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Anthropogenic drivers of mangrove degradation on the north coast of Java: insights from recent studies

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Mangrove ecosystems are among the most important components of coastal ecosystems, providing vital ecological, economic, and social functions. However, in the northern coastal area of Java Island, mangrove ecosystems have experienced significant degradation under pressure from anthropogenic activities. This study aims to analyze and classify the primary anthropogenic factors contributing to the degradation of mangrove ecosystems in the northern coastal area of Java, based on the latest available studies. The method employed is a scoping review, guided by the PRISMA-ScR framework. The data were collected from various national and international databases, including Scopus, DOAJ, EBSCO, Garuda, and Google Scholar, covering publications from January 2010 to April 2025. From the literature selection process, 44 scientific articles met the inclusion criteria and were analysed qualitatively. The study's results showed that mangrove degradation occurred in 18 districts/cities on the north coast of Java, with the highest levels of damage in metropolitan areas such as Jakarta, Semarang, and Surabaya. The primary factors contributing to degradation include converting land into ponds, industrial and residential development, coastal reclamation, pollution from industrial and domestic waste, illegal logging, and the expansion of coastal infrastructure. This combination of pressures has resulted in the loss of approximately 70% of Java's native mangrove forests over the last three decades. Recommended mitigation efforts include implementing sustainable aquaculture systems (silvofishery), developing buffer zones and green infrastructure, and adopting the Building with Nature (BwN) approach to nature-based restoration. Additionally, community-based ecological mangrove restoration (CBEMR) needs to be strengthened to enhance local participation. A cross-sectoral, science-based approach is key to achieving sustainable mangrove management on the north coast of Java Island.

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Environmental significance

Mangrove ecosystems along the northern coast of Java Island pose one of the most critical environmental challenges in Indonesia due to intense and diverse human pressures. This study synthesises findings from 44 recent studies to identify the main anthropogenic drivers of mangrove degradation. The results indicate that nearly 70% of Java's original mangrove forests have been lost due to development activities that ignore environmental sustainability. Key contributing factors include land conversion for aquaculture ponds, industrial and residential expansion, coastal reclamation, pollution from industrial and domestic waste, illegal logging, and the growth of coastal infrastructure. These findings underscore the need for cross-sectoral policy integration and the implementation of nature-based and community-based restoration strategies for the long-term sustainability of coastal ecosystems.

1. Introduction

Coastal ecosystems, including mangrove forests, coral reefs, seagrasses, and wetlands, are among the most productive yet vulnerable ecosystems.[1] Mangroves play a crucial role in providing ecosystem services.[2–4] The role of mangroves includes coastal natural buffer zones, protecting coastlines from erosion, storms, and tsunamis.[5,6] Mangroves are also significant carbon sinks, storing three to five times more carbon than terrestrial forests, both in the form of biomass and sediment.[2,7] Mangroves also function as a nutrient biofilter that maintains the water quality of coastal lagoons, carbon sinks, and their tourism and cultural value.[8,9] In addition, mangroves support biodiversity, fisheries, and livelihoods of coastal communities, especially in vulnerable zones such as tropical and subtropical coasts.[7,10]

Mangrove forests are spread across 124 countries, covering 14 to 15 million hectares in Asia.[11] One of the countries with extensive mangrove forests is Indonesia, but its mangrove area has decreased by 40% over the last three decades.[12] The total

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Table 1 Database and Boolean formulas

Database	Boolean formulas
Scopus DOAJ EBSCO Garuda Google Scholar	TITLE-ABS-KEY ("mangroves" OR "mangroves") AND ("degradation" OR "damage" OR "loss") AND ("north coast" OR "north Java" OR "northern Java" OR "north coast of Java" OR "Java coast") AND ("anthropogenic" OR "human activities" OR "land conversion" OR "ponds" OR "pollution" OR "subsidence" OR "reclamation" OR "Industry" OR "Infrastructure Development" OR "Coastal Development" OR "Logging" OR "Exploitation")

area of mangroves in Indonesia is 3 364 080 hectares.[13] One of the mangrove distributions in Indonesia is found along the coasts of Java Island. Dominant species include *Avicennia marina* and *Rhizophora mucronata*, with secondary species such as *Nypa fruticans*.[14] Density and health: mangrove density in certain zones ranges from 503 to 726 individuals per ha, with soil properties characterised by a sandy clay texture, and environmental parameters including water temperature (29–31 °C) and water salinity (29–30 ppt).[15]

On the other hand, the northern coastal area of Java Island is often referred to as "Pantura," an important national and regional corridor known for its dense settlements, extensive industrial estates, and dynamic economic activity.[16,17] Significant population growth has occurred in the region, rising from 13.6 million in 2010 to more than 15.2 million in 2020, particularly on the northern coast of Central Java.[16] The expansion of settlements is driven by their proximity to economic opportunities and important infrastructure projects. The region is also a nationally prioritised industrial corridor, home to large-scale industries such as manufacturing, electronics, automotive, and food processing. In addition, economic activities on the southern coast of Java are highly diverse, encompassing both the primary sector (*e.g.*, fisheries, aquaculture, and agriculture) and the secondary/tertiary sectors (industrial manufacturing, logistics, trade, and services).[18] High population and industrial density put significant pressure on local ecosystems, especially in sensitive coastal and mangrove areas.[19] Wardhani's research indicates that the northern coast of Java has experienced a 70% decline in mangrove cover in specific areas, primarily due to human activities and exacerbated by climate change.[20]

Several previous studies have demonstrated that mangrove degradation on the north coast of Java is closely linked to land-use changes, sedimentation, and pollution.[21–24] However, most studies are local and have not provided a comprehensive synthesis of the main anthropogenic factors contributing to such degradation.[25] A literature review is necessary to integrate findings from various studies, assess degradation patterns, and identify the primary pressures affecting different areas of the northern coast of Java.

The objective of this paper is to analyze and classify anthropogenic factors that cause mangrove degradation on the north coast of Java, Indonesia, through a synthesis of recent empirical research conducted in both urban and district-level coastal areas across the provinces of Banten, Jakarta, West Java, Central Java, and East Java. The results can provide a comprehensive understanding of the relationship between human activities and mangrove degradation in densely populated coastal areas, serving as a scientific reference for policymakers, academics, and conservation institutions in designing effective mitigation and rehabilitation strategies.

2. Methods

The method employed in this study utilises a literature review approach, incorporating a scope review.[26] The scope review was chosen because it is relevant to exploring the scope and trends, aiming to comprehensively identify key concepts by understanding the findings.[27] The framework of this study is based on the work of Levac *et al.* (2010). It mentions the five stages of the review scope: (1) identifying research questions, (2) identifying relevant studies, (3) selecting literature, (4) mapping data, and

Table 2 Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication period	Published studies from January 2010 to April 2025	Not published from January 2010 to April 2025
Publishing type	Articles, conferences paper	Reports, books, book chapters, and other
Language	English and Indonesian	Not in English and Indonesia
Geographical location	The study was conducted in the Java Coast region (including Banten, West Java, Jakarta Central Java, and East Java), which has coastlines	The study was conducted outside the Java Coast
Accessing	Open-access publications to ensure transparency, accessibility, and reproducibility of the review process	Hybrid-access and closed-access publications due to access limitations

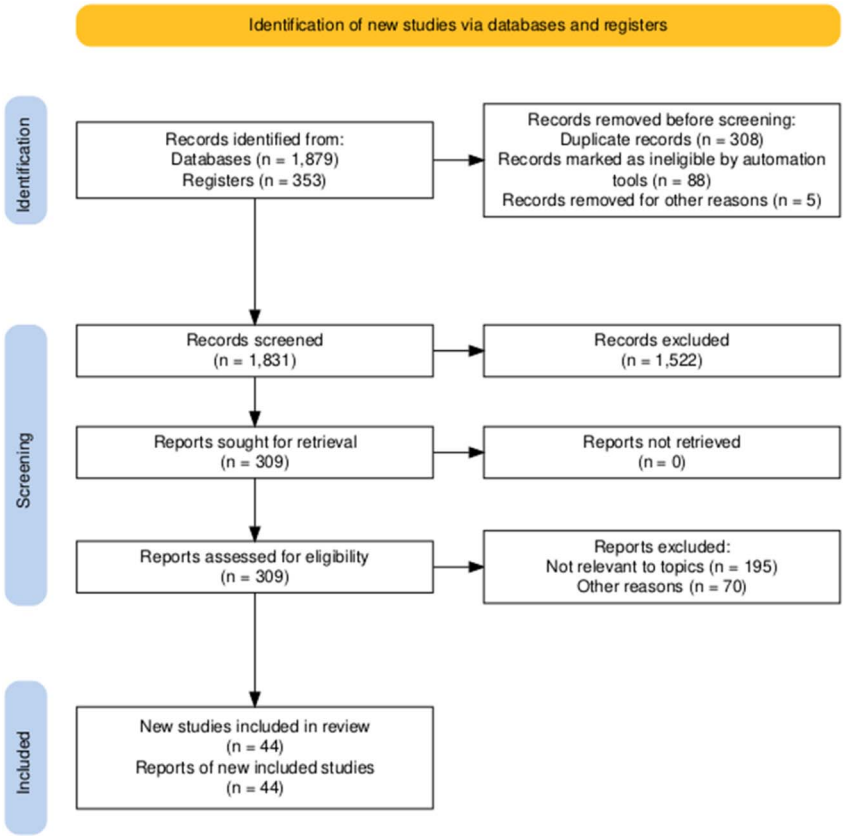

Fig. 1 Flowchart of the final article search process for the investigation.

(5) reporting and presenting interpretations of the reviewed literature.[28] This study also used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR).[29,30] PRISMA-ScR ensures transparency in the literature and traceability of the review process.[31] Research Question (RQ) is prepared based on the PEO (Population, Exposure, Outcome) framework as follows:[32]

Population (P): mangrove ecosystems on the north coast of Java Island (administrative area: Banten Province, West Java Province, Central Java Province, East Java Province).

Outcome (O): mangrove degradation, decrease in mangrove area, decrease in ecosystem function (nurseries, carbon storage), decrease in biodiversity, increase in disaster vulnerability.

The Boolean search formula used to find the literature on the impact of climate change on mangroves on the Java Coast is shown in Table 1. The data used in this study were sourced from international and national databases, including Scopus, Garuda, DOAJ, EBSCO, and Google Scholar. The variety of databases used enables a comprehensive meta-analysis of these results using Boolean formulas.[33] The search string is developed from keywords relevant to the PEO component, using Boolean (AND, OR) operators. Inclusion and exclusion criteria are established to ensure the research's focus. The inclusion and exclusion criteria are shown in Table 2.

The selection process is carried out in two stages: (1) screening based on titles and abstracts, and (2) feasibility assessment based on full text. At the screening stage, studies that are clearly irrelevant or not original research will be excluded. Studies that pass the screening will proceed to the feasibility assessment stage, where the full text will be reviewed to ensure the fulfilment of the inclusion criteria. This process is simulated based on the information available from the initial search results. Data from selected studies were systematically extracted and recorded in tables. The information extracted included: authors, year of publication, impact of human activities on mangrove degradation discussed, study location, publication sources, and research methods used. Data synthesis was conducted qualitatively to identify trends, working mechanisms, and research patterns emerging from the included studies. Quantitative synthesis (meta-analysis) is not performed due to data heterogeneity and the nature of the included studies, which are better suited to narrative analysis. The results of the article selection are illustrated in the prism diagram adopted from Haddaway *et al.* (2022), shown in Fig. 1.[34]

3. Result

Search results from international and national databases identified 44 scientific articles on the influence of anthropogenic factors on the degradation of mangrove forests in the north coast of Java. The annual increase in publications indicates that mangrove degradation remains a significant focus for researchers, especially in the North Coast region of Java (see Fig. 2). Most studies on mangrove degradation attributed to

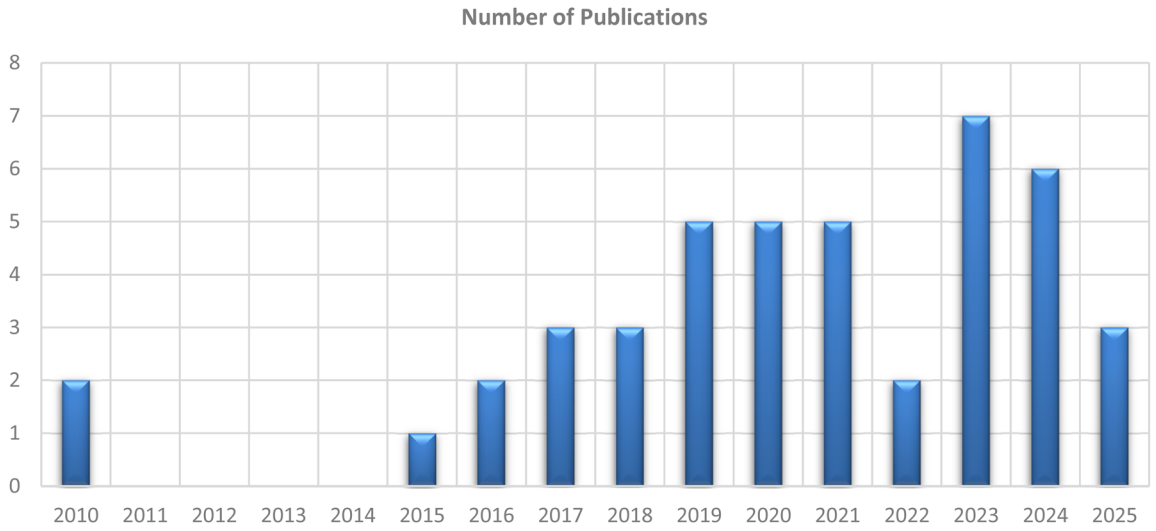

Fig. 2 Number of publications.

anthropogenic factors are mostly conducted in provincial capital areas or districts/cities that serve as industrial hubs, suggesting that these areas typically experience considerable economic development pressure, which can result in damage to mangrove ecosystems; thus, researchers can refer to this as a reason for the critical significance of their investigation or the identification of research gaps. Big cities such as Semarang, Jakarta, and Surabaya have been found to have conducted multiple studies on mangrove degradation. The city of Semarang, as the capital of Central Java Province, recorded four studies. The city of Jakarta, as the capital of Indonesia, recorded six studies. The city of Surabaya, as the capital of East Java Province, recorded two studies. Overall, research related to mangrove degradation due to anthropogenic factors has been conducted across 18 districts/cities/provinces, which include Madura, Bekasi, Brebes, Cirebon, Demak, Gresik, Indramayu, Jepara, Karawang, Kendal, North Jakarta, Pasuruan, Semarang, Surabaya, Banten, Pemalang, Sidoarjo, and Subang.

3.1 Anthropogenic factors causing land degradation

Based on the results of the investigation, the selected articles (see Table 3) show that the degradation of mangroves on the north coast of Java is caused by various anthropogenic factors, which include clearing of ponds/aquaculture land, land clearing for industry, settlements, and urban development, reclamation, pollution, illegal logging, and infrastructure development. The most prominent factor identified was the conversion of mangrove land to farmland/aquaculture, as evidenced by 24 studies. In addition, other important factors include land conversion for industrial development and urban settlements (16 studies); pollution from sewage and garbage (17 studies); illegal logging (5 studies); infrastructure development (5 studies); and land reclamation (4 studies).

The conversion of mangrove forests into ponds, which contributes to mangrove degradation in North Java, is driven by economic incentives, particularly the pursuit of fishery production, a national program that was once in place. This practice occurs to a significant extent due to deep-rooted economic interests.[35] The situation in Northern Java reflects a broader regional trend in which the economic attractiveness of aquaculture has led to widespread mangrove destruction, necessitating an integrated approach to restore and conserve these vital ecosystems.[36] On the other hand, many large cities are located on the north coast of Java, allowing for rapid urbanisation. This rapid population growth and urban expansion further exacerbate land demand, leading to the conversion of mangrove forests into residential and commercial areas.[37]

The anthropogenic factors driving mangrove degradation on the north coast of Java are described as follows:

3.1.1 Pond land clearing. Land clearing for agriculture and aquaculture is a significant driver of mangrove destruction and deforestation on the north coast of Java, Indonesia. Human activities, especially those related to creating space for livelihoods, are the leading cause of mangrove degradation. These activities include converting mangrove forests to various land uses, such as agricultural land, aquaculture ponds for shrimp and fish, infrastructure, and human settlements.[79]

On the north coast of Java, most mangrove habitats have been converted into rice paddies and settlements, with river mouths often converted into ponds.[79] In particular, in Central Java, land conversion for cultivation is the leading cause of mangrove loss.[69] This trend is also seen in East Java, where mangrove forests have been cleared for aquaculture ponds.[80]

A survey conducted on Karimunjawa Island revealed that 61.65% of respondents agreed that the development of ponds has led to a decrease in mangrove coverage, and 48.87% agreed that the development of infrastructure for aquaculture has led to mangrove degradation.[78] In Muara Angke, North Jakarta, the conversion of mangrove areas into fish ponds is a significant contributor to environmental degradation.[24] In the Bedono mangrove ecosystem in Demak, Central Java, the development of aquaculture fisheries also contributes to the reduction of mangrove areas.[76] Even in Cirebon Regency, six sub-districts in the northern coastal area were identified as experiencing

Table 3 Characteristics of anthropogenic factor findings from selected studies[a]

No.	Author, year	Research location	Factor anthropogenics					
			A	B	C	D	E	F
1	Sejati *et al.*, (2020)[38]	Semarang		V				
2	Suryono, (2019)[39]	DKI Jakarta				V		
3	Sodikin *et al.* (2017)[40]	Indramayu	V	V			V	
4	Tanjung *et al.*, (2024)[41]	Pasuruan	V			V	V	
5	Raharjo *et al.* (2016)[42]	Cirebon	V					
6	Radita *et al.* (2010)[43]	Gresik		V				
7	K. Prasetyo, (2021)[44]	Surabaya		V	V	V		V
8	K. A. Putri *et al.*, (2022)[45]	Bekasi	V	V		V		
9	Latifah *et al.*, (2018)[46]	Jepara	V					
10	Kamal *et al.*, (2016)[47]	Jepara	V					
11	Safitri *et al.* (2023)[48]	Semarang	V					V
12	Maulani *et al.*, (2021)[49]	Bekasi	V	V				
13	Nugroho *et al.*, (2020)[15]	Semarang, Pemalang, and Demak	V			V		
14	Saleha *et al.*, (2023)[50]	Banten		V				
15	A. D. A. S. Putri *et al.*, (2024)[51]	Demak				V		
16	Wijdanisa *et al.*, (2025)[52]	Indramayu				V		
17	Wahyuningsih & Fatimatuzzahroh, (2019)[53]	Cirebon	V					
18	Solahudin *et al.* (2024)[54]	Demak						V
19	Dzulfigar *et al.*, (2024)[55]	Subang	V					
20	Rahmawati *et al.*, (2024)[56]	Bekasi	V					
21	Asy *et al.*, (2023)[57]	Subang	V					
22	Hidayah & Muzayanah, (2018)[58]	Gresik	V					
23	A. Prasetyo *et al.*, (2017)[59]	Gresik	V					
24	Maulana *et al.* (2022)[60]	Banten				V		
25	Indriawan *et al.*, (2021)[61]	Bekasi				V		
26	Radita *et al.* (2010)[43]	Gresik	V					
27	Haryanti *et al.*, (2020)[62]	Tangerang		V				
28	Bayan *et al.* (2016)[63]	DKI Jakarta				V		
29	Siringoringo *et al.*, (2018)[64]	Subang	V					
30	Nur & Hilmi, (2021)[65]	Indramayu	V	V		V		
31	Salsabela *et al.*, (2023)[66]	Jepara				V	V	
32	Pranoto *et al.* (2019)[67]	Karawang	V	V				
33	Rifandi & Ratnasari, (2023)[68]	Pemalang				V		
34	Candraningtyas *et al.*, (2025)[69]	Demak, Brebes, Cirebon, Pemalang, and Kendal	V	V				V
35	Usman *et al.*, (2023)[70]	Jakarta Utara		V		V		
36	Sari & Soeprobowati, (2021)[71]	Semarang				V		
37	Slamet *et al.*, (2020)[72]	Jakarta		V	V			
38	Putra, (2019)[12]	Jakarta			V			
39	Ramadhani *et al.*, (2024)[73]	Madura	V		V	V		
40	Maryantika & Lin, (2017)[74]	Sidoarjo		V			V	
41	Wardhani & Zikra, (2020)[75]	Surabaya		V				
42	Soeprobowati *et al.* (2023)[76]	Demak	V	V				
43	Haryeni & Kamal, (2025)[77]	Jakarta Utara	V	V		V	V	
44	Puryono & Suryanti, (2019)[78]	Karimun Jawa, Jepara	V					V

[a] Informations: A = pond land clearing; B = conversion of industrial land, settlements and urban development; C = reclamation; D = pollution; E = illegal logging; F = infrastructure development.

a decrease in mangrove area due to the conversion of mangrove areas into ponds.[42,53] This practice is driven by the community's perception that being a fisherman earns a lower income than that from pond-based fish or shrimp farming.[81] Another area of the north coast of Java that has experienced mangrove degradation due to the conversion of mangrove land to pond land is Indramayu Regency, Bekasi Regency, Karimun Jawa, Semarang City, Subang Regency, Gresik Regency, and Karawang Regency, as well as Madura.

Aquaculture expansion is often supported by government initiatives to increase fishery production, which can lead to the opening of additional mangrove areas.[79] In addition to aquaculture, the rapid expansion of rice farming is also a major driver of mangrove forest conversion on the north coast of Java. These extensive land-use changes for agriculture and

aquaculture result in the loss of mangrove habitat, fragmentation, and a decline in the overall function and health of ecosystems.[79,80]

3.1.2 Conversion of industrial land, settlements and urban development. Industrial land clearing and associated urban development pose a significant threat to preserved mangrove ecosystems, leading to habitat loss, fragmentation, and degradation. This activity is a major driver of mangrove deforestation on the north coast of Java, transforming vital coastal habitats into industrial, residential, and infrastructure development areas. This conversion not only reduces the total area of mangrove forests but also disrupts their ecological functions, such as shoreline protection, carbon sequestration, and biodiversity support. The expansion of industrial and residential areas is often a key factor in mangrove decline, as seen in various estuaries along the northern coast of Central Java.[69,79] In addition, the population increase in the northern coastal area of Java has led to a greater need for housing resources. This increased demand has led to higher exploitation of coastal resources, including mangrove forests, which are crucial ecosystems currently under threat.[40] This was found in the city of Surabaya which shows that the mangrove area has changed for office and housing development needs is found in the Kenjeran mangrove area, the Keputih mangrove area, the Gununganyar mangrove area, and the Benowo mangrove area.[44] Other areas on the north coast of Java that experience mangrove degradation due to the conversion of mangrove forests to residential land include Muara Gembong, Bekasi; Tangerang; Indramayu; Karawang; and North Jakarta.

Sidoarjo Regency in East Java provides a clear example of this impact. As a rapidly growing economic and industrial centre, Sidoarjo has undergone significant changes in land use. Mangrove forests, especially along inland river systems, have been cleared for agriculture and industrial purposes.[74] Between 1995 and 2005, there was a dramatic decline in interior mangrove forests, with about 792 hectares converted to farmland and 108 hectares to residential areas for industrial and agricultural purposes. The rapid growth of industrial and residential estates in Sidoarjo Regency presents a direct risk to the remaining mangrove forests. Similarly, a study in Surabaya, East Java, found that industrial growth and the conversion of mangrove areas to residential land threaten the sustainability of the coastal environment.[75]

On the north coast of Java, specifically in the Semarang metropolitan area, it was found that industrialisation is the primary factor contributing to the degradation of mangrove ecosystems.[38] The growth of this industry has led to significant land reclamation activities, transforming coastal ecosystems into areas built for industrial purposes. The construction of the Kendal Industrial Park, which began in 2016, is a notable example of such development, spanning 2700 hectares. This industrialisation substantially reduced vegetation/mangrove land cover, with a 1469.28 hectare (8%) decrease between 2015 and 2019 in the Semarang metropolitan area. As a result, overall blue carbon storage in the coastal area of the Semarang metropolitan region decreased by 24 781.6 tons between 2015 and 2019, with the most significant changes attributed to the loss of mangrove forests. In addition to large industrial areas, home industries/MSMEs can also threaten mangrove existence. Mangrove forests in areas such as the village of Banyu Urip, Ujung Pangkah, have been extensively converted to the home-grown shellfish industry. The presence of many green clam cages (more than 100 owned by 85 individuals) puts pressure on mangrove areas. The degradation of mangrove ecosystems, which reached 40% in 2010, is particularly pronounced in the northern coastal areas, including the districts of Panceng and Ujung Pangkah.[43] Other areas whose mangroves have been degraded due to industrial development on the north coast of Java include the Muara Gembong Bekasi area, Banten Bay Coast, Indramayu, Karawang, North Jakarta, and Demak.

3.1.3 Beach reclamation. Reclamation activities in the northern region of Java include large-scale projects, such as the construction of new islands in Jakarta and Surabaya Bays, as well as post-mining landscape restoration. The initiative has significant environmental and socioeconomic consequences, affecting sedimentation patterns, mangrove ecosystems, and soil quality in coastal areas.

In East Java, reclamation is carried out in Surabaya, a city on the north coast of Java. One of the reclamation locations is in Romokalisari village, which is included in the Benowo mangrove forest area. In this area, container port facilities and loading and unloading facilities have been built through reclamation. According to Prasetyo, port development through reclamation can damage coastal ecosystems, especially mangrove forests.[44]

Other case studies in Jakarta Bay and Serang demonstrate that reclamation activities present both challenges and opportunities for ecological recovery. Slamet *et al.* argue that the impact of reclamation is twofold. On the one hand, it can threaten coastal ecosystems; on the other, it can promote ecological restoration under certain conditions.[72] The construction of reclaimed islands slows down the flow of water, resulting in sediment deposition.[82] The construction of reclaimed islands slows down the flow of water, resulting in increased sedimentation. This process creates a new habitat suitable for the natural growth of mangroves.[73]

On the other hand, data from October 2013 to August 2015 show that mangrove area on the reclaimed islands increased from 0 to 2647 hectares, with an average annual growth of 1.32 hectares. This natural growth is supported by the spread of mangrove propagules to new areas rich in sediment. In addition, the same study identified approximately 30 hectares of additional land with potential for mangrove planting activities, suggesting that planned restoration interventions can accelerate the regeneration of coastal vegetation.

In contrast, reclamation projects also require large amounts of fill material, which is generally sourced from nearby coastal areas. In Serang, Banten, sand mining activities for the Jakarta Bay reclamation project have altered the local landscape. However, after mining was halted in 2013, the former mining area began to show signs of recovery in the mangrove ecosystem. The area of mangrove forests increased from 22.41 hectares in 2012 to 30.15 hectares in 2015.[72] Despite this, the ecosystem is still relatively vulnerable. Carbon stocks in

mangrove forests in Serang are much lower than those in more mature and protected mangrove forests in Angke, Jakarta, suggesting that ecosystem restoration has not been optimally implemented.[72]

3.1.4 Pollution from agricultural, household and industrial waste. Household and industrial waste pose a significant threat to mangrove ecosystems by altering the physical and chemical conditions of the surrounding aquatic environment. Pollution originating from residential areas, hotels, restaurants, and industrial activities introduces various contaminants, including heavy metals and excess organic matter, into coastal ecosystems. The accumulation of waste has significant ecological impacts, including disruption of the natural regeneration process due to the closure of the soil surface, inhibition of the growth of mangrove seedlings, decreased levels of dissolved oxygen in water due to the anaerobic decomposition process, and the formation of toxic conditions due to the production of sulfide and ammonia compounds. These changes, taken together, can lead to the death of mangrove trees, reduce biodiversity, and disrupt the life cycles of aquatic organisms, such as fish and shrimp, that depend on these ecosystems.

Various studies on the north coast of Java show the real impact of sewage pollution on mangrove ecosystems. In the coastal area of Tambakrejo, Semarang City, domestic and industrial waste has been shown to contribute to increased heavy metal concentrations in coastal waters.[71] The same study also noted that the increase in domestic waste load lowered the pH value of water in the East Canal Flood area. Water quality monitoring in the Bedono mangrove area revealed the highest pollution index in October, indicating moderately polluted conditions due to elevated concentrations of phosphates and nitrates from domestic waste.[51]

Similar conditions were observed in the mangrove ecosystem of Pantai Indah Kapuk, where macrodebris, including plastic (77.7%) and Styrofoam (18.1%), was found in significant amounts. In Muara Angke, the accumulation of solid waste directly impacts the growth and health of mangroves.[39,63] Meanwhile, in the Benowo mangrove area, Surabaya City, field observations showed a change in the mangrove area's function to a plastic waste disposal site.[44] Several other areas on the north coast of Java that also experience mangrove degradation due to waste pollution include Muara Gembong District, Bekasi Regency, Indramayu, Kedung Jepara District, Pemalang, North Jakarta, and Madura.[73]

In addition to pollution by waste, the degradation of mangroves on the north coast of Java is also caused by waste from aquaculture activities, both fish ponds and salt ponds. In Madura, salt pond activities alter soil characteristics and cause water pollution, inhibiting the growth of mangrove vegetation. Increasing the nutrient content of pond waste also has the potential to alter the structure of mangrove communities.[73] In other areas, such as Demak Regency, Pemalang, and Semarang City, poor pond waste management systems have been identified as sources of pollutants that negatively affect the survival of organisms in mangrove ecosystems.[15]

Additionally, in the northern coastal region of western Java, particularly in North Banten, mangrove degradation is also triggered by oil spills.[60] The Pertamina pipeline leak incident in July 2019 reportedly had an indirect impact on mangrove species in Tirtayasa District. The oil spill even reached the Muara Gembong (Bekasi) area, Karawang Regency, and the Thousand Islands.[61]

Overall, various forms of pollution on the north coast of Java have the potential to degrade the quality and quantity of mangrove ecosystems if not controlled immediately. The combination of pollution, land conversion, and reclamation activities has reduced mangroves' important ecological function as a natural barrier against abrasion and tidal flooding.[24,70] The accumulation of garbage around the mangrove area also interferes with the tidal circulation of seawater, so that mangrove trees appear less fertile with a low density level.[39]

3.1.5 Illegal logging. Mangrove ecosystems across various areas on the north coast of Java are degrading due to logging for household purposes, such as firewood and building materials. This practice is often driven by a combination of economic pressures on local communities and a lack of public understanding of the vital role mangrove forests play as life-sustaining systems.[40,77] This is supported by the research of Salsabela *et al.*, which states that the main factor of mangrove damage in Kedung District, Jepara Regency, is irresponsible illegal logging.[66]

In Sidoarjo Regency, many illegal logging practices were also found to be used as ponds.[74] The practice of illegal logging is also prevalent in Pasuruan City, which is primarily attributed to the livelihood of some residents in coastal areas who collect mangrove wood.[41] Seeing an opportunity to earn an income, they are forced to engage in illegal logging. Furthermore, in Muara Angke, North Jakarta, pressure from the local community contributed to mangrove destruction by clearing mangroves for firewood.[24] Similarly, on Karimunjawa Island, the logging of mangroves for purposes such as firewood, household materials, and boat materials is a recognised factor in ecosystem degradation.[78] A study on the island found that mangrove logging had the strongest correlation with mangrove degradation among various human activities, with 59.4% of the surveyed population agreeing that fishermen cut down mangrove trees for sale, which interferes with the forest's function.[78] A study on the island found that mangrove logging had the strongest correlation with mangrove degradation among various human activities, with 59.4% of the surveyed population agreeing that fishermen cut down mangrove trees for sale, which interferes with the forest's function.

3.1.6 Infrastructure development. Studies show that infrastructure development is a significant contributor to mangrove degradation in various coastal areas of Northern Java.[69] This degradation occurs through the direct conversion of land for various projects and the indirect effects of related activities.[44,78] Infrastructure development identified as the cause of mangrove degradation in the north coast of Java includes road construction, tourism, and port infrastructure.[44,48,54,78] Infrastructure development, such as the Pantura route toll road that connects Semarang to other cities on the north coast of Java. As a result of the construction of this toll road, it is projected to affect 46 hectares of mangrove land, further reducing mangrove areas in

Central Java, especially in Semarang City and Demak Regency.[54] The Semarang-Demak toll road is a National Strategic Project (PSN) in Central Java that is designed not only to improve connectivity between regions but also to serve as a sea embankment and polder system to reduce coastal flooding (tidal flooding). Although it is considered an infrastructure for disaster mitigation in the event of a storm, it creates a new problem: the degradation of mangroves, which serve as a natural mitigation measure against the storm. This is supported by research by Safitri *et al.*, which shows that the density of mangroves has decreased by approximately 270 327 ha (65.5%). This is due to the construction of the Semarang-Demak sea embankment.[48]

The construction of tourism facilities also plays an important role in the degradation of mangroves on the north coast of Java. On Karimunjawa Island, respondents identified the development of tourism facilities as the primary driver of mangrove degradation.[78] The form of tourism infrastructure development includes the construction of homestays, roads, restaurants, and transportation facilities (both land and sea), carried out to meet the needs of tourists. Similarly, port development, such as the Teluk Lalong port on the North Surabaya Coast.[44] A container terminal and port have been developed through land reclamation. This reclamation process can damage coastal ecosystems, especially Benowo mangrove forests. As a responsibility for the damage, Indonesia Port Corporation 3 Inc., Ltd has attempted to replant the damaged mangrove area in Lalong Bay to reduce the impact of reclamation.

The construction of facilities to support cultivation, such as roads and canals, can alter the land use patterns and hydrology of the coastal environment, further damaging mangrove ecosystems.[78] The transformation of mangrove areas into garbage dumps has also been observed as a consequence of nearby development, as seen in the Benowo mangrove area.[44]

3.2 Policy recommendations

The north coast of Java faces serious threats related to mangrove degradation. Various natural and anthropogenic factors cause this. However, previous studies have shown that the most significant factor in mangrove degradation is anthropogenic factors. These anthropogenic factors include the clearing of pond/aquaculture land, land clearing for industry, settlements, and urban development; reclamation; pollution; illegal logging; and infrastructure development. Due to pressure from various anthropogenic factors, Java Island has lost about 70% of its original mangrove forests over the past few decades, with deforestation on the northern coast beginning in the 1980s. Java experienced a huge loss of mangrove forests, about 800 000 hectares, over 30 years.[83–85] On the other hand, the current governance is inadequate to support sustainable mangrove management due to institutional fragmentation, weak law enforcement, inconsistent spatial planning, limited community participation, and inadequate financing mechanisms. Indonesia's mangrove governance is experiencing severe institutional fragmentation between the Ministry of Environment and Forestry (MoEF), which manages mangroves in state forest areas, and the Ministry of Marine Affairs and Fisheries (KKP), which oversees mangroves in coastal areas outside forest areas. This overlap of jurisdictions creates contradictory and competing policies driven by sectoral interests rather than coordinated conservation objectives.[86–88] In addition, law enforcement for mangrove protection faces critical challenges despite the existence of applicable laws and regulations, including Law No. 41/1999 on Forestry, Law No. 32/2009 on Environmental Management, and Law No. 39/2014 on Plantations.[89] In addition, law enforcement for mangrove protection faces critical challenges despite the existence of applicable laws and regulations, including Law No. 41/1999 on Forestry, Law No. 32/2009 on Environmental Management, and Law No. 39/2014 on Plantations.[83] Law enforcement is particularly weak in cases involving the conversion of mangrove land for aquaculture or industrial development, with many violations going unpunished due to limited oversight and inadequate law enforcement capacity.

Another problem is institutional fragmentation related to the importance of spatial planning between regions, which exacerbates mangrove degradation. Institutional fragmentation leads to poor coordination between national programs that emphasise restoration and local governments that prioritise different objectives, such as urban infrastructure in Jakarta, aquaculture in West Java, and tourism in Banten.[90] This misalignment between national conservation goals and regional development priorities fundamentally weakens mangrove protection efforts on the northern coast of Java. In addition to the problem of spatial planning between different regions, problems related to mangrove management at the regional level are also not optimal. Although community-based mangrove management projects have been implemented in various regions, the involvement of stakeholders in mangrove management decision-making, particularly communities, NGOs, and the private sector, remains limited. This case was found in Karangsong, Indramayu Regency, which demonstrates positive steps towards collaborative governance, where communities participate in zoning and ecotourism management. However, many conservation programs lack transparency in budgeting and implementation, leading to mistrust.[83] Based on the various management problems on the north coast of Java, policy recommendations for sustainable mangrove management are needed, focusing on anthropogenic factors that cause mangrove degradation. Suggested policy recommendations are as follows:

3.2.1 Sustainable aquaculture alternatives and integration. The conversion of aquaculture to a more sustainable system is a strategic step in overcoming the degradation of mangrove ecosystems. The silvofishery and Integrated Mangrove Aquaculture (IMA) system is an alternative that strikes a balance between economic productivity and environmental conservation. In practice, two main models are widely applied, namely the Trench Dam and the Komplang System. The first model raises fish in a central pond surrounded by mangroves on the outer edge, while the second model plants mangroves along the edges and in a grid pattern in the same pond as the aquatic

livestock.[91,92] Empirical studies show that the silvofishery system can provide ecosystem services worth USD 3318.49 per hectare per year. However, lower than natural mangroves, but it is still an environmentally friendly economic choice. Research in Vietnam has even recorded a high survival rate of biota, with shrimp yields reaching 20 grams per head, crabs at 250 grams, and fish at 300 grams, generating profits of more than 125 million VND per hectare.[93]

The implementation of Associated Mangrove Aquaculture (AMA) in Demak, Central Java, shows the success of mangrove green belt restoration through an integrative approach. In this system, part of the pond land is converted into a natural habitat for mangroves by building new embankments and sluices that allow for sedimentation and the natural growth of mangroves within one year. Ideally, each watershed should have a minimum 20 meter mangrove green belt on both sides to maintain its ecological function. The program successfully involved about 150 farmers who converted 10% of their total 104 hectares of ponds. Through the implementation of Low External Input Sustainable Aquaculture (LEISA), farmers' profits increase by up to 300% sustainably, while strengthening the economic resilience of coastal communities through increasing fisheries productivity.[94–96] The success of the program can be applied throughout the north coast of Java, especially the areas with the primary income from ponds.

3.2.2 Development of buffer zones and green infrastructure. Industrial development and urban settlements in coastal areas must be balanced with mangrove protection efforts through the establishment of buffer zones and the implementation of sustainable green infrastructure. The protection of mangrove resources involves determining the proportion of undisturbed mangrove areas for nature conservation, as well as establishing green belts along coastlines and riverbanks. The results show that the green belt of mangroves, hundreds of meters wide, can reduce the height of wind waves or tidal waves by up to 50% at a distance of 100 meters, making it a natural solution for coastal disaster mitigation.[86] The green belt concept emphasised the importance of mangroves not only for the welfare of local and national communities, but also for the balance of the global ecosystem.

3.2.3 Green infrastructure development. Infrastructure development in coastal areas is often a primary cause of mangrove ecosystem degradation, resulting from disturbances to natural processes, sediment accumulation, and land subsidence due to excessive groundwater extraction. The Building with Nature (BwN) approach in the north coast of Java offers innovative solutions by integrating ecological engineering, mangrove and river restoration, and sustainable land use to address these problems.[97] Unlike conventional complex infrastructure approaches that rely on sea walls and concrete embankments, BwN uses bamboo structures or semi-permeable shrubs to dampen wave energy and prevent sediment erosion. This method enables the creation of environmental conditions that support the natural growth of mangrove seedlings, with a success rate of up to 70%, significantly surpassing traditional planting methods, which typically achieve rates of only 10–20%.[98]

On the other hand, an effective coastal protection strategy demands an approach tailored to the socioeconomic and biophysical conditions of each region. In the northern coastal region of Java, for example, there is a need for the establishment of a specialised institution, such as the North Coast Sea Embankment Authority, to coordinate integrated management across sectors and regions. A comprehensive approach should combine "act and plan" measures through pilot projects in high-risk areas before being widely implemented.[99] The strategy not only relies on the technical engineering aspect but also emphasises the importance of sustainable funding and the active involvement of stakeholders. Research confirms that engineering-based solutions alone are insufficient to address complex coastal challenges. Therefore, nature-based solutions, such as the soft Building with Nature concept, need to be put forward because they provide multifunctional benefits, ranging from coastal protection and increasing biodiversity to providing recreational spaces and high flexibility in adjusting management to the dynamics of the coastal environment.

3.2.4 Community-based ecological mangrove restoration. Community-Based Ecological Mangrove Restoration (CBEMR) is one of the policies that can be implemented on the north coast of Java. This approach is a holistic method for restoring mangrove ecosystems that emphasises the involvement of local communities and the application of ecological principles to facilitate natural regeneration. Unlike conventional mangrove planting, which often fails due to improper site selection and species selection, CBEMR focuses on understanding and restoring the natural processes that allow mangroves to thrive. This includes addressing hydrological connectivity and other ecological stressors that led to mangrove degradation in the first place.[100,101] This approach integrates scientific knowledge with local ecological and social insights, ensuring that restoration efforts are tailored to the specific conditions of each site. In practice, CBEMR involves pre-project assessments of the site's ecology and hydrology, followed by interventions that facilitate natural regeneration, such as penetrating embankment walls and constructing tidal channels to improve water flow.

4. Discussion

The results of a study examining 44 scientific articles indicate that complex and interrelated anthropogenic activities primarily drive the degradation of mangroves in the northern coastal area of Java. Human pressure is the primary factor contributing to the decline in the area and quality of mangrove forests in Indonesia.[85,88] The main factors causing degradation identified include land clearing for ponds and aquaculture, conversion of industrial and residential land, coastal reclamation, pollution from domestic and industrial waste, illegal logging, and large-scale infrastructure development. The pattern of research distribution, which is more widely conducted in industrial and urban areas such as Jakarta, Semarang, and Surabaya, reveals a strong relationship between the intensity of economic activity and the rate of degradation of mangrove ecosystems. The most dominant factor identified from various studies on the northern coast of Java is the

conversion of mangroves into ponds or aquaculture land. Economic incentives to increase fishery production encourage communities to convert mangrove forests into shrimp and fish ponds.[81] This practice provides short-term economic benefits, but ecologically causes the loss of mangroves' function as a natural protector of the coast, a carbon sink, and habitat for marine life. This pattern is similar to that found in the Mekong Delta, Vietnam, where aquaculture expansion is a major driver of mangrove deforestation.[102–104] However, in contrast to Vietnam, which has begun to implement the integrated mangrove-shrimp farming (IMSF) system as an ecological and economic solution,[105] most of the northern coastal areas of Java have not yet adopted a sustainable aquaculture model. The study highlights new findings that Indonesia has not integrated a cross-border management model that has proven successful in Southeast Asia. This indicates a knowledge gap in the transfer of regional policies and sustainable mangrove management.

Urbanisation and coastal industrialisation are also important factors that accelerate the degradation of mangroves in Indonesia. Land clearing for industry and settlements has significantly changed the coastal landscape, especially in Semarang, Kendal, and Surabaya. The development of large industrial estates in the area has resulted in habitat fragmentation and reduced connectivity of coastal ecosystems.[74,87] These results are in line with research in Bangladesh and India, which shows that the development of ports and coastal industrial areas contributes significantly to mangrove loss.[106,107] However, in contrast to Bangladesh, which has an Integrated Coastal Zone Management (ICZM) program to balance development and conservation,[108] Similar policies in Indonesia are still limited to sectoral programs. Interestingly, this study reveals a new pattern: mangrove degradation not only occurs in industrial areas, but also in non-industrial areas undergoing economic transformation. The shift in people's livelihoods from fishermen to industrial workers in the hinterland area has led to an increase in demand for land for settlements and social infrastructure, which indirectly adds to the pressure on coastal ecosystems. This phenomenon has not been widely discussed in previous research, indicating that mangrove degradation is now triggered not only by direct activities but also by the indirect impact of changes in the economic structure of coastal communities.

Coastal reclamation activities in Jakarta, Surabaya, and Serang also put additional pressure on coastal ecosystems. Although reclamation sometimes creates new habitats through natural sedimentation processes, the productivity and capabilities of these new ecosystems cannot replace the ecological role of natural mangrove forests.[72] A similar phenomenon has also been observed in Thailand, where reclamation projects have resulted in the degradation of coastal ecosystems and a significant loss of blue carbon stocks.[109] The difference between Indonesia and Thailand lies in their approach to restoration; Thailand has implemented an eco-engineering restoration system based on current dynamics and natural sediments,[110] while most rehabilitation programs in Indonesia still use conventional planting approaches without considering the geomorphological character of the coast. From the results of the article synthesis, new findings were identified that changes in sedimentation patterns due to infrastructure development, such as the Semarang-Demak toll road and ports in Surabaya, are a degradation factor that is now more significant than reclamation. These findings mark a paradigm shift, indicating that coastal infrastructure development not only impacts vegetation loss but also alters the hydrodynamic systems that underpin the natural regeneration of mangroves.

In addition to land conversion and reclamation, pollution is also a serious threat to the sustainability of mangroves. Various studies have noted that domestic, industrial, and agricultural waste accelerates mangrove degradation through the accumulation of heavy metals, microplastics, and harmful chemicals.[63] The northern coast of Java is characterised by a unique and severe impact of plastic pollution on mangroves, coupled with a distinctive ecological resilience threshold and a relatively strong local conservation policy context, which distinguishes it from other Indonesian mangrove regions where the impact of sewage pollution is distinct or exacerbated by other environmental pressures. These environmental pressures include rising sea levels and land subsidence.

Illegal logging in several areas, such as Jepara, Karimunjawa, and Pasuruan, also highlights the connection between the community's socioeconomic conditions and environmental degradation. The dependence on mangrove wood for household needs indicates that local economic factors remain the primary cause of pressure on the ecosystem. However, this study identified a new phenomenon in Pasuruan, where the conversion of mangrove areas into commercial land has caused ecological disturbances, prompting the development of ecotourism as a sustainable alternative to manage mangrove ecosystems.[111] This shift represents a paradigm shift in society, transitioning from extractive utilisation to ecosystem service utilisation. While it has the potential to reduce illegal logging, it also poses a risk of ecological commodification if not regulated with precise environmental justice mechanisms in place. These findings broaden the discourse on mangroves not only as a natural resource, but also as a political economy instrument in the context of green development on the north coast of Java.

Institutionally, mangrove management in Indonesia continues to face complex governance challenges. The dualism of authority between the Ministry of Environment and Forestry (KLHK) and the Ministry of Maritime Affairs and Fisheries (KKP) often leads to policy overlap and weak coordination in the field.[88] This study also found a discrepancy between regional climate change adaptation policies and mangrove management policies. In some districts, such as Demak and Kendal, coastal adaptation programs still focus on physical development, including seawalls. In contrast, natural ecosystem-based approaches, like mangrove restoration, have not been a top priority. These findings confirm that mangrove degradation in Indonesia is not only an ecological issue, but also a governance and policy coordination problem.

5. Conclusion

Based on a review of 44 scientific articles related to the degradation of mangrove forests on the north coast of Java, it is

evident that massive anthropogenic activities primarily destroy mangrove ecosystems. Degradation occurred in 18 districts/cities, with the highest level of damage in metropolitan areas such as Jakarta, Semarang, and Surabaya, which are under pressure from urbanisation and industrialisation. The primary factors contributing to degradation include the conversion of mangrove land into ponds, industrial and residential development, coastal reclamation, pollution from various waste sources, illegal logging, and the expansion of coastal infrastructure. As a result, Java Island has lost approximately 70% of its original mangrove forests, which has been exacerbated by weak law enforcement, institutional fragmentation, and low community participation in coastal environmental management.

To address these problems, an integrated and sustainability-based management strategy is needed. Some of the recommended efforts include the implementation of sustainable aquaculture systems such as silvofishery, the construction of buffer zones and green infrastructure, and the implementation of the "Building with Nature" (BwN) approach as a nature-based solution to restore ecosystem balance. Additionally, community-based ecological mangrove restoration (CBEMR) needs to be developed to enhance the local role in mangrove conservation. A cross-sectoral, scientific, and participatory approach is crucial to the success of conservation efforts, ensuring that the mangrove ecosystem on the north coast of Java continues to provide ecological and economic benefits to coastal communities in a sustainable manner.

Conflicts of interest

There are no conflicts to declare by the authors.

Data availability

This study is a review article, and no new data were generated or analyzed during the course of this research. All data discussed and referenced are available in the publicly accessible sources cited within the article.

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