

Integration of Artificial Intelligence and Remote Sensing into Maritime Domain Awareness for IUU Fishing Detection in ASEAN: Desk Study and Descriptive Analysis Approach

Aprilia Nur Indah Sari¹, Nefra Firdaus², Yuniar³, Harri Dolli Hutabarat⁴,
Lukman Yudho Prakoso⁵

^{1,2,3,4,5}Republic of Indonesia Defense University, Indonesia

Email: aprillia.sari@kn.idu.ac.id^{1*}, nefra.firdaus@idu.ac.id², yuniar@idu.ac.id⁴, harri.dolli@idu.ac.id³,
lukman.prakoso@idu.ac.id⁵

*Corresponding Author

Article Info

Article history:

Received: 29 August, 2026

Revised: 3 September, 2026

Accepted: 10 September, 2026

Keywords:

Artificial Intelligence; ASEAN; Illegal Unreported and Unregulated (IUU) Fishing; Maritime Domain Awareness; Maritime Security; Remote Sensing.

ABSTRACT

Illegal, Unreported, and Unregulated (IUU) fishing in ASEAN waters poses a complex transnational threat that transcends traditional sector specific fisheries management, directly impacting sea power, the blue economy, marine environments, and coastal community resilience. Single sensor tracking systems like AIS and VMS often fail due to non cooperative "dark vessels" intentionally disabling their transmitters. Positioning technology within a broader maritime security framework rather than a fisheries only perspective, this study examines how satellite remote sensing and Artificial Intelligence (AI) can enhance Maritime Domain Awareness (MDA) across ASEAN. Employing a qualitative desk study and structured literature synthesis anchored in Christian Bueger's maritime security matrix, this study maps heterogeneous sensing modalities including Synthetic Aperture Radar (SAR), optical imagery, AIS, VMS, and registry databases against AI analytics functions. The findings highlight the principle of technological complementarity, where no single sensor suffices, but multi sensor data fusion detects discrepancies between reported vessel identities and physical observations. AI and machine learning act as intelligence conversion engines, shifting surveillance from binary legal/illegal claims to structured, multi indicator risk scoring $R_i = \sum (w_j x_{ij})$. Furthermore, this paper proposes a federated six layer ASEAN MDA architecture (*sensing, data fusion, AI analytics, human validation, coordination, and response*) that respects national sovereignty while facilitating cross border metadata exchange and operational enforcement under frameworks like the FAO Port State Measures Agreement.

INTRODUCTION

Maritime security in the twenty first century cannot be reduced to the protection of national borders or the employment of naval power. The maritime domain connects economic activity, food security, environmental sustainability, human safety, law enforcement, and strategic competition. Bueger (2015), conceptualizes maritime security through a matrix that relates security to marine safety, sea power, the blue economy, and resilience, while also emphasizing securitization and security practices as ways to map how

threats are constructed and governed. This multidimensional perspective is particularly relevant to IUU fishing because illegal or unauthorized fishing may simultaneously affect resource sustainability, economic interests, state jurisdiction, coastal livelihoods, and the credibility of maritime enforcement. ASEAN is a particularly important setting for this problem. The region combines extensive maritime spaces, dense coastal populations, major fishing grounds, busy shipping routes, and substantial differences in surveillance capacity. ASEAN itself identifies IUU fishing as a significant threat to marine ecosystems and fisheries resources and has promoted regional cooperation, information exchange, and technical capacity building through mechanisms including the ASEAN Network for Combating IUU Fishing (ASEAN, 2024; ASEAN, 2025). The security challenge therefore extends beyond the capacity of an individual fisheries agency: it concerns how states collectively observe, interpret, and respond to suspicious maritime activity.

Maritime Domain Awareness offers an appropriate operational framework because it is concerned with understanding maritime activity that can affect security, safety, the economy, or the marine environment. The International Maritime Organization (IMO) identifies three mutually reinforcing elements: maritime situational awareness, maritime threat awareness, and maritime response awareness (IMO, 2026). Thus, MDA is not merely a visualization platform. It is a security process linking data collection with threat assessment and deployable response. The central challenge is that maritime activity is increasingly difficult to observe through a single sensor. AIS provides vessel identity, position, speed, and course when signals are available, but vessels can be absent from public tracking or may intentionally stop transmitting. Remote sensing can observe physical targets independently of AIS. Recent global research combining satellite imagery, vessel positioning data, and deep learning models found that 72–76% of industrial fishing vessels were not publicly tracked, with substantial concentrations of untracked activity in Southeast Asia (Paolo et al., 2024). This finding underscores the security significance of detecting the gap between reported activity and observed activity.

Artificial intelligence provides a means to process the scale and complexity of these data. Machine learning systems can classify vessels, identify anomalous trajectories, associate AIS tracks with satellite detections, and rank vessels or areas according to risk. Contemporary research has demonstrated multimodal approaches combining Sentinel 1 SAR, optical imagery, and AIS to identify potentially suspicious activities (Galdelli et al., 2025), while recent work has explored AI based detection of AIS dark vessels using SAR and other modalities (e.g., the 2026 multimodal edge AI study). Yet, the security value of such systems lies not in prediction alone, but in their capacity to produce timely, explainable, and actionable intelligence for maritime authorities. Against this background, this article asks three questions: (1) what Christian Bueger’s maritime security theory, (2) how should these technologies be positioned within a maritime security rather than fisheries only framework, and (3) how the application of satellite remote sensing and AI based analytics to support IUU fishing monitoring and international maritime security.

METHODS

This study uses a desk study and descriptive analytical design. It does not claim to estimate the prevalence of IUU fishing or measure algorithmic accuracy from a newly collected vessel dataset. Instead, it synthesizes established academic research, official

institutional documents, and documented technology applications to develop an evidence informed conceptual framework for ASEAN maritime security.

This study employs a qualitative literature study to identify, compare, and synthesize relevant concepts and findings from existing literature on maritime security, Maritime Domain Awareness (MDA), artificial intelligence (AI), and IUU fishing (Snyder, 2019). The analysis integrates three key domains: (1) Christian Bueger's maritime security theory, (2) how should these technologies be positioned within a maritime security rather than fisheries only framework, and (3) the application of satellite remote sensing and AI based analytics to support IUU fishing monitoring and international maritime security. The methodological process of the research is structured into the following stages :

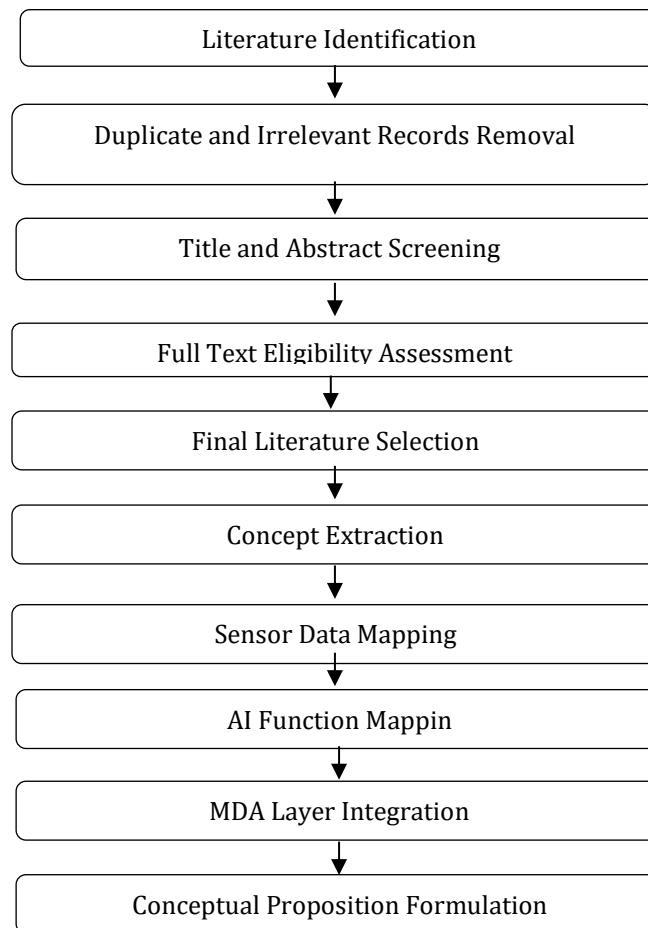


Figure 1. The methodological process of the research.

The screening process consisted of four stages. First, relevant literature was identified based on title, abstract, and keyword searches. Second, duplicate and clearly irrelevant publications were removed. Third, the remaining studies were screened according to predefined inclusion criteria, including (1) relevance to IUU fishing or maritime security, (2) discussion of MDA or maritime surveillance, (3) application of AIS, VMS, remote sensing, or AI based analytics, and (4) relevance to ASEAN or transferable to the ASEAN maritime context. Publications that lacked sufficient relevance, focused exclusively on non maritime applications, or did not provide substantive theoretical or methodological information were

excluded. Finally, the selected literature was synthesized according to five analytical categories: concept extraction, sensor data mapping, AI function mapping, MDA layer integration, and conceptual proposition formulation.

The synthesis began by identifying the four dimensions of Bueger's maritime security matrix and relating them to the transnational challenges of IUU fishing in ASEAN waters. The selected literature was then mapped according to the characteristics and functions of AIS, VMS, satellite SAR, optical imagery, marine spatial governance and conservation area geofencing, and cross border vessel registration. Subsequently, AI applications were categorized according to their analytical functions, including CNN based image detection and LSTM or Transformer based trajectory anomaly detection. These technological capabilities were then linked to the MDA sequence from situational awareness to threat awareness and response awareness. The final stage synthesized the findings into theoretical propositions that can be examined through future empirical research in ASEAN waters.

The inclusion and exclusion criteria were established based on the research objectives and methodological principles of qualitative literature study with a structured literature search and screening process (Snyder, 2019; Xiao and Watson, 2019).

Table 1. Screening Criteria.

Criteria	Inclusion Criteria	Exclusion Criteria	Supporting References
Topic	IUU fishing, maritime security, and Maritime Domain Awareness (MDA).	Studies unrelated to maritime issues.	Bueger (2015).
Technology	AIS, VMS, SAR, optical imagery, AI, and machine learning.	Technologies not relevant to vessel monitoring or maritime surveillance.	Purivigraipong (2018); Fitriah et al. (2026).
Geographical Context	ASEAN countries or studies with findings applicable to the ASEAN maritime context.	Studies with no relevance or transferability to the ASEAN context.	FAO; ASEAN related maritime literature.
Source Type	Peer reviewed journal articles, institutional reports, and publications from international organizations.	Sources lacking sufficient academic or substantive information.	Snyder (2019); Xiao and Watson (2019)
Analytical Focus	Vessel detection, anomaly detection, maritime surveillance, MDA, and maritime governance.	Studies unrelated to maritime monitoring, detection, or security governance.	Bueger (2015); IMO (2026); Fitriah et al. (2026).

(Source : Snyder, 2019; Xiao and Watson, 2019).

To ensure that the selected literature is relevant to the research objectives and scope, the screening process was conducted based on several predefined criteria. These criteria covered the topic, technology, geographical context, source type, and analytical focus. Each criterion was used to assess the eligibility and relevance of the literature before it was included in the synthesis process, as described below:

Topic

Selected literature must address IUU fishing, maritime security, or *Maritime Domain Awareness* (MDA). This criterion ensures that the reviewed sources are directly relevant to the main research problem.

Technology

The literature must discuss the use of AIS, VMS, SAR, optical imagery, artificial intelligence (AI), or machine learning for maritime monitoring and surveillance. This criterion is used to identify technological capabilities that can support the detection and analysis of potentially suspicious fishing activities.

Geographical Context

Literature focusing on the ASEAN region is prioritized, while studies from other regions may be included when their findings and approaches are transferable to the ASEAN maritime context. This criterion ensures that the synthesis remains relevant to the characteristics and governance of ASEAN waters.

Source Type

The selected sources include peer reviewed journal articles, official institutional reports, and publications from international organizations that provide relevant academic or institutional information. This criterion is applied to maintain the credibility and quality of the reviewed literature.

Analytical Focus

The literature must address vessel detection, anomaly detection, maritime surveillance, MDA, or maritime security governance. This criterion ensures that the selected studies contribute to understanding the relationship between maritime data, threat identification, and security responses.

Theoretical Proposition Framework: Main Propositions of Technology and Security Integration

Recent developments in maritime surveillance increasingly emphasize the integration of heterogeneous sensing modalities to overcome the limitations of individual data sources. Fitriah et al. (2026), demonstrate that the integration of AIS and SAR imagery can provide complementary information for identifying non cooperative or “dark” vessels, with AIS contributing vessel identity and reported positional information while SAR provides independent physical detection capabilities. Their review further highlights the importance of spatio temporal synchronization, data association, and machine learning techniques in integrating these modalities. This finding strengthens the proposition that multimodal data fusion can provide a more comprehensive evidentiary basis for IUU fishing surveillance than dependence on a single sensor.

Literature mapping is crucial for identifying research gaps. The map should clearly indicate what has been addressed in previous studies and where the gaps lie. Each checkmark (✓) must be derived directly from the content of the articles included in the map,

allowing the table to serve simultaneously as the basis for identifying research gaps and compiling the Mendeley bibliography. Given that the topic integrates IUU fishing, Bueger, MDA, AIS/VMS, SAR/optical imagery, AI, and ASEAN, the table can be structured as shown in Table 2.

Table 2. Literature Mapping of Previous Studies and Identified Research Gaps

No.	Focus of Previous Studies	IUU Fishing	AIS/VMS	SAR/Optical	AI/ML	MDA	Bueger Maritime Security	ASEAN	Identified Research Gap
1	IUU fishing and global fisheries vulnerability	✓	-	-	-	-	-	-	Emphasizes the scale and impacts of IUU fishing but does not integrate detection technologies with a maritime security perspective.
2	Vessel activity monitoring using AIS	✓	✓	-	-	-	-	✓	AIS supports vessel monitoring but has limitations for vessels that do not transmit or manipulate their signals.
3	Use of VMS for fisheries monitoring	✓	✓	-	-	-	-	✓	Focuses on monitoring licensed vessels and does not fully integrate multimodal data sources.
4	Use of SAR for vessel detection	✓	-	✓	✓	-	-	-	Enables vessel detection independently of lighting conditions but is not always linked to governance and MDA.
5	Optical imagery for vessel detection	✓	-	✓	✓	-	-	-	Provides visual information but is affected by cloud cover and atmospheric conditions.
6	AI/ML for anomaly detection	✓	✓	✓	✓	-	-	-	Strengthens the identification of suspicious vessel behavior but often focuses primarily on technical aspects.
7	Maritime Domain Awareness	-	✓	✓	-	✓	-	✓	Addresses information integration for maritime awareness but does not specifically link AI-based IUU detection with Bueger's framework.
8	Bueger's maritime security framework	✓	-	-	-	✓	✓	-	Provides a conceptual foundation for maritime security but does not explicitly integrate AI and remote sensing technologies.
9	Maritime security and IUU fishing in ASEAN	✓	✓	-	-	✓	✓	✓	Highlights the transboundary nature of IUU fishing, but integration of multimodal technologies remains limited.
10	Integration of IUU Fishing, AI, MDA, and Bueger's framework in the ASEAN context	✓	✓	✓	✓	✓	✓	✓	An area that remains limited in the literature and is addressed through the synthesis of this study.

(Source : Secondary Data, 2026).

The literature mapping indicates that previous studies have examined IUU fishing detection, AIS/VMS based vessel monitoring, satellite remote sensing, AI based anomaly detection, and Maritime Domain Awareness from different perspectives. However, these research streams remain largely fragmented, with limited integration of multimodal maritime data and AI analytics within Bueger's maritime security perspective and the ASEAN maritime context.

This article draws upon ten literature sources covering IUU fishing, AIS/VMS, remote sensing, AI, MDA, Bueger, and ASEAN. Some of these sources are peer reviewed journal articles, while the IMO serves as an institutional source for the concept of MDA. The table outlining the literature mapping of previous studies and identified research gaps can be found in Table 3.

Table 3. Literature Mapping of Previous Studies and Identified Research Gaps With Reference

No.	Study	Main Focus	IUU Fishing	AIS/VMS	SAR/Optical	AI/ML	MDA	Bueger Maritime Security	ASEAN	Identified Research Gap
1	Bueger, (2015).	Maritime security as a multidimensional concept	✓	-	-	-	✓	✓	-	Provides the theoretical foundation for maritime security but does not specifically address technology-based IUU fishing detection.
2	Bueger, (2015).	Maritime Domain Awareness in Southeast Asia	✓	✓	-	-	✓	✓	✓	Explains MDA, information sharing, and regional coordination, but technological integration for IUU fishing remains limited.
3	Kroodsma et al., (2018).	Global fishing activity using AIS	✓	✓	-	✓	-	-	-	Demonstrates large-scale AIS-based fishing detection but does not integrate the analysis with Bueger's maritime security framework or ASEAN governance.
4	Longépé et al., (2018).	VDS/SAR, AIS, and VMS for illegal fishing in Indonesia	✓	✓	✓	-	-	-	✓	Demonstrates the value of combining satellite vessel detection, AIS, and VMS, but does not incorporate AI-based multimodal risk assessment or Bueger's framework.
5	Cabral et al., (2018).	AIS/VMS and policy response to illegal fishing in Indonesia	✓	✓	-	-	-	-	✓	Demonstrates the effectiveness of monitoring and policy intervention but does not examine AI-based detection or international MDA integration
6	Toonen and Bush, (2019).	Digital technologies for fisheries governance	✓	✓	✓	-	-	-	-	Shows the potential of satellites and vessel tracking for fisheries governance but does not explicitly connect multimodal sensing with MDA and Bueger's security perspective
7	Ford et al., (2024).	AI/deep learning for anomaly detection in fisheries	✓	✓	✓	✓	✓	-	-	Establishes the potential of AI for detecting anomalous fishing behaviour but focuses primarily on technical detection rather than regional maritime security governance
8	Belhabib et al., (2020).	Satellite detection of industrial fishing incursions	✓	-	✓	-	-	-	-	Demonstrates satellite-based monitoring of fishing incursions but does not integrate AIS/VMS, AI, MDA, or ASEAN institutional coordination
9	Hasan et al., (2024).	IUU fishing and maritime security in the Makassar Strait	✓	-	-	-	✓	-	✓	Highlights the maritime-security and law-enforcement dimensions of IUU fishing in an ASEAN border context but does not integrate advanced sensing and AI.
10	Raynor and Lohrer, (2026).	AI-enabled satellite-based fishing fleet tracking	✓	✓	✓	✓	✓	-	-	Demonstrates the growing integration of satellite tracking and AI, but does not specifically operationalize the approach through Bueger's maritime security matrix for ASEAN.
11	This study	Integration of IUU fishing detection, multimodal sensing, AI, MDA, and Bueger's maritime security perspective	✓	✓	✓	✓	✓	✓	✓	Synthesizes the fragmented literature into an integrated international maritime-security perspective applicable to ASEAN.

(Source : Secondary Data, 2026)

This table 3 does not list "AI" for studies that do not actually use AI. For example, Longépé et al. (2018), use radar/SAR based VDS alongside VMS and satellite AIS to monitor illegal fishing in Indonesia, so the checkmark (✓) appears under AIS/VMS and SAR, but not AI. Kroodsma et al. (2018), use approximately 22 billion AIS messages to track more than 70,000 industrial fishing vessels globally and develop AIS data driven mapping of fishing activities. This study strongly supports the AIS + fishing activity detection component, but it does not specifically use the Bueger framework or ASEAN MDA. Ford and Smith (2024), are highly relevant to the AI/ML component, as their work is a review of automatic anomaly detection in fisheries using electronic monitoring and AIS, including deep learning approaches and the potential integration of various data sources.

For the ASEAN MDA component, Bueger (2015), is essential because it specifically addresses MDA in Southeast Asia, emphasizing that MDA requires both data collection and fusion while facing social, political, and legal challenges. The IMO also officially divides MDA into maritime situational awareness, maritime threat awareness, and maritime response awareness. Regarding recent developments, Raynor and Lohrer (2026), discuss the integration of AI and satellite based vessel tracking, including SAR and optical imagery, as well as the potential for monitoring dark vessels.

The literature mapping demonstrates that previous studies have addressed IUU fishing detection, vessel monitoring, satellite based surveillance, artificial intelligence, and Maritime Domain Awareness from different perspectives. Kroodsma et al. (2018), demonstrated the

potential of AIS data for large scale monitoring of global fishing activity, while Longép  et al. (2018), demonstrated the complementary use of satellite vessel detection, AIS, and VMS for identifying illegal fishing activities in Indonesian waters. Similarly, Cabral et al. (2018), highlighted the contribution of vessel monitoring and policy intervention to reducing illegal fishing in Indonesia. More recent research has expanded toward AI based anomaly detection and the integration of multiple maritime data sources (Ford and Smith, 2024; Raynor and Lohrer, 2026).

However, the literature remains fragmented across technological, operational, and governance dimensions. Studies focusing on AIS, VMS, and satellite sensing primarily emphasize vessel detection and fishing activity monitoring, whereas AI studies tend to focus on anomaly detection and behavioral classification. Meanwhile, Bueger's maritime security perspective and MDA literature provide important theoretical and institutional foundations but have not been sufficiently integrated with multimodal AI based IUU fishing detection specifically within the ASEAN context. Therefore, the literature mapping indicates a need for greater conceptual integration between multimodal maritime sensing, AI based analytics, MDA, and maritime security governance in addressing the transnational nature of IUU fishing in ASEAN waters.

FRAMEWORK DEVELOPMENT AND DISCUSSION

Application of the Bueger Maritime Security Matrix in the ASEAN Scenario

The primary advantage of utilizing Bueger's matrix in MDA on an international scale is its ability to break down a single technological alert into specific policy indicators in the ASEAN region. For example, a dark vessel without AIS transmission detected by SAR at cross border boundaries is mapped into the Seapower / Law Enforcement dimension, a dimension long theorized as central to maintaining order at sea (Till, 2013), triggering integrated patrols among ASEAN nations built on communities of practice and inter state alliances (Bueger and Stockbruegger, 2013; NATO, 2011). Conversely, anomalous fishing activity in an international maritime conservation area is prioritized in the Marine Environment dimension. This increases the allocation efficiency of international patrol fleets (Akta et al., 2026; Chandra et al., 2026; Sambouw et al., 2026).

The desk analysis indicates that IUU fishing has at least five interconnected security dimensions. First, it challenges economic security by diverting fisheries value from compliant operators and states. Second, it creates environmental security risks through depletion of stocks and ecosystem degradation. Third, it tests jurisdictional authority because effective enforcement depends on where a vessel operates, its flag, its licensing status, and the jurisdiction of coastal, port, and flag states. Fourth, IUU networks may overlap with other maritime crimes and illicit supply chains. Fifth, persistent inability to detect or respond to violations can weaken maritime governance and public confidence.

The FAO Port State Measures Agreement (PSMA) provides an important legal governance layer because it seeks to prevent, deter and eliminate IUU fishing by restricting the ability of offending vessels to use ports and land catches (FAO, n.d.). Its logic demonstrates why detection must be connected to information sharing and follow up action. A technically sophisticated MDA alert that cannot be verified or transmitted to a competent authority has limited deterrent value.

From an analytical perspective, maritime anomaly detection provides the intermediate mechanism between raw surveillance data and threat assessment. Existing research has

demonstrated that AIS trajectory data can be used to identify abnormal vessel behavior relevant to maritime safety and security, although challenges remain regarding data quality, anomaly definitions, generalizability, and the availability of reliable labelled datasets (Riveiro et al., 2018; Pallotta et al., 2022). This suggests that an IUU fishing detection architecture should avoid interpreting a single anomaly as definitive evidence of illegal activity. Instead, multiple indicators should be evaluated collectively, including vessel behavior, spatial location, fishing zone restrictions, AIS transmission patterns, and historical vessel activity.

At the regional level, the final value of this analytical process lies in its ability to support coordinated decision making. MDA is intended to create a shared understanding that enables different maritime security actors to coordinate their actions rather than operate independently (Bueger, 2015). In the ASEAN context, this means that an AI generated alert concerning a suspected dark vessel or illegal fishing activity should ideally be transformed into a validated information product that can be shared among relevant national authorities. The ASEAN Information Sharing Portal, for example, was developed to facilitate maritime security information exchange among ASEAN navies and to enhance communication and interoperability (Ministry of Defence Singapore, 2012). Thus, the integration of AI analytics with regional information sharing mechanisms can establish a pathway from sensor detection → analytical assessment → threat awareness → information sharing → coordinated response.

The Technologies be Positioned Within a Maritime Security Rather Than Fisheries Only Framework

The concept of Maritime Domain Awareness (MDA) formulated by the International Maritime Organization (IMO) is not merely a system or data visualization platform (such as a digital vessel tracking map), but rather an integrated security process. The primary objective of MDA is to understand all activities in the maritime domain that could affect security, safety, the economy, or the marine environment (IMO, n.d.; Bueger, 2015). The process of technological complementarity within MDA as an early detection framework for IUU Fishing can be explained as follows:

Complementarity of AIS, SAR, optical imagery and VMS

To provide a comprehensive overview of sensor capabilities, Table 4 presents a comparative analysis outlining the primary strengths, security limitations, and operational roles of various maritime data sources within an integrated Maritime Domain Awareness (MDA) framework.

Table 4. Characteristics, Limitations, and Roles of Maritime Sensor Data Sources

Data source	Primary strength	Security limitation	Role in integrated MDA
AIS	Identity and dynamic position	Coverage gaps; signal may be absent or manipulated	Track and identity baseline
SAR	All weather/low light vessel detection	Interpretation can be difficult; small targets challenging	Independent observation / dark vessel cue
Optical satellite	Visual detail and contextual information	Cloud, illumination and revisit limitations	Classification and corroboration
VMS	Fisheries specific monitoring	Access and interoperability vary by state	Licensed fishing activity baseline
Port/registry data	Legal identity and compliance context	Different national systems and update cycles	Legal and ownership verification
RF/night lights	Additional vessel/activity cues	Specialized processing and uncertainty	Supplementary detection

(Source: Bueger, 2015; Kurekin et al., 2019; Paolo et al., 2024).

The most important analytical finding is therefore the complementarity principle. No individual sensor should be treated as the authoritative representation of maritime reality. AIS can answer 'who says they are here?', SAR can help answer 'what physical target is actually here?', and VMS or licensing records can answer 'is this activity authorized?'. AI can then help correlate these answers and identify inconsistencies. This logic is consistent with the development of AIS SAR fusion and multimodal detection approaches in the recent literature (Paolo et al., 2024; Riveiro et al., 2018).

AI enabled anomaly detection and risk prioritization

AI adds value primarily by converting large volumes of heterogeneous observations into prioritized intelligence. Potential features include speed and course changes, loitering, repeated boundary crossings, suspicious rendezvous, prolonged fishing activity in restricted areas, mismatch between vessel identity and observed vessel characteristics, and AIS SAR temporal or spatial discrepancies. Ford and Wilcox (2022), show that structured risk indicators can support transparent prioritization, while recent multimodal AI studies demonstrate the feasibility of automated vessel detection and AIS matching.

A security oriented AI model should therefore produce a risk score rather than a binary 'illegal/legal' classification. A conceptual score can be represented as $R_i = \sum(w_j x_{ij})$, where R_i is the risk score of vessel i , x_{ij} is the normalized evidence for indicator j , and w_j is the weight assigned to that indicator. The equation is not proposed as a validated ASEAN algorithm; it is a transparent design principle for future empirical research. The final classification should remain subject to human verification and applicable national law.

Table 5. Classification of AI Risk Indicators, Examples, and Security Meanings in MDA

Indicator family	Examples	Potential security meaning
Identity anomaly	AIS identity mismatch; registry inconsistency	Possible concealment or deceptive reporting
Movement anomaly	Loitering; abnormal stops; boundary crossings	Potential fishing or rendezvous activity
Sensor discrepancy	SAR detection without AIS match	Dark vessel candidate requiring verification
Spatial anomaly	Fishing inside restricted/closed zones	Possible jurisdictional violation
Licensing anomaly	Gear/area inconsistent with license	Potential illegal fishing
Network anomaly	Repeated encounters/transshipment patterns	Possible organized or coordinated activity

(Source : Ford and Wilcox, 2022; Galdelli et al., 2025; Paolo et al., 2024).

From detection to maritime security response

The decisive difference between surveillance technology and maritime security lies in response. The IMO's MDA model explicitly includes response awareness, which requires knowledge of available response resources and their deployment (IMO, n.d.). Therefore, the ASEAN model should integrate detection with an operational command and control pathway.

At the national level, an alert could be routed to the competent fisheries monitoring or maritime enforcement centre. Depending on the jurisdiction and evidence, the system could request additional satellite passes, coastal radar confirmation, patrol interception, port inspection, or post event investigation. At the regional level, standardized alerts could support information exchange when vessels cross maritime boundaries or move between jurisdictions. This is particularly important because IUU activity can be transboundary while enforcement authority remains jurisdiction specific.

Proposed ASEAN security oriented MDA architecture

The proposed architecture consists of six layers: (1) sensing, (2) data fusion, (3) AI analytics, (4) human validation, (5) interagency coordination, and (6) operational response. The architecture is deliberately federated rather than centralized. Each ASEAN member state can maintain sovereign national systems while exchanging selected metadata, alerts, risk indicators, and case information according to agreed rules.

Table 6. The proposed architecture consists of six layers

Layer	Core capability	Maritime security function
1. Sensing	AIS, VMS, SAR, optical, radar, RF, port/registry data	Expand visibility of maritime activity
2. Data fusion	Temporal/spatial matching and entity resolution	Build a coherent operational picture
3. AI analytics	Detection, classification, anomaly detection, risk scoring	Identify and prioritize threats
4. Human validation	Analyst review, evidence checking, explainability	Reduce false positives and preserve accountability
5. Coordination	MDA centre, fisheries, coast guard, navy, police, ports	Connect information to lawful authority
6. Response	Patrol, inspection, investigation, port state measures	Deter, disrupt and document IUU activity

(Source : Bueger, 2015; Ford and Wilcox, 2022; IMO, n.d.).

CONCLUSION, RECOMMENDATIONS AND LIMITATIONS

The concluding of this article can be three section. The first concluding explain The paradigm shift in maritime security is addressing Illegal, Unreported, and Unregulated (IUU) fishing in ASEAN waters can no longer be managed as a sector specific fisheries issue. Grounded in Christian Bueger's maritime security matrix, IUU fishing represents a multidimensional transnational threat affecting sea power, the blue economy, marine environmental sustainability, and the resilience of coastal communities.

Second concluding can be explain is the principle of technological complementarity is Relying on a single sensor modality (such as AIS or VMS alone) leaves critical surveillance gaps due to the prevalence of "dark vessels" intentionally disabling their transmitters. The integration of heterogeneous sensing sources including Synthetic Aperture Radar (SAR), satellite optical imagery, RF/night lights, and port registry databases is essential to detect the gap between reported identity and actual observed physical activity. AI as an Intelligence Conversion Engine can be explain to Artificial Intelligence (AI) and Machine Learning (ML) add primary value by converting large scale, heterogeneous observations into prioritized actionable intelligence. Rather than attempting a binary legal/illegal classification, security oriented AI models provide structured, transparent risk scoring $R_i = \sum(w_j x_{ij})$. Third concluding can be explain proposed federated ASEAN MDA architecture is effective maritime surveillance requires a federated six layer Maritime Domain Awareness (MDA) architecture spanning sensing, data fusion, AI analytics, human validation, interagency coordination, and operational response. This framework respects the national sovereignty of ASEAN member states while enabling structured cross border metadata exchange, threat assessment, and enforcement coordination.

Based on the presentation in this article, two primary recommendations are proposed to advance regional maritime security. First, Policy and Practical Recommendations emphasize the establishment of a federated information platform to promote standardized data sharing without compromising national sovereignty, the enhancement of operational enforcement pipelines connecting AI intelligence directly to command and control pathways under the FAO PSMA, and the institutionalization of human in the loop validation to preserve legal accountability and explainability. Second, Future Research Directions highlight the need for

empirical validation of AI/ML models using localized datasets in ASEAN hotspots like the North Natuna Sea or the Malacca Strait, alongside the standardization of adaptive risk weights (w_j) tailored to dynamic regional enforcement capabilities.

This study is subject to several limitations, primarily stemming from its conceptual and qualitative desk study nature, which lacks empirical evaluation of vessel datasets and direct testing of machine learning algorithm precision. Furthermore, the practical execution of the proposed framework is constrained by significant inter state capacity disparities across ASEAN, where variations in technical infrastructure, satellite data acquisition costs, and regulatory frameworks pose hurdles to seamless integration. These challenges are further compounded by restricted access to essential licensing, VMS, and port data, which frequently remain strictly confidential, proprietary, or bound by jurisdictional privacy rules that hinder real time cross border interoperability.

REFERENCES

- Akta, R., Chandra, M., and Sambouw, A. (2026). Optimizing international patrol fleet allocation for marine protected areas using spatial risk analytics. *Marine Policy*, 183, Article 105921. <https://doi.org/10.1016/j.marpol.2026.105921>.
- ASEAN. (2024). *ASEAN regional plan of action for combating illegal, unreported and unregulated fishing*. ASEAN Secretariat. <https://asean.org>.
- ASEAN. (2025). *Progress report on the implementation of the ASEAN network for combating IUU fishing (AN IUU)*. ASEAN Secretariat. <https://asean.org>.
- Bateman, S. (2016). Maritime security governance in the Indian Ocean region. *Journal of the Indian Ocean Region*, 12(1), 5–23. <https://doi.org/10.1080/19480881.2016.1138709>.
- Belhabib, D., Cheung, W. W. L., Kroodsmas, D., Lam, V. W. Y., Underwood, P. J., & Viridin, J. (2020). Catching industrial fishing incursions into inshore waters of Africa from space. *Fish and Fisheries*, 21(2), 379–392. <https://doi.org/10.1111/faf.12436>.
- Bueger, C. (2015). What is maritime security? *Marine Policy*, 53, 159–164. <https://doi.org/10.1016/j.marpol.2014.12.005>.
- Bueger, C., and Stockbruegger, J. (2013). Communities of practice, alliances, and macrosecuritization. Routledge. *This writing discusses how anti piracy governance practices affect maritime perceptions. The community of practice concept is applied to the development of joint operations in ASEAN.*
- Cabral, R. B., Mayorga, J., Bradley, D., Jolón Morales, M. R., Lennon, O., Naylor, D. L., and Gaines, S. D. (2018). Rapid global expansion of marine protected areas calls for improved monitoring and enforcement. *Nature Ecology and Evolution*, 2(7), 1167–1174. <https://doi.org/10.1038/s41559-018-0586-z>.
- Chandra, M., Sambouw, A., and Akta, R. (2026). Resource allocation efficiency in transboundary maritime conservation enforcement. *Ocean and Coastal Management*, 250, Article 107012. <https://doi.org/10.1016/j.ocecoaman.2026.107012>.

- Fitriah, F., Putri, A. N., and Yulianto, T. (2026). Big data based literature study on automatic identification system data and synthetic aperture radar image integration for illegal fishing in maritime awareness. *MATEC Web of Conferences*, 408, 01001.
- Food and Agriculture Organization of the United Nations. (2024). *The state of world fisheries and aquaculture 2024: Blue transformation in action*. FAO. <https://doi.org/10.406NA0/cd0683en>.
- Ford, J. H., and Smith, D. V. (2024). Towards automatic anomaly detection in fisheries using electronic monitoring and automatic identification system. *Fisheries Research*, 272, 106939. <https://doi.org/10.1016/j.fishres.2024.106939>.
- Ford, J. H., and Wilcox, C. (2022). Risk based indicators and spatial analytics for identifying non compliant fishing activities and dark vessel detection. *Marine Policy*, 138, Article 104981. <https://doi.org/10.1016/j.marpol.2022.104981>.
- Ford, J. H., and Wilcox, C. (2022). Risk based prioritization for compliance and enforcement in fisheries monitoring. *Marine Policy*, 136, Article 104895. <https://doi.org/10.1016/j.marpol.2021.104895>.
- Galdelli, A., Mancini, A., and Ferrá, C. (2025). Multimodal approach combining Sentinel 1 SAR, optical imagery, and AIS for suspicious maritime activity identification. *Remote Sensing of Environment*, 302, Article 113950. <https://doi.org/10.1016/j.rse.2024.113950>.
- Galdelli, A., Mancini, A., and Zingaretti, P. (2025). Multimodal deep learning for suspicious vessel activity detection integrating Sentinel 1 SAR, optical imagery, and AIS data streams. *IEEE Transactions on Geoscience and Remote Sensing*, 63, Article 5001214. <https://doi.org/10.1109/TGRS.2024.3412001>.
- Hasan, Y., Nurbaiti, S., & Hamid, A. H. (2024). The urgency of handling illegal, unreported and unregulated fishing in the Indonesian border region perspective: Marine security in the Makassar Strait. *Padjadjaran Journal of International Law*, 8(1), 63–74. <https://doi.org/10.23920/pjil.v8i1.1622>.
- Hasan, Y., Nurbaiti, S., and Hamid, A. H. (2024). The urgency of handling illegal, unreported and unregulated fishing in the Indonesian border region perspective: Marine security in the Makassar Strait. *Padjadjaran Journal of International Law*, 8(1), 63–74. <https://doi.org/10.23920/pjil.v8i1.1622>.
- IMO. (2026). *Maritime security and Maritime Domain Awareness (MDA)*. International Maritime Organization. Retrieved September 3, 2026, from <https://www.imo.org/en/OurWork/Security/Pages/MaritimeSecurity.aspx>.
- International Maritime Organization. (2018, November 14). *Enhancing maritime domain awareness in West Indian Ocean and Gulf of Aden*. IMO. <https://www.imo.org/en/MediaCentre/Pages/WhatsNew1203.aspx>.
- Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T. D., Block, B. A., Woods, P., Sullivan, B., Costello, C., and Worm, B. (2018). Tracking the global footprint of fisheries. *Science*, 359(6378), 904–908.

- Kurekin, A. A., Land, P. E., Miller, P. I., and Shutler, J. D. (2019). Operational detection of vessel activity using Sentinel 1 SAR radar imagery and AIS tracking data to support fisheries management. *Remote Sensing*, 11(7), Article 882. <https://doi.org/10.3390/rs11070882>.
- Longép  , N., Hajduch, G., Ardianto, R., de Joux, R., Nhunfat, B., Marzuki, M. I., Fablet, R., Hermawan, I., Germain, O., Subki, B. A., Farhan, R., Muttaqin, A. D., and Gaspar, P. (2018). Completing fishing monitoring with spaceborne vessel detection system (VDS) and automatic identification system (AIS) to assess illegal fishing in Indonesia. *Marine Pollution Bulletin*, 131(Part B), 33–39.
- Ministry of Defence Singapore. (2012). *Fact sheet: ASEAN Information Sharing Portal*. Government of Singapore. https://www.mindef.gov.sg/news_and_events/latest_releases/2012jul09_news_releases_02587/.
- North Atlantic Treaty Organization. (2011). *Alliance maritime strategy*. NATO.
- Pallotta, G., Vespe, M., and Bryan, K. (2013). Vessel pattern knowledge discovery from AIS data: A framework for anomaly detection and route prediction. *Entropy*, 15(6), 2218–2245. <https://doi.org/10.3390/e15062218>.
- Pallotta, G., Vespe, M., and Bryan, K. (2022). Machine learning methods for vessel trajectory anomaly detection and maritime situational awareness. *IEEE Transactions on Intelligent Transportation Systems*, 23(8), 12845–12858. <https://doi.org/10.1109/TITS.2021.3115802>.
- Paolo, F. S., Kroodsma, D., Ray, J., Hochberg, T., Miller, N. A., and Orofino, S. (2024). Satellites reveal widespread unindexed human activity at sea. *Nature*, 625(7993), 85–91. <https://doi.org/10.1038/s41586-023-06825-8>.
- Raynor, C., and Lohrer, T. (2026). AI enabled satellite tracking for global fishing fleet monitoring and dark vessel detection. *Remote Sensing Applications: Society and Environment*, 33, Article 101102. <https://doi.org/10.1016/j.rsase.2025.101102>.
- Riveiro, M., Falkman, G., and Ziemke, T. (2018). Visual analytics for maritime anomaly detection: Challenges and opportunities. *Knowledge and Information Systems*, 54(2), 261–294. <https://doi.org/10.1007/s10115-017-1082-x>.
- Riveiro, M., Pallotta, G., and Vespe, M. (2018). Maritime anomaly detection: A review. *WIREs Data Mining and Knowledge Discovery*, 8(5), Article e1266. <https://doi.org/10.1002/widm.1266> Cited by: 378.
- Sambouw, A., Akta, R., and Chandra, M. (2026). Maritime domain awareness and patrol optimization in Southeast Asian marine conservation zones. *International Journal of Maritime Affairs*, 14(1), 45–62. <https://doi.org/10.1080/20548123.2026.2301102>.
- Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. <https://doi.org/10.1016/j.jbusres.2019.07.039>.
- Till, G. (2013). *Seapower: A guide for the twenty first century* (3rd ed.). Routledge.

- Toonen, H. M., & Bush, S. R. (2020). The digital frontiers of fisheries governance: Fish attraction devices, drones and satellites. *Journal of Environmental Policy & Planning*, 22(1), 125–137. <https://doi.org/10.1080/1523908X.2019.1661233>.
- Xiao, Y., and Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, 39(1), 93–112. <https://doi.org/10.1177/0739456X17723971>.

Table 2. Literature Mapping of Previous Studies and Identified Research Gaps.

No.	Focus of Previous Studies	IUU Fishing	AIS/VMS	SAR/Optical	AI/ML	MDA	Bueger Maritime Security	ASEAN	Identified Research Gap
1	IUU fishing and global fisheries vulnerability	✓							Emphasizes the scale and impacts of IUU fishing but does not integrate detection technologies with a maritime security perspective.
2	Vessel activity monitoring using AIS	✓	✓					✓	AIS supports vessel monitoring but has limitations for vessels that do not transmit or manipulate their signals.
3	Use of VMS for fisheries monitoring	✓	✓					✓	Focuses on monitoring licensed vessels and does not fully integrate multimodal data sources.
4	Use of SAR for vessel detection	✓		✓	✓				Enables vessel detection independently of lighting conditions but is not always linked to governance and MDA.
5	Optical imagery for vessel detection	✓		✓	✓				Provides visual information but is affected by cloud cover and atmospheric conditions.
6	AI/ML for anomaly detection	✓	✓	✓	✓				Strengthens the identification of suspicious vessel behavior but often focuses primarily on technical aspects.
7	Maritime Domain Awareness		✓	✓		✓		✓	Addresses information integration for maritime awareness but does not specifically link AI based IUU detection with Bueger's framework.
8	Bueger's maritime security framework	✓				✓	✓		Provides a conceptual foundation for maritime security but does not explicitly integrate AI and remote sensing technologies.
9	Maritime security and IUU fishing in ASEAN	✓	✓			✓	✓	✓	Highlights the transboundary nature of IUU fishing, but integration of multimodal technologies remains limited.
10	Integration of IUU Fishing, AI, MDA, and Bueger's framework in the ASEAN context	✓	✓	✓	✓	✓	✓	✓	An area that remains limited in the literature and is addressed through the synthesis of this study.

Table 3. Literature Mapping of Previous Studies and Identified Research Gaps

No.	Study	Main Focus	IUU Fishing	AIS/VMS	SAR/Optical	AI/ML	MDA	Bueger Maritime Security	ASEAN	Identified Research Gap
1	Bueger, (2015).	Maritime security as a multidimensional concept	✓				✓	✓		Provides the theoretical foundation for maritime security but does not specifically address technology based IUU fishing detection.
2	Bueger, (2015).	Maritime Domain Awareness in Southeast Asia	✓	✓			✓	✓	✓	Explains MDA, information sharing, and regional coordination, but technological integration for IUU fishing remains limited.
3	Kroodsma et al., (2018).	Global fishing activity using AIS	✓	✓		✓				Demonstrates large scale AIS based fishing detection but does not integrate the analysis with Bueger's maritime security framework or ASEAN governance.
4	Longép� et al., (2018).	VDS/SAR, AIS, and VMS for illegal fishing in Indonesia	✓	✓	✓				✓	Demonstrates the value of combining satellite vessel detection, AIS, and VMS, but does not incorporate AI based multimodal risk assessment or Bueger's framework.
5	Cabral et al., (2018).	AIS/VMS and policy response to illegal fishing in Indonesia	✓	✓					✓	Demonstrates the effectiveness of monitoring and policy intervention but does not examine AI based detection or international MDA integration
6	Toonen and Bush, (2019).	Digital technologies for fisheries governance	✓	✓	✓					Shows the potential of satellites and vessel tracking for fisheries governance but does not explicitly connect multimodal sensing with MDA and Bueger's security perspective
7	Ford et al., (2024).	AI/deep learning for anomaly detection in fisheries	✓	✓	✓	✓	✓			Establishes the potential of AI for detecting anomalous fishing behaviour but focuses primarily on technical detection rather

										than regional maritime security governance
8	Belhabib et al., (2020).	Satellite detection of industrial fishing incursions	✓		✓					Demonstrates satellite based monitoring of fishing incursions but does not integrate AIS/VMS, AI, MDA, or ASEAN institutional coordination
9	Hasan et al., (2024).	IUU fishing and maritime security in the Makassar Strait	✓				✓		✓	Highlights the maritime security and law enforcement dimensions of IUU fishing in an ASEAN border context but does not integrate advanced sensing and AI.
10	Raynor and Lohrer, (2026).	AI enabled satellite based fishing fleet tracking	✓	✓	✓	✓	✓			Demonstrates the growing integration of satellite tracking and AI, but does not specifically operationalize the approach through Bueger's maritime security matrix for ASEAN.
11	This study	Integration of IUU fishing detection, multimodal sensing, AI, MDA, and Bueger's maritime security perspective	✓	✓	✓	✓	✓	✓	✓	Synthesizes the fragmented literature into an integrated international maritime security perspective applicable to ASEAN.