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**Coastal Climate Change Adaptation: A Review of Engineering, Nature-Based, Governance,
and Socio-Economic Adaptation Strategies**

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Coastal Climate Change Adaptation: A Review of Engineering, Nature-Based, Governance, and Socio-Economic Adaptation Strategies

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Abstract

Adaptation is becoming a key part of climate policies, including the Paris Agreement, for coastal areas, which host a large proportion of the world's population. Coastal areas are prone to intensive urbanization and tourism, which can exacerbate the threats of sea-level rise, storm intensification, erosion, and saltwater intrusion. Existing reviews have examined engineering, ecological, governance, and socio-economic aspects of coastal system adaptation to climate change, but these studies have generally been limited to a single discipline and offer limited cross-domain information. Such fragmentation can limit their applicability to planners who are interested in context-specific, integrated solutions. This review offers a critical synthesis of engineering, nature-based, governance, and socio-economic adaptation approaches used in coastal areas worldwide. The synthesis suggests that no single adaptation pathway performs uniformly well across settings. Rather, the effectiveness of the strategies depends on asset density, ecological and sediment conditions, governance capacity, and the urgency of the hazard. Hard engineering solutions provide a stable short-term solution in urban environments, but they externalize erosion costs and interfere with natural sediment transport. Nature-based solutions provide greater ecosystem and long-term co-benefits but require specific physical conditions to be achieved, which diminishes their transferability. While governance instruments and socio-economic measures help ensure effective, equitable, and sustainable outcomes, they do not directly provide measurable reductions in risk. The review compares the domains to identify points of overlap, interdependencies between strategies, and implementation challenges unique to each domain, and highlights the lack of standardized evidence across domains as an area for future research. This study focuses on integrated, context-adapted solutions that account for physical, ecological, and institutional dimensions to support sustainable and climate-resilient coastal development amid rapid environmental change.

Keywords: Climate change, SDG, Policy, Adaptation, coastal communities

1. Introduction

Around 40% of the world's population lives within 100 km of the coast. As ecotones, coastal areas are among the most biodiverse regions in the world and contribute to the nation's economy. However, they are vulnerable to climate change risks such as sea level rise, erosion, and submergence. Saltwater intrusion driven by sea-level rise further degrades freshwater resources, affecting both ecosystems and coastal societies. IPCC's Sixth Assessment Report highlights the harsh reality that, without adaptation, coastal flooding is expected to increase in both frequency and intensity by the end of the century (IPCC, [2022](#)). This makes coastal adaptation measures

inevitable and serves as the foundation of global frameworks such as the UNFCCC and the Paris Agreement.

In recent years, anthropogenic activities have greatly contributed to global warming. As the planet's average temperature increases by approximately 1 degree Celsius (NOAA, 2024), glaciers and ice sheets begin to melt, posing the threat of submergence for coastal areas and many island nations as the melting ice caps lead to sea-level rise. The impact of climate change is not limited to a warmer surface temperature; it also includes droughts, heat waves, storms, water scarcity, and wildfires. In Figure 1, some of the significant impacts of climate change on coastal regions are shown. It includes

- Increased frequency and intensity of storms driven by warmer ocean temperatures. (Thomas R. K et al., 2021)
- Coastal erosion, inundation, and saltwater intrusion due to Sea level rise. Globally, sea-level rise will threaten the majority of coastal regions worldwide during the 21st century (Bennet et al., 2023)
- Ocean acidification (Rayhan, 2024)
- Coral bleaching and biodiversity loss (Nabila et al., 2024)
- Vegetation loss and infrastructural damage (Bernardini et al., 2024)

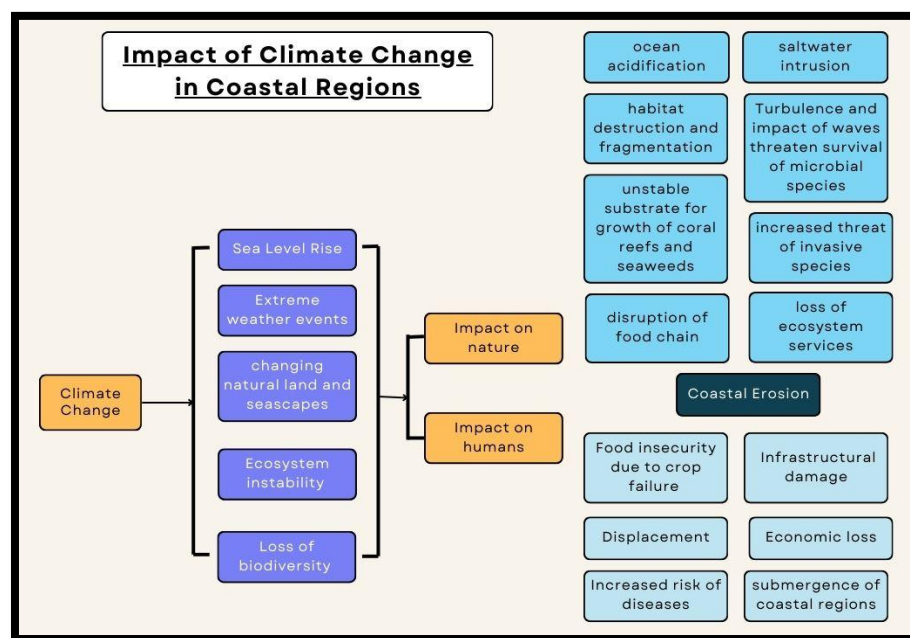


Figure 1: Impact of climate change in coastal regions

While the volume of literature on coastal adaptation has increased, current reviews have tended to explore adaptation strategies through a single disciplinary lens, examining engineering solutions,

ecosystem-based adaptation, governance architectures, or socio-economic aspects in isolation. (Hinkel et al., 2018; Seddon et al., 2020) These assessments tend to be severely limited, failing to account for interactions, complementarities, and trade-offs among adaptation pathways, thereby reducing their value to planners and practitioners seeking to build integrated adaptation strategies. The identified knowledge gaps highlight the necessity for a holistic synthesis that goes beyond a descriptive summary of adaptation strategies to a more analytical assessment. In this context, this review critically synthesizes the strategies that coastal areas around the world have adopted to adapt to climate change, making a holistic analytical effort to include engineering-based, nature-based, governance-based, and socio-economic-based approaches. The review not only presents adaptation measures in isolation but also provides a framework for assessing their effectiveness, implementation challenges, ecological and socio-economic implications, and policy relevance, and identifies examples of complementarities and trade-offs among adaptation measures. It also highlights important research gaps, trends, and future research priorities to advance coastal development that is resilient to climate change. This review will synthesize evidence from multiple adaptation domains to help researchers, practitioners, planners, and policymakers design effective, equitable, and sustainable adaptation strategies for vulnerable coastal areas.

2. Methodology

This review paper adopts a narrative review with thematic synthesis rather than a systematic review or meta-analysis to map and critically synthesize the existing literature on climate change adaptation strategies in coastal regions. As a review, the primary focus was on mining the published literature. In the first step, an extensive search was conducted using academic databases such as Google Scholar with keywords such as "climate change adaptation," "coastal regions," "sea level rise," "coastal erosion," "hard engineering," "nature-based solutions," and then articles published from the year 2002 to 2024 were narrowed down. Articles were selected from credible peer-reviewed sources, reports, and case studies, with inclusion criteria emphasizing relevance to coastal adaptation, empirical data, and comprehensive datasets on the strategies. The identified literature was filtered for relevance and quality, with the next step examining features such as adaptation strategies, implementation methods, effectiveness, challenges, and results. In the third step, the selected publications were reviewed and categorized into five main groups: **a.** hard engineering solutions, **b.** soft engineering and nature-based solutions, **c.** policy and governance approaches, and **d.** socio-economic and **e.** behavioral adaptation measures. The fourth step involved selecting case studies from various regions that displayed successful adaptation practices, with criteria including geographic diversity, adaptation approach, and implementation scale. A qualitative analysis of all the publications was performed in the fifth step to extract relevant information. Finally, the sixth step involved analyzing the results and making statements. This methodology ensured a systematic, thorough, and evidence-based review of climate change adaptation strategies in coastal regions, providing valuable insights and guidance for future efforts.

3. Results

Adaptation Strategies in Coastal Regions

The world's coastal regions include thousands of kilometers of developed beaches, dunes, barrier islands, bluffs, and clifftops, and these areas are threatened by erosion and/or flooding over the next several decades. This is not an individual problem; rather, it affects neighborhoods, towns, houses, Resorts, roads, parking spaces, airports, power stations, sewage treatment plants, pumping stations, electricity pylons, and any other structures built on sandy shores or on the crests of cliffs or bluffs. This challenge affects almost all coastal communities worldwide and is projected to become more frequent and more costly in the future (Chowdhury et al., 2019). The future expected losses will prove to be huge. (Hoggart et al., 2014). Mitigation measures need to be implemented depending on the location, economic inputs, and Environmental Impact Assessment (EIA) requirements. At present, sea-level rise seems more of a distant problem; however, it requires planners to embrace reliable climate change information and consider how coastal communities, innovations, buildings, environments, and other coastal assets are organized. In addition, there needs to be planning to prevent and/or address hazards such as El Niño, hurricanes, and tsunamis.

Some measures to address or mitigate these threats are shown in Figure 2. They are listed below in detail:

1. Hard Engineering Solutions
2. Soft Engineering and Nature-Based Solutions
3. Policy and Governance Approaches
4. Socio-Economic Approaches
5. Behavioral Adaptations

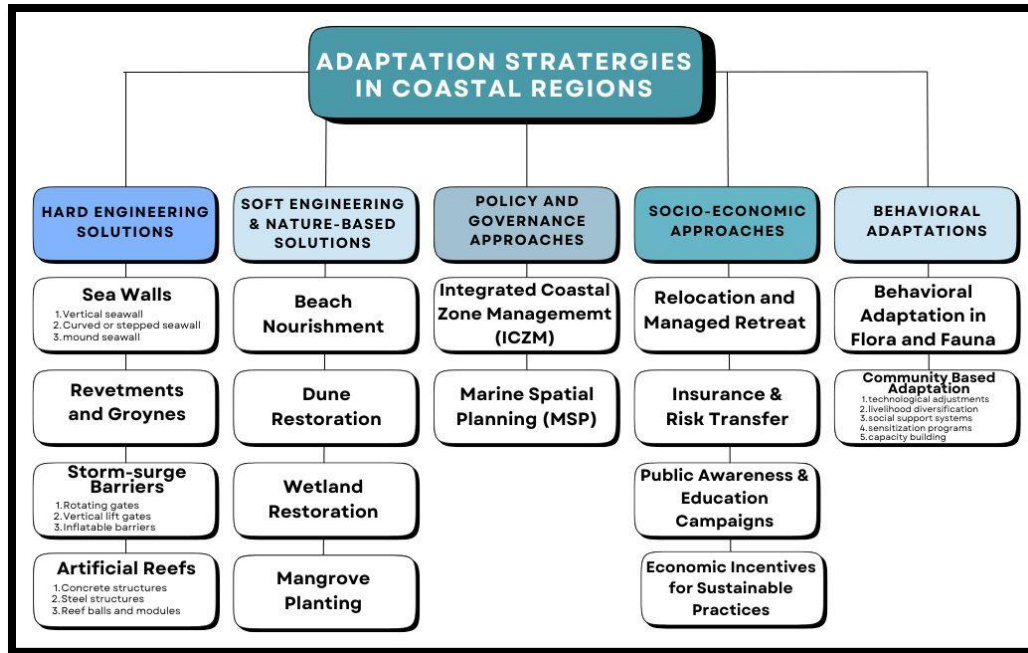


Figure 2: Adaptation Strategies in Coastal Regions- at a glance

3.1. Hard Engineering Solutions

3.1.1. Sea walls

Sea walls are designed to stop shoreline erosion caused by wave action. Sea walls work by reflecting wave energy into the ocean, thus reducing the impact and erosion that beaches can experience. The appropriate seawall design and type depend on the site's characteristics, including surrounding erosion processes. (Karti & Sathya, 2018). Sea walls are substantial, often vertical or near-vertical structures constructed along coastlines to prevent erosion and protect inland areas from flooding due to high tides, storm surges, and waves. These structures are a prominent form of hard engineering used in coastal defense strategies. Sea walls can be made from various materials, including concrete, steel, rocks, and boulders, and are designed to reflect wave energy to the sea, thus mitigating the impact of waves on the shore.

Types of Sea Walls

1. Vertical Sea Walls: These are vertical formations offering a direct defense against wave movements. They are ideal in high-energy conditions where waves are energetic. (Jin et al., 2013).
2. Curved or Stepped Sea Walls: These designs work better in dispersing the energy of waves more so than vertical walls. Forming the coast into a curved or step-like structure changes wave forces

and reduces wave intensity; therefore, the waves do not cause much erosion. (Ranasinghe, et al.,[2012](#))

3. Mound Seawall: Mound-type seawalls are constructed using sheathing or riprap and are used where low-energy erosion working methods are not needed. The lowest-cost options are partitions, sandbags, or geotextile coverings. These are used to armor the beach and reduce erosion and can be impermeable or porous, allowing water to be filtered after wave power has dissipated (Karti & Sathya, [2018](#)).

Sea walls shield coastal infrastructure, homes, and businesses. They have a strong impact on protecting against coastal flooding and erosion (Hinkel et al, [2014](#)). When built and properly maintained, seawalls can last for years and provide long-term protection for coastal areas. These structures provide quick, effective defense against wave action, making them a good fit for places that need immediate protection. Seawalls protect coasts but also disrupt coastal processes and negatively impact local ecosystems. They lead to low-level coastal erosion and alter marine and terrestrial habitats by changing how sediment moves and settles (Dugan et al., [2011](#)). Building and maintaining seawalls is expensive and requires a significant financial commitment. Many coastal communities in developing countries find this challenging. Seawalls also require ongoing maintenance and repairs. Storms can damage them, and daily use wears them down, so they need more investment (Linham & Nicholls, [2012](#)).

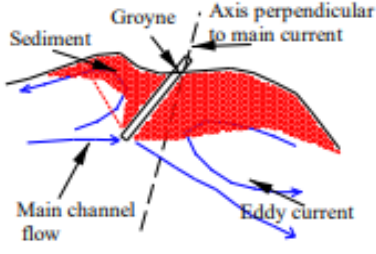
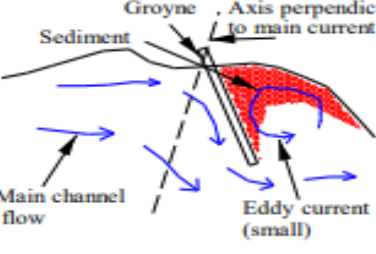
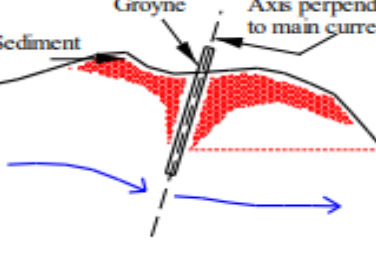
3.1.2. Revetments and groynes

People have implemented coastal protection projects to address coastal erosion and restore eroded beaches. To stabilize the beach, they often install revetments, seawalls, and piers (Ariffin et al., 2019; Rashidi et al., [2021](#)). Bank protection is a slope-front engineering model that people have used since ancient times. The Handbook of Coastal Engineering says that humans have used reclaimed materials to protect sensitive coastal areas since 27 BC, as shown by Vitruvius' classic treatise, Herodotus, Josephus, Suetonius, and the Puppeteer. In addition to protecting beaches, engineers design structures that serve a second purpose, such as parking spaces and pathways that facilitate easy access to beaches, thereby enhancing the local coastal touring experience (Sanitwong-Na-Ayutthaya et al., [2022](#)). It is made from materials like stone, concrete, or geotextile and designed to stop coastal erosion and protect coastal areas. The coating soaks up and disperses wave energy, reducing the impact on the coastline (French, [2011](#)). Some coastal practitioners agree that revetments enhance beach aesthetics (Sanitwong-Na-Ayutthaya et al., [2022](#)). Some, however, consider them eyesores (Griggs & Patsch, [2019](#)). Further, observations indicate that repairing aged revetment and topping it with a new pedestrian walkway is preferred. This promotes recreational activity. It also enhances the aesthetic view. Additionally, revetments could create new opportunities for fishing and tourism, enhancing local economies.

Groynes are structures constructed at an angle to the flow to deflect flowing water away from critical zones. They are made of stone, gravel, rock, earth, or piles. These begin at the

riverbank with a root and end at the regulation line with a head. They serve to maintain a desirable channel for flood control. Improved navigation and erosion control are also achieved (Yossef M., 2002). Groynes may have a negative visual effect, and as they prevent the transportation of sediment to beaches further down the coast, they may indirectly aid in erosion in those beaches. Table 1 shows the orientation of groynes and their advantages.

Table 1 - Groyne Orientation (King, Hans, 2009).

Groyne Orientation	Sketch	Advantages
Groyne Pointing upstream		• Attracts silts upstream and downstream of the structure • Pushes the main current away from bank • Has great potential for scour head at the head
Groyne pointing downstream		• Attracts only silt downstream of the structure • Does not form much eddy current and pulls the main current to the bank • Has relatively low potential for scour at the head • Definitely not recommended for concave bend
Groyne perpendicular to flow direction.		• Groyne attracts moderate amounts of sediment upstream and downstream • Keeps current more or less parallel to the bank • Has medium potential for scour at the head

3.1.3. Storm surge barriers

Storm surge barriers, as their name suggests, are intended for shielding coastal regions from the destructive force of storm surges and tidal bores. These are blown shut during storms. This helps ensure that seawater does not reach the hinterland. This has been considered an important component in coastal protection measures. Such approaches are essential in areas

vulnerable to the effects of climate change. Consequently, threats such as rising sea levels (Mooyaart Leslie et al. [2023](#)). That said, these structures are suspended in water and may therefore hinder the travel pathways of marine organisms and alter water salinity and temperature.

Types of Storm Surge Barriers

- (i) **Rotating Gates:** These gates rotate to close off waterways during storm surges. An example is the Maeslantkering in the Netherlands. This structure protects Rotterdam and the surrounding areas. Rotating gates pivot into position to block the flow of water during storm surges. They are typically used in wide waterways where a single large barrier can be more effective than multiple smaller ones. The Maeslantkering consists of two massive gates that swing into place during high-risk events. When not in use, these gates are stored in special docks. This allows for unimpeded navigation and water flow (Aerts et al. [2014](#)).
- (ii) **Vertical Lift Gates:** These gates are lifted vertically to block water during high tides or storm surges. Vertical lift gates rise from the seabed to form a barrier against storm surges. The Thames Barrier consists of ten steel gates. These can be raised within 30 minutes. Each gate is supported by concrete piers. The piers house the machinery required to operate the gates. This design ensures the barrier can be quickly deployed to protect London from flooding while allowing for normal river traffic when not in use (Haigh et al. [2016](#)).
- (iii) **Inflatable Barriers:** Made from flexible materials, these barriers can be inflated to provide temporary flood protection and deflated when not in use. They are suitable for areas where permanent structures may not be feasible. Inflatable barriers are an innovative solution for temporary flood protection. These barriers can be rapidly deployed. They are particularly useful in urban areas. Space constraints there prevent the construction of permanent barriers. When a storm surge is imminent. The barriers are inflated with air or water to form a robust defense. After the threat has been overcome, they deflate and are stored away. This minimizes their impact on the environment and urban landscape (Nicholls & Tol, [2006](#))

Storm surge barriers, therefore, must be capable of withstanding the pressure and force of storm surges. They provide a dependable security measure or line of protection. These barriers also help to control the invasion of seawater into coastal areas, protecting residential areas, critical infrastructure, and natural ecosystems from devastating effects. For instance, the Thames Barrier has protected the London area from flooding more than once. This goes to illustrate why structures of such nature are effective. These reduce flood impacts and demonstrate the limit of flood reduction (Kates et al, [2006](#)). Structurally, storm surge barriers are highly flexible because of the operational flexibility inherent in them. They respond to different environmental conditions. Where there is no risk of flooding, the barriers remain down. This is possible by allowing the water to flow freely without any hindrance. Navigation is also helped, and it guarantees that these barriers do not disrupt the normal lighting of maritime operations. They also help maintain the ecological balance of waterways (Nicholls et al. [2011](#)).

The justification for the costs of constructing storm surge barriers includes initial expenses such as design, materials, construction, and technology costs. Estimates for the construction of the Thames Barrier were approximately £534 million. The current dollar assembly costs of the Thames Barrier are estimated at about £1.6 billion (Booth et al. 2018). By preventing seawater from inundating coastal areas, these barriers protect residential areas, critical infrastructure, and natural habitats from severe damage. They have protected London from flooding on multiple occasions. While this demonstrates the effectiveness of such structures, it can't be denied that this could be very expensive for developing countryside regions, and a developing region may need government or international funding to build a barrier (Kates et al., 2006; Temmerman & Kirwan, 2015).

3.1.4. Artificial reefs

Artificial reefs are structures placed underwater to mimic the features of natural reefs. What is artfully achieved in building these underwater structures is that they serve multiple functions: enhancing marine biodiversity, providing habitat for marine organisms, protecting the coasts from erosion, and aiding both leisure and industrial fishing. They are made from various materials, specifically from reef balls, which are mainly designed to mimic a reef in an area, as well as concrete and metal. These are placed in locations where, if possible, natural reefs are damaged or the habitat is insufficient to attract marine life.

Types of Artificial Reefs

- (i) **Concrete Structures:** Concrete systems are desired for their durability and structural integrity. They may be prefabricated in numerous styles and sizes, allowing for personalization to meet the needs of the marine environment. Concrete is likewise pH-neutral, which prevents any detrimental effects on the encircling water chemistry (Broughton, 2012).
- (ii) **Steel Structures:** Decommissioned ships, subway cars, and other massive steel items are frequently repurposed as synthetic reefs. These structures offer a tremendous surface area for marine organisms to colonize. Steel structures are ideal for creating large, complex habitats that attract a wide variety of marine species. Ships and other huge objects provide diverse habitats, promoting biodiversity. However, careful instruction is vital to remove any hazardous materials before sinking (Walker et al., 2009).
- (iii) **Reef Balls and Modules:** These specially designed systems are crafted from environmentally friendly materials and are fashioned to offer ultimate habitats for marine life. Reef balls are commonly used in artificial reef initiatives due to their effectiveness and simplicity of deployment. Reef balls and modules are engineered to provide optimal conditions for coral and fish colonization. They feature numerous holes and crevices that mimic the complexity of natural reefs, supplying refuge and

breeding grounds for marine organisms. These structures are often used in restoration projects to rehabilitate degraded reef areas (Barile, [2008](#)).

Anchored artificial reefs are now seen as having a promising role as dynamic ecosystem habitats, supporting diverse fish and coral communities as well as invertebrate species. These man-made structures increase the carrying capacity of species that require structurally complex habitats; assist in the recolonization of fish stocks; and provide protection and resources for exploitation, nesting, or breeding for the Yangtze sturgeon and other important species. For many marine species, these resources are required for existence and reproduction. Studies show that properly designed artificial reefs and their placement can support sustainable levels of species diversity similar to those of live reefs and may therefore be used effectively to supplement marine conservation efforts (Bohnsack & Sutherland, [2014](#)).

However, apart from their ecological value, artificial reefs also greatly contribute to coastal defense. They essentially suck energy out of incoming waves, acting like submerged barriers that prevent coastlines from eroding and protect shore structures. Thus, floating artificial reefs minimize the effects of hurricane surges and large waves that cause coastal erosion and damage to shore properties. Therefore, artificial reefs are not only a protective body for marine ecological systems, but they also serve people's protective purposes with a balancing effect; as a result, it is a two-in-one advantage (Ferrario et al., [2014](#)). But solutions are not always free of faults. Artificial reefs also have some consequences. While it is obvious that these structures can become sources of marine debris if they are poorly constructed or sited, they can also unintentionally modify local currents as they degrade over time. Such outcomes could disrupt important environmental systems, such as natural habitats for animals and plants, and increase negative scores for other natural consequences of the activity. The structure, materials, and placement of artificial reefs need to be carefully chosen so that they blend in with their environment. Risk mitigation through detailed environmental impact assessments and the use of sustainable materials is critical (Pickering & Whitmarsh, 2013). For this reason, artificial reefs require not only proper implementation but also ongoing care and maintenance to remain functional over an extended period. This puts the authorities in a better position to determine when damage or deterioration results from external forces (Sherman & Spieler, [2013](#)).

3.2. Soft Engineering and Nature-Based Solutions

3.2.1. Beach nourishment

Beach nourishment, also known as beach replenishment or beach fill, is a coastal management technique in which large amounts of sand or sediment are placed on eroding beaches. The process mitigates shoreline erosion, widens beaches, and prevents damage to coastal infrastructure from storms and rising sea levels. It is a widely used measure for the maintenance and restoration of the natural appearance and recreational value of beaches, as well as for providing

critical habitat for coastal ecosystems. Beach nourishment requires that the first step be to identify suitable sediment sources. These sources are offshore dredging sites, riverbeds, or inland quarries. For the sediment to be compatible and sustainable, it should be similar in grain size, composition, and color to the native beach material (Dean & Dalrymple, 2004). Therefore, its characteristics need to be similar to those of the original place. Once a suitable source for the sediment is identified, the sediment is extracted from it and transported to the nourishment site. Dredging, which typically uses specialized equipment designed to scoop or vacuum sediment from the site, is usually the course taken. Afterward, the sediment is conveyed to the beach by pipelines, barges, or trucks (de Schipper et al., 2021). At the nourishment site, the sediment is pumped or placed on the beach and spread to the desired profile. Bulldozers and other heavy equipment grade and reshape the new beach material to its natural slope and contour (Elko & Briggs, 2020). After the sediment is placed, nourished beaches are monitored for performance and environmental impacts. Monitoring through periodic questionnaires and surveys would indicate variations in beach width, sediment distribution, and health parameters of the beach ecosystem. Further maintenance might include additional nourishment to address any erosion or other issues that may have occurred (Hinkel & Nicholls, 2018). Beach nourishment is a highly effective way to address shoreline erosion by increasing beach width and sediment volume. A buffer zone will naturally absorb wave energy, reducing storm and high-tide action.

This, in turn, will better protect coastal properties and infrastructure while also aiding the natural process of sediment transport. Further, it can reduce the impacts of storms on coastal communities by reducing property damage and enhancing public safety through increased beach width and elevation (Hanson et al., 2002). This becomes particularly important in areas prone to hurricanes, typhoons, and other extreme weather events. One major constraint to implementing beach nourishment projects is their high cost. This may be provided from federal, state, and local government budgets, as well as from private-sector sources and through public-private partnerships. Cost-benefit analyses are often undertaken to justify the investment and pinpoint the most cost-effective approaches (Brown & McLachlan, 2019). As the sea level rises, it consumes part of the beach. Replenishment of the beach with additional sand slows the rate of coastal erosion and its detrimental side effects.

3.2.2. Dune restoration

Dunes have emerged as a management strategy for addressing the dangers posed by erosion, storm surge, and sea-level rise. Coastal dunes, hence, provide some measure of protection to manmade structures and other coastal features. Not only do they safeguard these exceptionally sensitive zones, but dunes are also host to numerous other kinds of plants and animals. The restoration methods used here are similar to those used in dune stabilization and in improving vegetation and associated ecosystem services.

Dunes are significant in coastal defense because they act as a barrier that will decrease storm surge and shoreline erosion. Therefore, they safeguard access to the coastline, particularly against high water levels and often storms, while also helping preserve sustainable landscapes and buildings. Apart from protecting the inland area, the dunes also protect dune vegetation and other inland plants from the dangers of strong winds and water action (Hesp, 2013). Namely, apart from erosion control, dune ecosystems have some special functions: subordinate functions of special plant species. Halophytes stabilize sand and serve as a microcosm and breeding ground for birds, insects, rodents, and other species. They provide nourishment to coastal systems to increase their efficiency in coastal regions (Maun & Perumal, 2018).

Stabilization of dunes can be started by planting natural vegetation such as beach grasses (*Ammophila* species), shrubs, and other trees. The massive plants, due to their expansive root structures, prevent sand sedimentation by reducing wind speed and also provide a rest stop for wildlife (Brown & McLachlan, 2002). Recommendations often focus on species that can tolerate coastal conditions, including salt spray and wind. In addition to stabilizing dunes, sand fences and biodegradable geotextiles are installed to reduce sand accumulation, thereby creating more dunes. Sand fences function by reducing wind velocity at the base, causing sand particles to turn and deposit along the fence lines. It facilitates dune building, especially in regions vulnerable to wind strength (Cooper, 2008).

Reconstructed dunes increase height and volume as they receive additional beach sand, thereby presenting a greater barrier to erosion by coastal currents and storms. Sand used for rebuilding dunes may be collected from the seabed or other locations and then effectively deployed on site to coax natural dune-formation processes and support plant life. Besides reinforcing dune profiles, the method advances the overall resistance of coastal areas (Dugan & Hubbard, 2010). Therefore, restored dunes reduce wave energy and the degree of exposure to storm surges, and mitigate the threat of flooding and coastal erosion. They serve as an even stronger shield for interior land areas and structures against wave impacts that trigger storm effects. They also help stabilize beach profiles, protecting shorelines from problems such as high sea levels. Moreover, climate-resistant dunes provide several ecosystem services, namely carbon storage, water recharge, and species support, to act as an investment in sustainable coastal development and climate change adaptation (Barbier et al., 2011)

3.2.3. Wetland restoration

Wetland restoration is the process of rehabilitating natural wetland ecosystems that have been degraded or lost due to human activities such as urbanization, agriculture, and drainage. These important ecosystems- marshes, swamps, and bogs have other important uses such as floodwater management, water purification, carbon storage, and support of additional plant and animal life. The main objectives of wetlands restoration are enhancing water quality, adding species, and making ecosystems more resistant to disturbances; promoting sustainable

development and assisting communities in addressing the impacts of climate change (Smith & Johnson, 2013). So, the primary function of wetlands is to remove nutrients and pollutants from the surface water. A study shows that wetland plants and soils can filter nitrogen and phosphorus, thereby reducing water pollution in rivers, lakes, and coastal areas. This filtration also helps improve downstream water quality, benefiting fisheries and offering better opportunities for fishing and bird watching, among other recreational activities (Craft et al., 2009).

Last but not least important function of wetlands is flood control. They hold large amounts of water that would otherwise cause downstream flooding during and after the rainy season, then slowly release it. This regulation helps mitigate flood risks for those living and working in flat areas by retaining water in its location so it does not flow downstream, carrying jobs with it as it erodes land. Besides flood control, wetlands play an important role in maintaining the water table, making them important in water resource management in riverine and coastal basins (Keddy et al., 2010).

3.2.4. Mangrove planting

Mangrove plantation refers to the deliberate planting of mangroves in degraded coastal or estuarine areas with the specific aim of replacing losses in these ecosystems, replenishing lost mangrove cover in marine and aquatic habitats, and preventing future costly losses from erosion and storm surges. Those trees and shrubs are likely suited to high-salinity conditions, as they produce fruit in the intertidal zone and many have uses in coastal environments. Besides, mangroves are expected to improve energy from waves and protect coasts, and to serve as the foundation for coastal estates and construction; they also provide protection from calamities and tidal booms (Alongi, 2008).

The uses of mangroves include the following: trapping of sediments, erosion barrier and habitat for various species. Their connected-rhizosphere structure allows them to hold onto sediments, thus acting as barriers or buffer zones for coastal areas. Therefore, as the cost breakdown shows, mangrove plantations are a more economical and much more sustainable land use than seawalls or revetments. They also reduce nutrient concentrations in seawater, thereby improving water quality and clarity (Friess & Webb, 2014). The advantages of mangrove forests are not only associated with the preservation of certain coastal zones, but also with the marine environment in general; they offer the equally valuable double benefit of increasing the ecosystem and community defensive capacity that are the Alpha and Omega of coastal defense. Leading to the development of resilient coastal ecosystems. (Lewis III, R. R., 2005).

3.3. Policy and Governance Approaches

3.3.1. Integrated Coastal Zone Management (ICZM)

Many have regarded ICZM as a powerful tool for climate change adaptation in coastal zones, as it is holistic, integrative, and adaptive. ICZM takes into account these complex interactions between land and sea, enabling management that accounts for the ever-changing coastal zones. Thousands of farmers have adopted a holistic approach that emphasizes ecosystem health and fortifies against the impacts of climate change. It conserves and rehabilitates natural habitats, such as mangroves, coral reefs, and wetlands that impart critical functions, including coastal protection, carbon sequestration, and water purification. For instance, in the Philippines, more successful efforts at mangrove rehabilitation have been under ICZM auspices (Supsup et al. [2023](#)). These efforts have greatly increased coastal resistance to storm surges and rising sea levels, while ensuring the provision of goods and services through local support and participation. (Cruz-Trinidad et al., [2009](#)).

One of the most notable features of ICZM is its focus on stakeholder participation. This process brings together community, government, private sector, and NGO stakeholders in a decision-making platform. That involvement of a wide range of stakeholders brings with it a vast array of views and experience to the process of coastal management—the result: adaptation strategies which are locally attuned and culturally relevant. In this way, Integrated Coastal Zone Management makes these strategies more efficient and, hence, more sustainable. One example can be found in the Community-Based Adaptation projects developed in Bangladesh under the ICZM framework. By intervening, these measures have minimized vulnerability to climate-induced flooding and, at the same time, enhanced agricultural productivity, leading to considerable improvements in the livelihoods of local populations (Huq & Rabbani, [2022](#)).

3.3.2. MSP (Marine Spatial Planning)

Marine Spatial Planning (MSP) is an important tool for planning the spatial distribution of marine space and uses throughout sectors, overlapping ecological, economic, and social considerations. The European Union's Marine Spatial Planning Directive—aimed at balancing economic and environmental uses, such as shipping, fishing, and energy production, with the sustainability of Europe's marine waters—required that environmental considerations be included in maritime planning efforts. It requires European countries to integrate climate impacts, including sea-level rise, ocean acidification, and biodiversity loss, into their maritime spatial planning. Through such measures, which include these seven key factors, the EU is working to build back better for nature and people by supporting the recovery of healthy marine ecosystems within a framework of responsible use (European Commission, [2021](#)).

Across the Atlantic Ocean in the United States, the National Oceanic and Atmospheric Administration (NOAA) sets out to plan. NOAA incorporates climate change adaptation components in ocean management by utilizing tools and information to assess vulnerabilities and implement adaptive responses along coastal areas. In areas like the Gulf Coast region, work focuses on ensuring climate change adaptation to address threats from rising sea levels, hurricanes,

and coastal erosion. NOAA collaborates with myriad government agencies at various levels to plan and jointly administer planning and management of aquatic resources in an effort to ensure a sustained, productive, and responsible use of ocean resources (NOAA Report, [2023](#)).

In Canada, Fisheries and Oceans Canada (DFO) has a relevant planning scope focused on ocean management, with an emphasis on Maritime Spatial Planning (MSP) to ensure marine activities while protecting and safeguarding biodiversity and supporting adaptations to climate change. An important aspect of MSP planning initiated by Canada incorporates indigenous knowledge and understandings, along with public dissemination and input, to inform decisions regarding marine resource use and conservation measures, and to prioritize local priorities. In regions like the Gulf Coast, work focuses on making the best investments to enhance climate resilience to sea-level rise, hurricanes, and coastal erosion (Fisheries and Oceans Canada, 2019; Fisheries and Oceans Canada, 2024).

3.4 Socio-Economic Approaches

Climate change poses significant threats to coastal regions, necessitating comprehensive adaptation strategies. Socio-economic approaches are crucial in addressing these challenges, as they integrate social, economic, and environmental considerations.

3.4.1. Relocation and Managed Retreat

Relocation and managed retreat entail the strategic relocation of communities and infrastructure from vulnerable coastal areas. This decision to move can be made either when protection is too expensive or when the risk to human life and property is considered too great. Managed retreat is a highly contested and potentially complex process. Proper planning with the community, at least, is crucial.

- Community Participation: The affected communities should be involved in decision-making to ensure that their concerns and preferences are taken into consideration.
- Economic Incentives: This involves the use of financial aid and other incentives to help in relocation and compensate for losses.
- Restoration and Creation: Restoring natural habitats in vacated areas, enhancing coastal resilience and biodiversity. Examples of successful managed retreat exist in places like New Zealand, where the government has already developed policies to withdraw communities from high-risk coastal areas.

Whereas relocation has succeeded in some communities, the challenges include attachment to place, the possibility of losing one's livelihood, lack of finance, limited access to suitable land, community support, and governance processes. (Dannenberget al. 2019)

3.4.2. Public Awareness and Education Campaigns

Public awareness and education campaigns are essential for fostering a culture of resilience and preparedness in coastal regions. These campaigns aim to inform and empower communities to take proactive measures in adapting to climate change. Organizing workshops and training sessions to educate residents about climate risks and adaptation strategies, utilizing various media platforms to disseminate information and raise awareness about climate change impacts and adaptation measures, and integrating climate change education into school curricula to build a knowledgeable and proactive future generation are some ways to increase public awareness.

Effective public awareness campaigns have been implemented in countries like Bangladesh, where community-based education programs have significantly improved disaster preparedness. Effective communication on climate change is essential to raising public understanding and awareness, which will boost participation in climate policy and ultimately lead to better policies and results. Numerous studies show that awareness and knowledge of climate hazards are strongly correlated with active participation, and that engagement can positively influence behavior and alter attitudes. Passive engagement is also significantly hampered by ignorance and a lack of awareness. (Khatibiet al. 2021)

3.4.3. Economic Incentives for Sustainable Practices

Economic incentives are a strong impetus to sustainable practices that strengthen the resilience of coastal regions. They inspire people, businesses, and governments to adopt environmentally friendly, climate-resilient behaviors. The following are some of the incentives that can be used to promote change in behavior towards the adoption of sustainable green growth practices:

- **Subsidies and Grants:** Offer financial support for sustainable projects like renewable energy installations and green infrastructure.
- **Tax Incentives:** Offered in the form of tax breaks and credits for activities that reduce carbon emissions and enhance climate resilience.

Incentivizing reductions in greenhouse emissions by introducing mechanisms that include carbon pricing and trading. Economic incentives are used in many countries, such as Denmark and the Netherlands, to encourage practices that enhance resilience in their coastal regions. According to a study by Kijewski et al. (2023), homeowners who believe that adaptation measures increase the market value of their properties are more likely to adopt climate change adaptation measures in their homes. Also, they have a higher likelihood of having more potent intentions to spend on future modifications, and a larger proportion have upgraded aspects of their homes since purchase.

Although affected by perceived affordability, this upgrading behavior does not seem to be related to those users' long-term goals.

3.5 Behavioral Adaptations

Climate change poses significant challenges to coastal regions, affecting both natural ecosystems and human communities. Behavioral adaptations are crucial for mitigating these impacts and ensuring the resilience of coastal areas.

3.5.1. Behavioral Adaptations in Flora and Fauna

Flora and fauna in coastal regions exhibit various behavioral adaptations to cope with the changing climate. These adaptations are essential for their survival and the maintenance of ecosystem services.

(a) Flora:

Phenological Shifts: Many plant species are altering their phenological events, such as flowering and fruiting times, to align with changing climatic conditions. For instance, some coastal plants are flowering earlier in the season to avoid the peak of summer heat. (Berman et al., 2020). Philadelphia Fleabane (*Erigeron philadelphicus*) is one such example.

Seed Dispersal Mechanisms: Coastal plants are adapting their seed dispersal strategies to ensure successful reproduction. Some species are developing mechanisms to disperse seeds over longer distances to colonize new areas with favorable conditions. Global climate change may negatively affect the seed dispersal patterns of vertebrate-dispersed plants, potentially influencing the fate of local and global biodiversity. These changes could be caused by shifts in air temperature, rainfall, wind speed, the biophysical environment (such as habitat quality and fruit availability), and plant/seed traits. (Hernandez, et al., 2023)

Salt Tolerance: With rising sea levels and increased salinity, certain coastal plants are evolving to become more salt-tolerant. On the other hand, the coastal vegetation that is not as salt-tolerant seems to be declining in number. An example as per the study led by Marcelo Ardón of NC State, Professors Justin Wright and Emily Bernhardt of Duke University. Two vegetation studies on the Albemarle-Pamlico Peninsula were carried out by the researchers. Regarding soil salt levels, they noted the locations and abundances of 112 understory plant species in the area. It was observed that, above the first critical threshold (265 g Na⁺/g), the plant community on the marsh floor suddenly shifts, as plants such as wax myrtle, swamp bay, and pennywort are replaced by rushes, reeds, and other plants that can better tolerate salty soils. (Anderson et al., 2022)

(b) Fauna:

Buchholz et al. (2019) have mentioned that an important determinant of the resilience of animal species to a rapidly changing global climate is behavioral traits. Many coastal animal species are adjusting their migration patterns in response to changing temperatures and food availability. For example, some bird species are migrating earlier or later than usual to coincide with the availability of food resources. (Reed et al., 2022)

Habitat Utilization: Coastal animals are modifying their habitat use to avoid extreme weather events and rising sea levels. Marine species, such as fish and crustaceans, are moving to deeper waters to escape warmer surface temperatures.

Reproductive Strategies: Some coastal faunae are changing their reproductive behaviors to enhance the survival of their offspring. For instance, certain fish species are spawning in different locations or at different times to avoid unfavorable conditions. Animals may alter their breeding and nesting behaviors to ensure the survival of their offspring. This can include changing nesting sites or timing reproductive cycles to avoid extreme weather events.

Dietary Adjustments: Some species adapt their diets to cope with changes in the availability of food sources. This flexibility can be crucial for survival in changing ecosystems.

3.5.2. Behavioral Adaptations in Human Communities: Human communities in coastal regions are adopting various behavioral adaptations to cope with the impacts of climate change. These adaptations are crucial for safeguarding livelihoods, infrastructure, and overall well-being. The type of exposure, the associated hazards, the socioeconomic and environmental determinants for the population and individual (e.g., age, gender, water coverage, sanitation, and hygiene systems), and the ability of health systems to protect against present and the future risks are just a few of the variables that affect the health of human communities (UN (2002); WHO (2015)). Undoubtedly, certain groups face disproportionate disadvantages when it comes to adapting to climate change, and they may also be more susceptible to stress-related psychopathological reactions and/or diseases. (Gamble et al. 2016) because of their geographic location (coasts, hurricane-prone areas, heat-wave-prone areas), their participation in climate-sensitive activities (pasture, fishing, agriculture, aquaculture), or their survival on natural resources and ecosystem services.

Successful adaptation planning in coastal communities requires an understanding of the local causes of climate change as well as its present and future effects (Metcalf et al. 2015).

4. Discussion

The evidence that has been synthesized in section 3 does not represent the existence of any single, best strategy for adaptation. It indicates that the optimal domain is systematically determined by

asset density and value, sediment and ecological context, governance capacity, and the degree of hazard urgency.

Firstly, hard engineering provides the absolute certainty of short-term protection in high asset-density urban shorelines exposed to near-term storm surge or flood risk, and where the cost of failure (e.g. another Katrina-like storm event) is many times more costly than construction, even within the scale of the Thames Barrier or Maeslantkering (Haigh, I. D, et al. 2016). This certainty comes with a cost beyond capital expenditure: hard structures reflect rather than absorb wave energy, thereby disrupting longshore sediment transport and displacing erosion to neighboring unprotected shorelines rather than stopping it (Linham & Nicholls, 2012). The evidence base for the domain is also its least extensive: most of the cases are high-income, high-density urban centers (London, Rotterdam, coastal regions of the Netherlands), so confidence in the applicability of its cost-benefit logic to lower-density or lower-income settings, where future coastal population growth is likely to occur, is limited (Cabana et al., 2023).

Second, and importantly, measures that rely on natural or soft engineering present long-run cost trajectories and ecological benefits such as carbon sequestration, habitat provision, and fisheries support, yet, because of their context-dependency, their efficacy is far more context-dependent than that of hard engineering (Hesp, 2013). Sediment availability, available land, and time to allow for vegetative and geomorphic systems to establish are all necessary for mangrove and wetland restoration, dune stabilization, or nourishment, at which time they generally do less well than their often-mentioned potential. This is a critical aspect of nature-based solutions: their comparative advantage is conditional on physical context, not universal.

Third, the governance instruments, most prominently Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP), are not adaptation measures, but mechanisms for coordination. This distinction is more important than what the current literature suggests. There is overwhelming evidence for the processes of ICZM and MSP – stakeholders were brought together, plans were adopted, and cross-sectoral coordination was strengthened (Alves et al., 2013). It is not a typical outcome evidence, as hard engineering and nature-based solution studies report outcomes such as reduction in flood area, erosion rate, or economic loss. Governance case studies from the Philippines, Bangladesh, the EU, and Scotland indicate that governance mechanisms can facilitate more effective and equitable implementation in the case of integration with other measures such as seawalls or storm-surge barriers (Supsup et al., 2023; Huq & Rabbani, 2022; European Commission, 2021; Marine Scotland, 2022). However, this review finds no case in the synthesized literature in which governance instruments were evaluated alone. Comparing governance and structural components in a single-ranked comparison oversimplifies the evidence.

Finally, the category of socio-economic and behavioral tools, including managed retreat, risk transfer, public awareness campaigns, and economic incentives, is highly contextual due to its

costs and benefits. Thus, socio-economic measures should not be viewed as a substitute for, but rather as an addition to, other areas, and this additional support is best provided together with the financing and institutional capacity that governance instruments are supposed to deliver. However, the adaptation policies should consider equity, inclusive decision-making, and accessible financial mechanisms to ensure that climate resilience benefits all sectors of society (Bill-Weilandt et al., 2026).

Overall, this review shows that climate-resilient coastal development cannot rely solely on engineering or other solutions. So, instead, we should opt for an integrated system that combines physical protection, ecosystem conservation, effective governance, and socio-economic resilience to combat coastal hazards for climate change adaptation. In Table 2 below, this trade-off is explicitly shown by scoring each domain against the same criteria applied in Section 3.

Table 2. Comparative analysis of adaptation strategies

Criteria	Hard Engineering Solutions	Nature-based Solutions	Governance (ICZM, MSP)	Socio-economic/behavioral
Effectiveness	High	Moderate (context-dependent)	Indirect	Indirect / risk-shifting
Capital cost	High to very high	Low to moderate	Low	Low to moderate (Distributional cost, eg, community relocation)
Ecological impact	Frequently negative (habitat loss, sediment interruption, etc)	Frequently positive	Neutral to positive (framework-dependent)	Neutral
Reversibility	Low	Moderate to high	High	Context dependent (Depends on factors like awareness, incentives)
Equity / Distributional effect	Externalizes erosion elsewhere	Generally favourable where implemented	Depends on the inclusiveness of the process	Frequently regressive unless deliberately designed otherwise
Evidence	High (outcome-based)	Moderate (outcome-based,	Low (framework-dependent)	Moderate (outcome-based for retreat; weaker for

		narrower geography)		awareness/incentive effectiveness)
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5. Conclusion

This review aimed to compare the approaches across engineering, nature-based, governance and socio-economic domains using a common evaluative framework, rather than cataloguing them in isolation. The key conclusion is that there is no single universal adaptation solution, since strategy performance depends on asset density, ecological and sediment context, and governance capacity, and integrated approaches require defined trade-offs, intended benefits defined and contexts. While hard engineering solutions provide the best short-term protection, they externalise the costs of erosion and have a very high ecological and capital cost, nature-based solutions provide superior co-benefits in terms of costs and ecological outcomes, but suffer from a lack of physical preconditions, governance instruments coordinate and enable adaptation while they do not provide measurable risk reduction, and socio-economic instruments are essential complements and distributional costs must be deliberately designed to avoid disproportionate impacts on those least able to bear them.

The significance of the study lies in its holistic approach, which aligns with the growing global recognition of the need for a combination of infrastructure and nature-based solutions to address coastal climate change adaptation. However, there are some limitations to this review. It takes a narrative synthesis approach rather than a systematic or meta-analytic one, because the different types of evidence across the four domains are highly variable. The synthesis is limited to the English-language literature and selected institutional reports and may have overlooked relevant regional studies and grey literature. In addition, while the review is conducted using a structured synthesis approach, differences in study design, geographical setting, and assessment techniques across the literature preclude direct comparisons between types of adaptations.

The way ahead would be a climate change plan that looks to adhere to the expected changes in the next 100 years and not only the imminent future. An urgent need to develop comprehensive coastal adaptation measures to deal with the effects of climate change is the need of the hour. Low-lying coastal areas, natural resources, human settlements, and animal and plant life are at great risk from flooding and storm surges as sea levels rise, coastal areas are eroded, and storms become severe. It is thus important to strike the right mix of engineering solutions - sea walls, storm surge barriers and natural measures-beach nourishment, dune restoration, and wetland conservation, etc. The adopted guidelines would not only safeguard such installations but also ensure consistency in the management of biological assets, helping mitigate climate effects. However, certain issues are yet to be addressed; some of them are as follows. The major problem affecting the implementation of such projects is financial constraints, especially in the developing world. Therefore, there are

policy gaps, coordination problems, and a lack of community participation, which may extend the time required or worsen the adaptation process. The effects of climate are also ambiguous; therefore, strategies for handling climate are highly dynamic and responsive to change. Lastly, this review calls for global cooperation and the development of innovative approaches to coastal adaptations. It is possible to suggest that the application of environmental, social, and economic measures in the sphere of coastal region protection can promote the formation of a sustainable future for coastal territories, ecosystems, and human settlements.

Ethics approval: The work is an independent review work and meets the required legal, professional, and moral standards. The authors have not used any generative AI tools in the research, writing, or editing of this work. All content has been created independently

Consent to participate: The authors confirm that written or verbal informed consent was obtained from all participants before the study started

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