maritime IoT Startups, Cloud Server Providers, Drone Companies)	Providing digital infrastructure such as marine sensors, computational servers, Android applications, and system maintenance services.
4	Community/ Society	Local Fishermen, Digital Fishermen Cooperatives, Community Monitoring Groups (Pokmaswas)	Acting as co-observers by submitting vessel activity reports through the MGI application and supporting Proof of Authority-based verification.
5	Media	Local Media (Batam Pos, Tribun Kepri), National Media, Environmental Journalists	Disseminating innovation outcomes, educating the public on digital maritime surveillance, and raising awareness of the risks of illegal STS activities.

From an economic perspective, the reduction of illegal ship-to-ship transfer activities can contribute to minimizing state losses associated with illegal fuel distribution, smuggling, and unauthorized maritime transactions. Improved monitoring capabilities may also support the sustainability of marine-based economic activities by creating a safer and more secure maritime environment. In the long term, better maritime governance can increase investor confidence in maritime industries, logistics services, and fisheries sectors operating within Indonesian waters. Consequently, the proposed innovation has the potential to contribute indirectly to regional economic development and maritime competitiveness.

In terms of governance, MGI promotes greater transparency and accountability in maritime monitoring processes. The integration of blockchain technology ensures that every verified report and detection result is securely recorded and cannot be altered without authorization. This feature provides a reliable audit trail that can support evidence-based decision-making by maritime authorities and policymakers. Furthermore, the availability of integrated maritime data can facilitate coordination among relevant institutions, including maritime security agencies, local governments, port authorities, and environmental monitoring organizations. Such coordination is essential for addressing increasingly complex maritime challenges that often require cross-sectoral collaboration.

The implementation of MGI is also expected to contribute to the development of digital transformation initiatives within the maritime sector. As governments around the world increasingly adopt smart governance approaches, the utilization of AI and blockchain technologies can serve as a model for modernizing maritime monitoring systems in Indonesia. The proposed system demonstrates how emerging technologies can be integrated into public sector governance to improve efficiency, responsiveness, and service quality. This innovation may also encourage further research and technological development in areas such as maritime big data analytics, predictive monitoring systems, and intelligent decision-support tools.

Another important target of the program is capacity building among students and young researchers. Through involvement in system development, data analysis, and stakeholder engagement activities, students can gain practical experience in applying interdisciplinary knowledge to real-world problems. This process supports the development of future professionals who possess competencies in technology, public policy, and maritime governance. In addition, the project provides opportunities for collaboration between universities, government institutions, and local communities, thereby strengthening the role of higher education institutions in producing innovative solutions to national challenges.

Ultimately, the success of MGI will not only be measured by its technological performance but also by its ability to create meaningful impacts for stakeholders and support sustainable maritime governance. By combining technological innovation, community participation, institutional collaboration, and policy relevance, MGI is expected to become a comprehensive solution that strengthens maritime security, improves monitoring effectiveness, and supports the long-term sustainability of Indonesia's marine resources.

Table 3. Targets

No	Target	Success Indicators
1	Coastal communities and local fishermen	a. Number of fishermen using the blockchain-based reporting application b. Increased public awareness and participation in safeguarding the marine territory of the Riau Islands c. Improved security and fish catch outcomes due to the reduction of illegal foreign vessels d. Establishment of a digital maritime research laboratory at UMRAH
2	UMRAH Students (Raja Ali Haji Maritime University)	a. Improved research and innovation capabilities in maritime technology b. Students becoming innovation agents and developers of real-time data-based foreign vessel detection systems
3	Maritime Authorities (Indonesian Navy, KKP, KSOP)	a. Response time to detected maritime violations reduced by ≥50% b. Improved monitoring efficiency and field data validity c. AI monitors vessel movement patterns, while blockchain ensures data authenticity for law enforcement
4	Riau Islands Provincial Government	a. Establishment of an integrated mentoring system at the provincial level b. Improvement of digital maritime data-driven policies c. Increased data-based decision-making d. Government utilization of AI and blockchain data for marine protection policies

Artificial Intelligence (AI) has demonstrated strong capabilities in automating object detection, anomaly identification, and situational awareness within maritime environments (Durlik et al., 2025). Recent advancements in AI and deep learning techniques have introduced promising solutions for intelligent automated systems to monitor, detect maritime security threats, and respond rapidly (Wolsing et al., 2022). Research conducted by Talpur et al. (2025) in the article entitled "AI in Maritime Security: Applications, Challenges, Future Directions, and Key Data Sources" discusses the utilization of AI in the maritime sector. The study indicates that AI is effective in identifying various maritime-related issues.

In line with this, the integration of AI and blockchain in maritime surveillance, particularly in the Riau Islands, offers a further approach by establishing an intelligent, transparent, and secure system to detect suspicious foreign vessels entering the territorial waters of the Riau Islands (Pranita et al., 2023). AI functions as a detector of suspicious vessel movements and as the core system that processes data from multiple sources, such as coastal radar, AIS signals, satellite imagery, and fishermen's reports. AI can provide early warnings regarding potential maritime boundary violations or illegal activities such as illegal fishing and smuggling (Talpur et al., 2025), while deep learning technology has been proven to improve the accuracy of automatic vessel detection through the analysis of satellite imagery and movement patterns (Ma et al., 2023). Meanwhile, blockchain serves as a decentralized recording system that ensures the authenticity and security of data generated by AI (Bhumichai et al., 2024), and its application in the maritime sector has been shown to enhance transparency (Ma et al., 2023).

All vessel movements and analytical results can be stored as immutable digital records within the blockchain network (Elmay et al., 2022). This enables all surveillance data to be securely shared among various stakeholders, such as the Indonesian Navy and local governments, without concerns regarding data manipulation. In addition, smart contracts are utilized to automate incident reporting (Ma et al., 2023). When AI detects foreign vessels entering the waters of the Riau Islands, automatic notifications are sent to maritime authorities. The novelty of this study compared to previous research is presented in the following (Appendix 3).

4. Conclusions

MGI demonstrates that the integration of machine learning and blockchain can serve as a modern, transparent, and collaborative solution for maritime surveillance in the waters of the Riau Islands. The system was developed through the collection of AIS data, satellite imagery, and reports from local fishermen. These data were analyzed using Isolation Forest and CNN models to detect suspicious vessel movement patterns and illegal ship-to-ship (STS) activities in offshore waters. The Isolation Forest and CNN models were incorporated into the MGI framework to support anomaly detection and satellite image analysis for identifying suspicious maritime activities. The integration of both models enables the system to provide real-time early warnings for vessels stopping at unusual locations or deactivating AIS signals. The analytical results were subsequently verified through a Proof of Authority (PoA) mechanism within the blockchain network, ensuring that all data stored on the ledger are permanent, secure, and tamper-proof. The implementation of blockchain serves as the foundation of system transparency and accountability, as each detection result is verified by trusted nodes involving students, fishermen, and maritime institutions.

This innovation also strengthens collaboration between UMRAH students and coastal communities through a participatory surveillance system. Students contribute to system development and data analysis, while local fishermen act as active observers by reporting suspicious vessel activities through digital applications. This synergy expands surveillance coverage in remote coastal areas and enhances collective public awareness in safeguarding Indonesia's maritime security. From a sustainable development perspective, MGI aligns with SDG 14, SDG 9, and SDG 16. This innovation not only reinforces maritime surveillance and law enforcement but also supports the establishment of a fair, inclusive, and sustainable maritime system. In the future, MGI has the potential to be developed into a national digital maritime surveillance system integrated with Bakamla, KKP, and Badan eteorology, Climatology, and Geophysical Agency/*Meteorologi, Klimatologi, dan Geofisika* (BMKG), serving as a foundation for intelligent, participatory, and adaptive maritime security in response to the challenges of the digital era.

Suggestions for further evaluation of this research include directing future MGI development toward enhanced integration of IoT-based marine sensor technologies and machine learning models. The synergy between these technologies can strengthen spatial analysis capabilities and improve detection accuracy for increasingly complex and dynamic maritime activity patterns. Through real-time data integration, MGI has the potential to function as an intelligent control center capable of predicting vessel movements, detecting suspicious activities, and providing early warnings against violations in Indonesian waters. However, the successful implementation of such advanced technologies depends not solely on digital systems but also on the readiness of human resources. Therefore, strengthening the capacity of coastal communities is equally essential. Regular training for fishermen, patrol officers, and maritime communities is necessary to ensure their ability to understand, operate, and independently utilize digital reporting systems. Thus, digital transformation in the maritime sector will not only create more efficient systems but also foster technologically literate and highly competitive coastal communities. Furthermore, cross-sector collaboration among local governments, maritime institutions, the fisheries industry, and UMRAH should be further reinforced. Such collaboration can establish an integrated maritime innovation ecosystem in which academic research, public policy, and operational technology mutually support one another. From a policy perspective, comprehensive regulatory studies are required to support the implementation of Artificial Intelligence and blockchain-based technologies within maritime security systems. An adaptive and innovation-oriented legal framework will ensure that technological development is conducted ethically, transparently, and in accordance with the principles of good ocean governance.

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Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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