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Comparative Analysis of Coastal Green Open Space Conversion and Its Environmental Consequences Across Coastal Districts of North Sumatra

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Abstract: This study examines the conversion of Coastal Green Open Space (CGOS) in the coastal areas of North Sumatra Province using a Systematic Literature Review (SLR) approach based on PRISMA, synthesizing findings from 25 scientific articles. The results indicate that CGOS conversion is a complex and multidimensional phenomenon driven by the interaction of anthropogenic, biophysical, and governance factors. Three primary conversion patterns are identified: rapid conversion in industrial and port areas, gradual conversion in aquaculture and plantation zones, and ecological fragmentation in land–sea transition areas. The main driving factors include coastal urbanization, economic and industrial expansion, land use change, climate change pressures, and weak policy implementation. Among these, urbanization and economic growth emerge as the most dominant forces accelerating land conversion. The environmental consequences are systemic, including the decline of ecosystem services, increased coastal flooding and disaster risks, biodiversity degradation, hydrological disturbances, and reduced environmental quality due to the loss of coastal vegetation. Comparative analysis reveals significant spatial variation among coastal districts, where highly urbanized areas experience more rapid and intensive conversion, while aquaculture-based regions undergo gradual yet cumulative changes. These findings highlight that the sustainability of coastal ecosystems is highly dependent on the presence of CGOS as natural protection and ecological support systems. Therefore, integrated and ecosystem-based coastal management is essential, emphasizing spatial planning, green infrastructure development, technological monitoring, and community participation to ensure long-term sustainability.

Keywords: Coastal Green Open Space; Mangrove Conversion; Coastal Urbanization; Coastal Land Use Change; North Sumatra

INTRODUCTION

The development of coastal regions and economic growth along the eastern shore of North Sumatra Province in recent decades have hastened alterations in land use within coastal zones. A major consequence is the escalating transformation of Coastal Green Open Space (CGOS), especially in mangrove habitats and vegetated coastal buffer areas that serve as natural defense mechanisms against environmental stressors. The transformation of CGOS not only modifies the configuration of coastal terrains but also diminishes the ability of ecosystems to deliver vital ecological services, including coastal defense, blue carbon storage, and the sustenance of coastal biodiversity (Pendleton et al., 2012). Moreover, the deterioration of coastal ecosystems can heighten the susceptibility of coastal regions to environmental hazards such coastal erosion, tidal inundation, seawater encroachment, and diminishing coastal water quality (Noor & Maulud, 2022).

Green open spaces are areas dominated by various types of vegetation that play a crucial role in maintaining environmental balance and improving ecosystem quality. Coastal zones are among the regions with high vegetation diversity (Nugroho et al., 2022). These areas represent transitional zones between land and sea, characterized by the presence of ecosystems such as mangrove forests, seagrass beds, and coastal wetlands. These ecosystems have significant ecological functions in maintaining coastal environmental stability while providing ecosystem services that support the well-being of coastal communities (Quevedo et al., 2025). Coastal vegetation not only provides habitats for diverse marine and coastal organisms but also mitigates wave energy, captures sediments, and sustains hydrological equilibrium.

The presence of coastal green open spaces also provides substantial ecological and social benefits. Coastal vegetation such as mangroves and mixed forests has been shown to improve environmental quality and human health, particularly within areas located approximately 150–300 meters from the shoreline, by enhancing air quality and thermal comfort (Leng et al., 2023). Moreover, coastal green spaces contribute to microclimate regulation. A balanced combination of vegetation and built structures in coastal areas can reduce air temperature by up to approximately 3.5°C, thereby improving environmental comfort (Widyasamratri, Karmilah, Musyafiq, Kusumawanto, & Noor, 2025). Thus, coastal green open spaces not only serve ecological functions but also hold important social and economic value in supporting sustainable coastal development.

Despite their importance, coastal green open spaces in various regions of Indonesia are facing increasing pressure due to coastal urbanization and economic expansion. A similar condition is observed in North Sumatra Province, particularly along the eastern coast bordering the Malacca Strait. The development of residential areas, industrial zones, port infrastructure, aquaculture activities, and other coastal economic activities has significantly driven the conversion of CGOS (Weng et al., 2021). This conversion process has the potential to cause various environmental consequences, including accelerated mangrove degradation, shoreline changes, disruption of coastal hydrological systems, increased risk of tidal flooding, and declining environmental carrying capacity (Kotta, Faslih, Hasan, & Hartono, 2020). In the long term, these conditions may weaken the natural protective capacity of coastal areas and increase their vulnerability to climate change impacts.

Previous studies have examined land use change dynamics and coastal ecosystem degradation in several coastal districts of North Sumatra. However, most of these studies are local in scope and focused on specific areas, resulting in a fragmented understanding of CGOS conversion dynamics (Li, Yue, Liu, Dai, & Li, 2025). Current studies predominantly focus on alterations in land cover or the deterioration of mangroves at a district or localized level, neglecting the examination of interregional connections within a province framework. Currently, there remains an absence of regional-scale comparative analyzes that methodically assess the variations in CGOS conversion trends, influencing factors, ecological impacts, and governance responses among coastal districts (Wang, Liao, Ye, Byrne, & Scown, 2024). This research gap limits evidence-based regional coastal management efforts and hampers policy coordination across administrative boundaries.

Based on these conditions, this study aims to conduct a comparative analysis of coastal green open space conversion and its environmental consequences across all coastal districts and cities in North Sumatra Province bordering the Malacca Strait. The novelty of this research lies in developing a subnational comparative synthesis that integrates the analysis of CGOS conversion patterns, ecological consequences, and the effectiveness of spatial governance instruments across multiple coastal districts within a single provincial context. Through this approach, the study is expected to provide a more comprehensive understanding of CGOS conversion dynamics and their implications for coastal ecological resilience, while also offering a scientific basis for developing more integrated and sustainable coastal management policies in North Sumatra Province.

RESEARCH METHODS

1. Research Design

This study employs a Systematic Literature Review (SLR) approach to comprehensively examine the dynamics of Coastal Green Open Space (CGOS) conversion and its environmental consequences in the coastal areas of North Sumatra Province. The SLR methodology was chosen as it facilitates a methodical scientific amalgamation of diverse published research, thus offering a more cohesive comprehension of trends, influencing elements, and ecological consequences of coastal green open space transformation. This study's systematic review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) structure, commonly utilized in review research to guaranty transparency, replicability, and uniformity in the discovery and selection of scholarly literature.

2. Study Area

The study area encompasses all coastal regencies and municipalities in North Sumatra Province that directly border the Malacca Strait, including Langkat Regency, Deli Serdang Regency, Medan City, Serdang Bedagai Regency, Batu Bara Regency, Asahan Regency, and North Labuhanbatu Regency, as well as other associated coastal areas. The eastern coastal region of North Sumatra was selected due to its relatively high levels of economic activity and urbanization. This area is characterized by various coastal development activities such as settlements, industry, ports, aquaculture, and coastal plantations, all of which have the potential to drive the conversion of coastal green open spaces, particularly mangrove ecosystems and coastal buffer vegetation. Moreover, this region plays a strategic role in coastal ecological systems as it serves as a habitat for various marine organisms and functions as a natural protective zone against coastal erosion, tidal flooding, and seawater intrusion.

3. Literature Search and Selection

The compilation of literature for this research was executed using multiple esteemed global scientific databases, particularly journals indexed in Scopus (Q1 to Q4), culminating in 25 pertinent publications. The selected literature focuses on publications from 2020 to 2025 to ensure that the analysis reflects the most recent studies on coastal environmental dynamics. The search process was carried out using a combination of keywords such as coastal green open space, mangrove conversion, coastal land use change, coastal ecosystem degradation, coastal urbanization, coastal environmental impacts, and North Sumatra coastal zone.

Subsequently, the literature selection process was conducted systematically following the PRISMA framework to ensure transparency and consistency in identifying and selecting relevant articles. The selection stages began with article identification based on keywords, followed by a screening process to remove duplicates and assess the relevance of titles and abstracts to the research focus on coastal green open space conversion and its environmental impacts. Articles that successfully navigated the screening phase underwent comprehensive full-text assessment to ascertain methodological pertinence, suitability of the research domain, and coherence with the study aims. Only articles meeting the inclusion criteria were included in the final analysis, namely those published between 2020 and 2025, addressing coastal land use change or ecosystem conversion, and examining environmental impacts in tropical coastal regions or areas with characteristics similar to the North Sumatra coast.

4. Data Analysis

Data analysis in this study was conducted using a comparative thematic analysis approach to identify patterns of coastal green open space conversion and its environmental consequences in the coastal areas of North Sumatra Province. The selected articles were systematically analyzed by categorizing key information related to types of coastal land use change, driving factors of conversion, and resulting ecological impacts. The analytical procedure encompassed the recognition of several types of coastal ecosystem alteration, including the conversion of mangrove forests into urban developments, aquaculture facilities, and industrial sectors. In addition, this study evaluates a range of environmental consequences reported in the literature, including mangrove ecosystem degradation, shoreline changes, disruption of coastal hydrological systems, and increased risks of coastal flooding and seawater intrusion. Through this comparative analytical approach, the study aims to provide a more comprehensive understanding of coastal green open space conversion patterns and to identify their ecological implications for the sustainability of coastal areas in North Sumatra Province.

RESULTS AND DISCUSSION

1. Literature Selection and Characteristics

To examine the dynamics of Coastal Green Open Space (CGOS) conversion and its environmental consequences in coastal areas, the literature collection process was conducted systematically using the PRISMA framework. The initial literature search was carried out through ScienceDirect and Web of Science with Scopus-indexed articles (Q1–Q4), using the main keywords “coastal green open space”, “mangrove conversion”, and “coastal land use change”, resulting in 32 initial articles. To broaden the scope of the study, a second search was conducted by adding the terms “coastal ecosystem degradation”, “coastal urbanization”, and “coastal environmental impacts”, yielding an additional 18 articles. Thus, the total number

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of articles identified in the initial stage reached 50.

In this research, the phrase coastal green open space encompasses various varieties of verdant open places in coastal regions, such as mangroves, coastal wetlands, beach flora, and ecosystem-oriented green infrastructure. Conversely, mangrove conversion denotes the alteration of mangrove ecosystems into alternative land utilizations such as aquaculture facilities, residential areas, or industrial zones. The keywords coastal land use change and coastal urbanization were used to capture spatial dynamics driven by development pressures, while coastal ecosystem degradation and coastal environmental impacts focused on the resulting ecological consequences. This amalgamation of keywords facilitated an exhaustive recognition of pertinent material according to the study aims.

All identified articles were then screened to remove duplicates, reducing the number to 41 articles. The subsequent phase entailed examining titles and abstracts to ascertain their pertinence to the research emphasis on CGOS conversion and its ecological consequences. Articles that do not pertain to coastal regions, do not discuss alterations in land use, or concentrate exclusively on methodological issues without connection to coastal ecosystems were omitted. At this point, 11 items were discarded, resulting in 30 articles remaining. The selection process continued with a full-text review to assess methodological suitability, study area relevance, and alignment with the comparative research objectives. Some articles were excluded due to insufficient information on land conversion dynamics or lack of clear environmental impact analysis. Conceptual review papers without empirical data were also excluded. After this evaluation, 25 articles met all inclusion criteria and were included in the final analysis.

The chosen 25 articles underwent additional examination to discern overarching research attributes, encompassing study topics, methodological strategies, and analytical emphasis. The literature was categorized into seven primary themes: (1) coastal green open space (3 articles), (2) mangrove conversion (3 articles), (3) coastal land use change (3 articles), (4) coastal ecosystem degradation (4 articles), (5) coastal urbanization (4 articles), (6) coastal environmental impacts (4 articles), and (7) North Sumatra coastal zone (4 articles). This distribution reveals that the majority of research focus on the correlation between alterations in coastal land use and their ecological consequences, utilizing diverse methodologies including spatial modeling, remote sensing, ecosystem valuation, and participatory techniques.

Table 1. Characteristics of Literature Analyzed in the SLR

No	Keywords	Number of Articles	Main Research Focus	Methodological Approaches
1	Coastal Green Open Space	3	Coastal green space dynamics and human well-being	GIS, surveys, field experiments
2	Mangrove Conversion	3	Mangrove conversion and blue carbon	Remote sensing, economic valuation
3	Coastal Land Use Change	3	Coastal land use change	Hydrological modeling, landscape analysis
4	Coastal Ecosystem Degradation	4	Ecosystem degradation and ecosystem services	DPSIR, GIS, economic valuation
5	Coastal Urbanization	4	Urbanization and coastal environmental pressure	NDVI, time-series analysis, GWR
6	Coastal Environmental Impacts	4	Environmental impacts and disaster risks	Hydrodynamic models, SLAMM
7	North Sumatra Coastal Zone	4	Coastal dynamics of North Sumatra	Simulation, spatial evaluation, biotechnology

Source: Primary data processing, 2026

2. Patterns of Coastal Green Open Space Conversion in North Sumatra

The patterns of Coastal Green Open Space (CGOS) conversion in the coastal areas of North Sumatra exhibit complex and spatially varied dynamics across regencies, influenced by the intensity of urbanization, economic expansion, and the biophysical characteristics of coastal environments. Based on the synthesis of 25 articles analyzed using a PRISMA-based Systematic Literature Review (SLR) approach, CGOS conversion primarily occurs in mangrove ecosystems, coastal wetlands, and coastal buffer vegetation, which are transformed into industrial

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zones, settlements, ports, and aquaculture ponds. These findings are consistent with studies in coastal cities in Ghana, which reported a reduction of green space by up to 25% due to uncontrolled urbanization, affecting both human well-being and environmental quality (Duku, Mensah, & Amadu, 2023). In North Sumatra, this phenomenon reflects similar development pressures along the eastern coastal region bordering the Malacca Strait, particularly in areas with high economic activity such as the Special Economic Zone (Sa'dia & Fitrady, 2023). Spatially, CGOS conversion patterns in North Sumatra can be classified into three main types: (1) rapid conversion in industrial and port areas, (2) gradual conversion in aquaculture and coastal plantation zones, and (3) ecological fragmentation in land–sea transition areas. In industrial and port areas, conversion occurs rapidly and extensively, characterized by large-scale loss of mangrove cover and the expansion of hard infrastructure. A summary of the identified CGOS conversion patterns is presented in the following table.

Table 2. Patterns of Coastal Green Open Space Conversion

No	Conversion Pattern Type	Main Characteristics	Ecological Impacts
1	Rapid conversion (industry & ports)	Large-scale mangrove conversion, infrastructure development	Reduced coastal protection capacity, increased flooding
2	Gradual conversion (aquaculture & plantations)	Transformation into ponds and production land	Loss of blue carbon, mangrove degradation
3	Coastal landscape fragmentation	Disruption of ecosystem connectivity	Decline in biodiversity
4	Biophysically driven degradation	Influenced by salinity, sea winds, sediment	Reduced vegetation survival
5	Governance-related conversion	Weak policies and economic pressure	Systemic ecosystem degradation

Source: Primary data processing, 2026

Based on Table 2, CGOS conversion patterns in North Sumatra are multidimensional and shaped by the interaction between economic, environmental, and governance factors. The variation in conversion patterns across regions indicates that coastal management approaches cannot be uniform but must be adapted to local characteristics. A study by Chávez et al., (2021) on coastal green infrastructure shows that the loss of natural vegetation can reduce flood absorption capacity by up to 60% and increase vulnerability to sea-level rise and coastal squeeze. Additionally, coastal industrial agglomeration has been shown to drive spatial restructuring and increase pressure on coastal ecosystems (Feng, Gao, & Zhang, 2025).

In aquaculture and coastal plantation areas, conversion tends to occur gradually but extensively, where mangrove ecosystems are transformed into ponds and production land. Blue carbon studies indicate that mangrove conversion results in the loss of carbon storage potential of approximately 15–20 Mg C/ha/year (Hilmi et al., 2025), resulting in elevated carbon emissions and ecological deterioration. Nonetheless, in certain instances, the restoration of mangroves has demonstrated the potential to elevate community revenue by as much as 30% while simultaneously diminishing flood effects by 50%, underscoring a balance between economic and ecological roles (Ebeler et al., 2025). Analysis satellite-based analysis using Sentinel-2 imagery indicates that mangrove conservation can increase biomass by up to 12%, emphasizing the importance of controlling land conversion (Farzanmanesh et al., 2024).

Beyond economic drivers, CGOS conversion patterns are also influenced by coastal biophysical conditions such as soil salinity, sediment dynamics, and coastal wind pressure. A research in Japan's coastal areas indicated that only around 75% of coastal vegetation can survive under high salt conditions, implying that environmental changes resulting from land conversion can exacerbate vegetation degradation (Yoshino & Asahiro, 2025). This condition is relevant to North Sumatra's coastal areas, which experience strong tidal dynamics and seawater intrusion, making CGOS conversion likely to further destabilize coastal ecosystems. Additionally, coastal geomorphological changes influenced by sediment dynamics and sea-level rise also play a role in determining land conversion patterns (Chapkanski et al., 2025).

From a land use change perspective, CGOS conversion in North Sumatra is associated with increased landscape fragmentation and reduced ecosystem connectivity. Studies in coastal China show that urbanization leads to landscape fragmentation of up to 28% and significantly reduces biodiversity indices (Zhai et al., 2025). Furthermore, alterations in landscapes influence human-environment dynamics, as demographic pressures and economic endeavors modify the configurations of coastal ecosystems (Chi et al., 2025). In the long term, such fragmentation contributes to declining ecosystem service quality and increased environmental degradation (Guan et al., 2024).

The findings indicate that CGOS conversion patterns are not solely determined by economic and environmental factors but also by the effectiveness of spatial governance and environmental policies. Studies based on the DPSIR framework show that development pressures not supported by effective policies can lead to systemic coastal ecosystem degradation (Han, Li, Zheng, Ding, & Shi, 2025). Conversely, participatory approaches such as community-based mapping can identify restoration potential of up to 35% of degraded areas (Polas, Ahammad, Topp, & Plieninger, 2025). In North Sumatra, the main challenges lie in weak coordination across administrative regions and inconsistent implementation of spatial planning policies, which accelerate the rate of CGOS conversion.

3. Driving Factors of Coastal Green Open Space Conversion

The primary influences on the transformation of Coastal Green Open Space (CGOS) highlighted in the examined literature indicate a robust relationship among developmental pressures, socio-economic issues, and global environmental shifts. These drivers can be broadly classified into several major groups: coastal urbanization, economic and industrial expansion, land use change, environmental pressures and climate change, and weaknesses in coastal governance. Similar to the variation in sensor usage in remote sensing studies, these factors operate simultaneously and reinforce one another in driving CGOS conversion across various coastal regions, including North Sumatra.

Coastal urbanization is one of the dominant factors driving CGOS conversion. Several studies indicate that population growth and the expansion of built-up areas significantly reduce green open spaces. Research by Munizaga et al., (2024) Unregulated urban expansion in coastal Chile has resulted in a reduction of green space and adversely impacted vegetation health.

Comparable results are documented in coastal China, where urban development has led to a 20% decline in vegetation and a 15% drop in natural area accessibility (Huang et al., 2023). Furthermore, multi-temporal analysis in coastal Turkey indicates urban expansion of up to 30% as a strong indicator of development pressure on coastal areas (Alphan, 2020). In this scenario, North Sumatra is anticipated to witness heightened growth of residential and coastal urban regions, especially in Medan and its vicinity, rendering urbanization a principal catalyst for CGOS transformation.

In addition to urbanization, coastal economic and industrial expansion is another critical factor driving CGOS conversion. Industrial activities, port development, and the establishment of Special Economic Zones (SEZs) exert significant pressure on coastal ecosystems. Findings by Feng et al., (2025) indicate that marine industrial agglomeration can increase economic resilience by up to 25%, but at the same time accelerate coastal land conversion and environmental degradation. Evaluations of SEZ development in North Sumatra also show economic growth of up to 12%, accompanied by increasing pressure on coastal ecosystems (Sa'dia & Fitrady, 2023). Moreover, intensified economic activities contribute to increased coastal pollution, as evidenced by a 40% rise in marine debris due to urbanization in Vietnam (Fulfer, Nguyen-ngoc, & Walsh, 2025). These findings highlight the trade-off between economic growth and environmental sustainability in coastal areas.

Coastal land use change, particularly the conversion of mangroves into aquaculture ponds and production land, is also a major driving factor. Blue carbon studies indicate that mangrove conversion is often driven by short-term economic needs, such as aquaculture expansion, which tends to overlook long-term ecological values (Hilmi et al., 2025). dditionally, hydrological modeling studies show that wetland conversion can increase flood risk by up to 40% in coastal areas (Sun et al., 2025). Landscape fragmentation due to land use change is also evident, with fragmentation increasing by up to 28% in coastal China (Zhai et al., 2025). However, some studies suggest that ecosystem restoration can improve human–environment relationships and reduce conversion pressures when implemented in an integrated manner (Chi et al., 2025).

Environmental factors and climate change also play a significant role in driving CGOS conversion, both directly and indirectly. The rise in sea levels, alterations in sediment movement, and the growing occurrence of coastal threats such tidal inundation and storms expedite the deterioration of coastal ecosystems. Research indicates that coastal wetlands can mitigate as much as 70% of storm energy, implying that the degradation of these ecosystems heightens coastal susceptibility (Rowland, Costa, Macreadie, & Wartman, 2025). Furthermore, predictive models indicate that sea-level rise can increase flood risk by up to 50% in areas with structural interventions such as levees (Xu et al., 2024). The coastal areas of North Sumatra are also located in disaster-prone zones, including tsunami risks and geomorphological changes due to tectonic and sedimentary dynamics (Jihad et al., 2020), which further influence the stability and sustainability of CGOS.

The ultimate determinant is government and coastal management strategy. Ineffective policy execution, insufficient intersectoral collaboration, and economic strains frequently lead to unregulated CGOS transformation. DPSIR-based evaluations suggest that developmental stresses lacking robust policies may result in comprehensive ecosystem deterioration (Han et al., 2025). Conversely, participatory approaches such as community-based mapping demonstrate that local involvement can identify restoration potential of up to 35% of degraded areas (Polas et al., 2025). ther studies emphasize the importance of green infrastructure in balancing development and conservation (Kaskevich, Villoslada, Ward, & Sepp, 2024), as well as the potential of mangrove biotechnology to support coastal ecosystem restoration (Mamangkey et al., 2021). A summary of the main driving factors identified in this study is presented in the following table.

Table 3. Driving Factors of Coastal Green Open Space Conversion

No	Driving Factors	Main Characteristics	Impacts
1	Coastal urbanization	Expansion of settlements and urban areas	Decline in vegetation area
2	Economic & industrial expansion	Industrial zones, ports, SEZs	Ecosystem degradation, pollution
3	Land use change	Mangrove conversion to aquaculture	Loss of blue carbon, flooding
4	Climate & environmental change	Sea-level rise, storms	Increased disaster risk
5	Governance & policy	Weak regulations and coordination	Uncontrolled conversion

Source: Primary data processing, 2026

Based on the analysis, it can be concluded that CGOS conversion in North Sumatra's coastal areas is driven by a complex interaction between anthropogenic and environmental factors. The primary force is development pressure, as evidenced by the dominance of urbanization and economic drivers. The impacts of conversion are either exacerbated or mitigated by environmental and governance factors. Consequently, sustainable coastal management necessitates a multidisciplinary strategy that integrates environmental policy, spatial planning, and community participation to regulate CGOS conversion.

4. Environmental Consequences of Coastal Green Open Space Conversion

The environmental consequences of Coastal Green Open Space (CGOS) conversion represent one of the most critical issues in both global and regional coastal dynamics. Changes in coastal land functions directly reduce the capacity of ecosystems to provide ecological services. A study by Pendleton et al., (2012) supported by findings from Yan et al., (2023) shows that the degradation of coastal wetland ecosystems can lead to a decline in ecosystem service values reaching billions of dollars over a certain period. This suggests that CGOS conversion possesses not only environmental consequences but also considerable enduring economic ramifications. A synopsis is provided in the subsequent table.

Table 4. Synthesis of Environmental Consequences of CGOS Conversion

No	Impact Aspect	Key Findings
1	Decline in ecosystem services	Ecosystem service values decreased significantly up to US$2.5 billion
2	Coastal flood risk	Risk increased by 40% due to land use change
3	Sea-level rise	Flood intensity increased by up to 50%
4	Natural protection	Wetlands absorb up to 70% of storm energy
5	Biodiversity degradation	Landscape fragmentation 28%, decline in biodiversity
6	Vegetation decline	Vegetation decreased by up to 20% due to urbanization
7	Coastal pollution	Marine debris increased by up to 40%
8	Disaster risk	High tsunami risk in North Sumatra
9	Economic pressure	SEZs boost the economy but pressure ecosystems
10	Restoration potential	Mangrove restoration up to 35% of degraded areas

Source: Primary data processing, 2026

Based on Table 4, coastal land use change also contributes to increasing regional vulnerability to hydrometeorological disasters. Research by (Sun et al., 2025) reveals that the combined effects of climate change and land conversion increase storm flood risk by up to 40% in coastal areas. This finding is consistent with (Xu et al., 2024) who show that sea-level rise in areas with structural interventions such as levees can increase flood intensity by up to 50%. This indicates that the loss of natural vegetation such as mangroves and wetlands reduces the natural protective function of coastal areas against wave energy and tidal forces.

In terms of natural coastal protection, ecosystems such as mangroves and coastal wetlands play a significant role in dissipating wave and storm energy. (Rowland et al., 2025) state that coastal wetland ecosystems can absorb up to 70% of storm energy, acting as a natural barrier against infrastructure damage. However, extensive CGOS conversion reduces this protective capacity. This condition is further exacerbated by increasing anthropogenic pressure in coastal areas, as explained by (Guan et al., (2024), where 30 years of urbanization have led to a 25% decline in ecosystem services and increased soil erosion due to the loss of vegetation cover.

Beyond physical protection, CGOS conversion also leads to biodiversity degradation and ecological imbalance (Zhai et al., 2025) show that landscape fragmentation due to land use change reaches 28% and significantly reduces biodiversity indices (Shannon Index). This finding is supported by (Munizaga et al., 2024) who report a 20% decline in vegetation in urbanized coastal areas due to human activity pressures. This loss of biodiversity not only affects ecosystems but also disrupts food chains and fisheries productivity in coastal regions.

CGOS conversion also disrupts coastal hydrological systems and water quality. (Chi et al., 2025) Exhibit how alterations in coastal landscapes affect human-environment interactions via modifications in population distribution and land utilization. Meanwhile, (Fulfer et al., 2025) eveal that coastal urbanization increases marine debris by up to 40%, reflecting declining environmental quality due to human activities. This indicates that CGOS conversion affects not only physical and ecological aspects but also overall environmental quality.

The environmental consequences of CGOS conversion become increasingly complex due to geophysical characteristics and regional disaster vulnerability (Jihad et al., 2020) state that North Sumatra’s coastal areas have a high tsunami risk based on coastal typology and settlement patterns. This is reinforced by (Chapkanski et al., 2025) Individuals elucidate that the coastal geomorphological processes in Sumatra are shaped by the interplay of rising sea levels, sediment influx, and tectonic movements. Consequently, CGOS conversion in this area could intensify disaster risks unless it is paired with ecosystem-oriented mitigation approaches.

In addition, economic development pressures further intensify environmental consequences in coastal areas. (Sa’dia & Fitrady, 2023) eport that the development of Special Economic Zones (SEZs) in North Sumatra increases economic growth by up to 12%, while simultaneously placing pressure on coastal ecosystems. This reflects a trade-off between economic development and environmental sustainability. Similarly, (Feng et al., 2025) note that marine industrial agglomeration can enhance economic resilience by up to 25%, but without proper management, it may accelerate coastal environmental degradation.

Interestingly, several studies suggest that restoration-based approaches and ecological innovations can mitigate the negative impacts of CGOS conversion. (Polas et al., 2025) emphasize the importance of participatory mapping in identifying degraded areas and restoration potential of up to 35%. Furthermore, (Mamangkey et al., 2021) highlight the biotechnological potential of mangrove ecosystems in North Sumatra, particularly through associated bacteria that can be utilized for coastal bioremediation. These findings indicate that despite the negative impacts of CGOS conversion, there are opportunities for recovery through science- and technology-based approaches.

In general, CGOS conversion has several environmental repercussions, such as the reduction of ecosystem services, heightened catastrophe risk, biodiversity loss, hydrological disturbances, and deteriorating environmental quality. These effects are interrelated and constitute a sophisticated framework that affects coastal resilience. Consequently, a cohesive and ecosystem-oriented coastal management strategy is essential to mitigate the effects of CGOS conversion and bolster the resilience of coastal regions in North Sumatra Province.

5. Comparative Analysis of CGOS Conversion Across Coastal Regencies

The comparative analysis of Coastal Green Open Space (CGOS) conversion across coastal regencies in North Sumatra Province reveals significant spatial variations in terms of patterns, intensity, and environmental consequences. These variations are influenced by differences in physical characteristics, levels of urbanization, and economic orientations of each regency. In this context, a comparative approach is essential to understand that CGOS conversion dynamics are not homogeneous, but instead form distinct patterns across industrial areas, aquaculture zones, and natural coastal regions. This finding is consistent with (Zhai et al., 2025) who demonstrate that land use changes in developing coastal regions result in landscape fragmentation of up to 28%, with varying intensity depending on development pressure in each area.

Regencies characterized by industrial and port activities, such as the coastal areas of Medan City and Deli Serdang, exhibit faster CGOS conversion rates compared to other regions. This is associated with the expansion of built-up areas, which significantly reduces coastal vegetation. (Guan et al., 2024) show that long-term coastal urbanization can reduce ecosystem services by up to 25%, while (Huang et al., 2023) report a decline of up to 15% in ecological space availability in coastal cities due to development pressure. These conditions indicate that coastal areas with high economic activity tend to experience more rapid ecological degradation, particularly in North Sumatra.

In contrast, coastal regions dominated by aquaculture and plantation activities, such as Serdang Bedagai and Batu Bara, exhibit more gradual but extensive and cumulative conversion patterns. The transformation of mangroves into aquaculture ponds and other productive land leads to ecosystem fragmentation and gradual environmental degradation (Ebeler et al., 2025) highlight that socio-economic and institutional dynamics in delta regions play a crucial role in determining whether mangrove conservation or conversion occurs. Meanwhile, (Hilmi et al., 2025) Highlight that the transformation of mangroves due to economic pursuits can be alleviated via blue carbon strategies that offer financial incentives while preserving ecological integrity.

Variations in conversion trends are also seen in coastal areas with minimal development involvement, such as certain regions of Langkat and North Labuhanbatu. These regions generally preserve more authentic coastal ecosystems, however they continue to encounter challenges from climate change and regional endeavors (Munizaga et al., 2024) indicate that even in areas with relatively low anthropogenic pressure, vegetation dynamics can decline by up to 20% due to long-term factors. Additionally, (Sun et al., 2025) confirm that even small-scale land use changes can increase coastal flood risk by up to 40% if not properly managed.

From the perspective of disaster risk and environmental vulnerability, differences among coastal regencies become particularly significant. (Jihad et al., 2020) show that coastal areas in North Sumatra have a high tsunami risk based on coastal typology and settlement patterns. Regencies with higher levels of CGOS conversion tend to have greater vulnerability to coastal hazards due to the loss of natural protective functions. This is supported by (Rowland et al., 2025) who state that wetland ecosystems can absorb up to 70% of storm energy, meaning that their loss directly increases exposure to disaster risks.

Beyond ecological factors, governance and policy aspects also play a crucial role in differentiating CGOS conversion dynamics across regencies (Han et al., 2025) demonstrate that governance effectiveness can influence ecosystem recovery levels, increasing resilience indices by up to 22%. Meanwhile, (Sa'dia & Fitrady, 2023) show that development policies such as Special Economic Zones (SEZs) can boost economic growth by up to 12%, but may also place pressure on coastal ecosystems if not supported by strict environmental regulations. This highlights that differences in policy implementation across regencies are key factors in determining CGOS sustainability.

In terms of restoration and adaptive capacity, some regencies show greater potential for implementing ecosystem-based approaches. (Polas et al., 2025) Exhibit that remote sensing technologies like Sentinel-2 can enhance the precision of mangrove biomass assessment by as much as 92%. Additionally, (Mamangkey et al., 2021) highlight the biotechnological potential of mangrove ecosystems in North Sumatra for supporting coastal restoration. These differences indicate that not all regencies have equal capacity to respond to the impacts of CGOS conversion.

Overall, this comparative analysis shows that CGOS conversion in North Sumatra's coastal areas is heterogeneous and influenced by a combination of economic, ecological, and policy factors. Industrial-oriented regions tend to experience rapid conversion and high levels of degradation, while aquaculture-based regions exhibit gradual conversion with cumulative impacts.

Conversely, regions with diminished development pressure continue to possess prospects for preserving natural ecosystems, albeit they are susceptible to enduring dangers. Consequently, coastal management strategies in North Sumatra should take into account the unique attributes of each regency to guaranty that policies are more efficient and responsive to local circumstances. A summary comparison of CGOS conversion across coastal regions in North Sumatra is presented in the following table.

Table 5. Comparison of CGOS Conversion Across Coastal Regencies

Regency/City	Main Characteristics	CGOS Conversion Pattern	Dominant Environmental Impacts
Medan & Deli Serdang	High industry & urbanization	Rapid and intensive	Decline in ecosystem services, coastal flooding
Serdang Bedagai & Batu Bara	Aquaculture & plantations	Gradual and extensive	Mangrove fragmentation, environmental degradation
Langkat	Relatively natural	Slow	Long-term vegetation decline
North Labuhanbatu	Mixed	Moderate	Flood risk and hydrological changes
Entire North Sumatra coast	Variable	Heterogeneous	Increased coastal disaster risk
SEZ Areas	High economic activity	Intensive	Pressure on coastal ecosystems

Source: Primary data processing, 2026

In summary, Table 5 shows that differences in coastal regional characteristics lead to variations in CGOS conversion patterns, which directly affect environmental conditions and vulnerability levels in each regency. This comparison includes key regional characteristics, conversion patterns, and dominant environmental impacts. Therefore, coastal management strategies need to be developed in a differentiated manner and based on local characteristics to achieve long-term sustainability.

6. Implications for Coastal Ecosystem Sustainability and Coastal Management Policy

The implications of Coastal Green Open Space (CGOS) conversion for the sustainability of coastal ecosystems reveal a strong linkage between ecological degradation and the effectiveness of coastal management policies. Based on a synthesis of 25 articles, it was found that the loss of coastal vegetation such as mangroves and wetlands directly reduces the ecosystem's capacity to provide natural protection services, carbon sequestration, and biodiversity support. A study by Rowland et al., (2025) shows that wetland ecosystems can attenuate up to 70% of storm energy, meaning that their conversion increases coastal exposure to disaster risks. This indicates that the sustainability of coastal ecosystems is highly dependent on the presence of CGOS as a natural defense system.

Furthermore, the implications for sustainability are reflected in the declining carrying capacity of coastal environments due to development pressures. Studies by (Yan et al., 2023) indicate that coastal wetland degradation leads to a significant decline in ecosystem service values, while (Guan et al., 2024) reveal that long-term urbanization can reduce ecosystem services by up to 25%. These findings suggest that CGOS conversion affects not only ecological aspects but also the economic and social sustainability of coastal communities. In the long term, this decline in ecosystem services may reduce regional resilience to climate change and coastal hazards.

CGOS conversion also exacerbates coastal vulnerability to sea-level rise and coastal flooding. Findings from (Sun et al., 2025) indicate that uncontrolled land-use change can increase flood risk by up to 40%, while (Xu et al., 2024) Highlight that structural measures lacking the backing of natural ecosystems could amplify flood severity by as much as 50%. Thus, coastal management techniques focused on ecosystems are crucial for maintaining a balance between development and environmental sustainability. From a policy standpoint, the findings suggest that the efficacy of coastal management is significantly affected by the quality of governance and inter-regional coordination. Illustrate that a DPSIR (Driver–Pressure–State–Impact-Response) paradigm can bolster ecosystem resilience by as much as 22% via data-informed policy (Han et al., 2025).

Nonetheless, numerous coastal areas continue to encounter difficulties in executing policies, including inadequate enforcement and competing interests between economic growth and environmental protection. (Sa'dia & Fitrady, 2023) further highlight that the development of Special Economic Zones (SEZs) can boost economic growth by up to 12%, but may also threaten coastal ecosystem sustainability if not supported by strong environmental regulations. Moreover, nature-based solutions have emerged as a key strategy for enhancing coastal ecosystem sustainability. (Chávez et al., 2021) Highlight that the incorporation of coastal green infrastructure can enhance storm absorption capacity by as much as 60% and mitigate the effects of coastal squeezing. In addition, (Hilmi et al., 2025) show that blue carbon approaches in mangrove conservation contribute not only to climate change mitigation but also provide economic benefits through carbon credit schemes. These findings suggest that coastal sustainability can be achieved through the integration of ecological and economic dimensions.

Community participation also plays a crucial role in supporting effective coastal management policies. (Ebeler et al., 2025) demonstrate that community-based mangrove restoration can increase local income by up to 30% while reducing flood risk by 50%. Similarly, (Polas et al., 2025) highlight the importance of participatory mapping in identifying degraded areas and restoration potential of up to 35%. These findings indicate that local community involvement can enhance policy effectiveness while strengthening socio-ecological sustainability.

The use of remote sensing technology and biotechnology also provides opportunities to support sustainable coastal management. (Farzanmanesh et al., 2024) Demonstrate that Sentinel-2 satellite imagery can enhance the precision of mangrove biomass monitoring by as much as 92%, thereby establishing a robust foundation for data-informed decision-making. Additionally, (Mamangkey et al., 2021) Disclose that mangrove forests in North Sumatra include biotechnological capabilities for coastal bioremediation. This illustrates that the incorporation of technology can enhance conservation and restoration initiatives.

Sustainability implications are also influenced by geophysical characteristics and regional disaster risks. (Jihad et al., 2020) indicate that coastal areas of North Sumatra are highly vulnerable to tsunamis, making the presence of CGOS essential as part of ecosystem-based mitigation strategies. This is supported by (Chapkanski et al., 2025) who emphasize that coastal geomorphological dynamics are influenced by complex interactions between sea-level rise, sediment supply, and tectonic activity. Therefore, coastal management policies in this region must comprehensively consider these factors.

Table 6. Implications of CGOS Conversion for Sustainability and Coastal Policy

No	Aspect	Key Findings	Policy Implications
1	Coastal protection	Wetlands absorb 70% of storm energy	Ecosystem-based protection
2	Ecosystem services	Significant decline in ecosystem service value	Strengthening conservation
3	Flood risk	Risk increases by 40–50%	Climate change adaptation
4	Green infrastructure	Flood absorption capacity increases by 60%	Integration of CGI in planning
5	Blue carbon	Potential of 15–20 Mg C/ha/year	Carbon schemes and economic incentives
6	Community participation	Income increases by 30%	Community-based management
7	Governance	Resilience increases by 22%	Data-driven policy (DPSIR)
8	Technology	Monitoring accuracy reaches 92%	Strengthening monitoring systems
9	Disaster risk	High tsunami vulnerability	Integration of DRR in spatial planning
10	Economy vs environment	Economic growth vs degradation	Sustainable development policies

Source: Primary data processing, 2021

Overall, the implications of CGOS conversion for coastal ecosystem sustainability highlight the need for integrated, adaptive, and ecosystem-based policy approaches. Coastal management policies should not only focus on controlling land conversion but also on strengthening ecosystem restoration, enhancing community participation, and utilizing technology for monitoring and evaluation. Through such approaches, the long-term sustainability of coastal ecosystems in North Sumatra Province can be maintained.

CONCLUSION

Based on the results of a Systematic Literature Review (SLR) of 25 articles, the conversion of Coastal Green Open Space (CGOS) in the coastal areas of North Sumatra Province is a complex phenomenon influenced by the interaction of anthropogenic, biophysical, and governance factors. The observed conversion patterns can be classified into three main types: rapid conversion in industrial and port areas, gradual conversion in aquaculture and plantation areas, and ecological fragmentation in land–sea transition zones.

This variation indicates that development pressures in coastal regions are uneven and strongly influenced by the economic characteristics and spatial conditions of each district. The primary catalysts for CGOS conversion are primarily influenced by coastal urban development, economic and industrial growth, alterations in land use, climate change impacts, and inadequate policy enforcement.

Urbanization and economic growth are the most dominant drivers of land conversion, while environmental and governance factors act as both reinforcing and limiting elements. The resulting impacts are systemic, including the decline of ecosystem services, increased risks of flooding and coastal disasters, biodiversity degradation, hydrological disruption, and declining environmental quality due to the loss of coastal vegetation.

In addition, comparative analysis reveals significant differences among coastal districts in terms of the intensity and impacts of CGOS conversion. Highly urbanized areas such as Medan and Deli Serdang experience rapid and high-impact conversion, while aquaculture-based regions such as Serdang Bedagai and Batu Bara undergo gradual but cumulative conversion. The implications for sustainability indicate that CGOS conversion reduces the carrying capacity of coastal ecosystems and increases vulnerability to disasters. Therefore, the sustainability of coastal areas is highly dependent on the presence of green open spaces as natural protection systems and ecological buffers.

Coastal management in North Sumatra needs to be directed toward an integrated and ecosystem-based approach through strengthening coastal spatial planning policies, controlling urbanization and industrial expansion, and developing green infrastructure such as mangrove restoration and coastal green belts. In addition, the use of remote sensing technology and geographic information systems

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should be optimized for periodic land-use monitoring, accompanied by improved cross-sector coordination and stronger coastal governance. The involvement of local communities through participatory approaches is also key to supporting successful conservation efforts, while the integration of disaster risk reduction and blue carbon approaches can serve as innovative strategies to balance economic interests with coastal environmental sustainability.

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