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Review

Coastal Restoration Challenges and Strategies for Small Island Developing States in the Face of Sea Level Rise and Climate Change

Edwin A. Hernández-Delgado [1,2,3]

[1] Interdisciplinary Studies Program, Faculty of Natural Sciences, University of Puerto Rico, San Juan 00925-2537, Puerto Rico; edwinhernandez@sampr.org
[2] Center for Applied Tropical Ecology and Conservation, University of Puerto Rico, San Juan 00925-2537, Puerto Rico
[3] Sociedad Ambiente Marino, San Juan 00931-2158, Puerto Rico

Abstract: The climate crisis poses a grave threat to numerous small island developing states (SIDS), intensifying risks from extreme weather events and sea level rise (SLR). This vulnerability heightens the dangers of coastal erosion, chronic water quality degradation, and dwindling coastal resources, demanding global attention. The resultant loss of ecological persistence, functional services, and ecosystem resilience jeopardizes protection against wave action and SLR, endangering coastal habitats' economic value, food security, infrastructure, and livelihoods. Implementing integrated strategies is imperative. A thorough discussion of available strategies and best management practices for coastal ecosystem restoration is presented in the context of SIDS needs, threats, and major constraints. Solutions must encompass enhanced green infrastructure restoration (coral reefs, seagrass meadows, mangroves/wetlands, urban shorelines), sustainable development practices, circular economy principles, and the adoption of ecological restoration policies. This requires securing creative and sustainable funding, promoting green job creation, and fostering local stakeholder engagement. Tailored to each island's reality, solutions must overcome numerous socio-economic, logistical, and political obstacles. Despite challenges, timely opportunities exist for coastal habitat restoration and climate change adaptation policies. Integrated strategies spanning disciplines and stakeholders necessitate significant political will.

Keywords: climate change adaptation; coral reefs; ecological restoration; seagrass meadows; mangroves; sand beaches; green infrastructure; hybrid infrastructure; small island developing states; urban coastal habitats

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1. Introduction

Small island developing states (SIDS), comprising approximately 65 million people across 39 United Nations (UN) member states and 18 non-member associated states, confront an increasing vulnerability to climate change and sea level rise (SLR) [1,2] due to limited adaptation capacity [3–6]. These islands exhibit significant variations in size, geography, governance, economy, and population density [7]. For instance, despite its vulnerability, the Commonwealth of Puerto Rico is not recognized as a SIDS, leading to exclusion from most economic assistance and international cooperation programs. The island faces multifaceted challenges stemming from its colonial history, economic downturn, population decline, aging demographics, low household income, high poverty rates, and health disparities [8]. These vulnerabilities are compounded by colonial legacies, ineffective oversight, environmental injustice, socio-economic and racial inequalities, substantial debt, poor governance, and weak infrastructure. Coastal municipalities, particularly those with low-income households, are disproportionately affected by disasters [9–11]. These interconnected challenges hinder adaptability to climate change and SLR, exacerbating vulnerability by constraining the ability to cope and respond to crises [12–16] (Figure 1). Given projections indicating intensified hurricanes and their socio-ecological impacts with climate change [17–20], there is a critical imperative need for SIDS and colonial island states to prioritize identifying and addressing coastal ecological restoration challenges through adaptive restoration strategies.

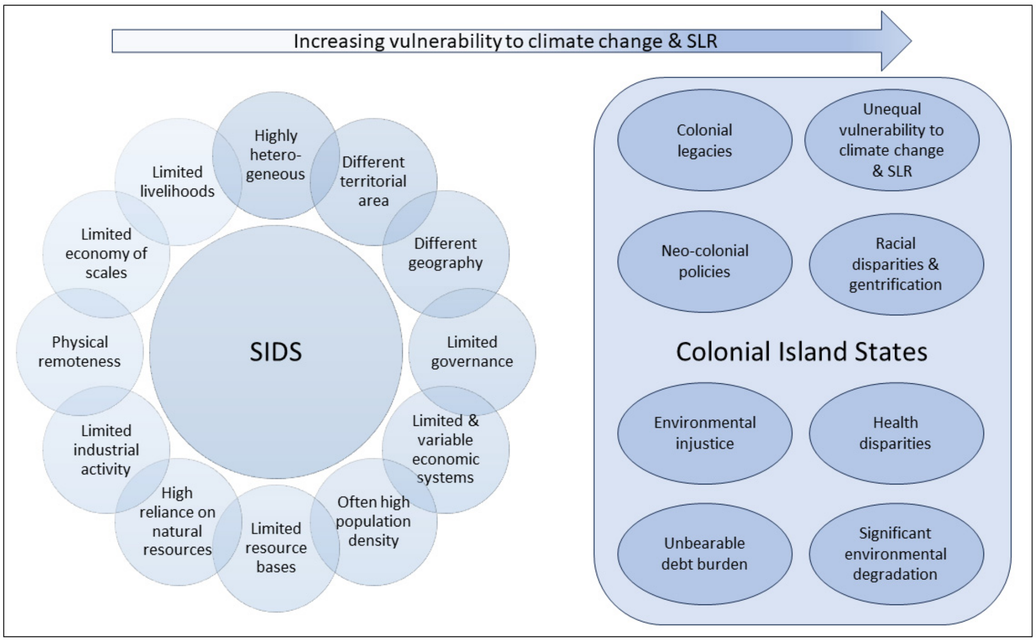

Figure 1. Conceptual diagram of the characteristics of small island developing states (SIDS). Colonial island states often share similar characteristics, but often have additional characteristics which enhance their vulnerability to disasters.

Climate change, SLR, increased coastal flooding, storm surge damage, and chronic erosion present severe threats to the stability of low-lying coastal areas and SIDS in the Anthropocene era [21–23]. The impacts of SIDS vary depending on habitat type [24,25], geomorphic characteristics, ecological factors [26], and local capacity to adapt to changing coastal conditions [27]. Significant habitat loss endangers biodiversity, ecosystem functions, and services, affecting the quality of life and livelihoods of coastal communities and disrupting local economies [28]. Even before direct infrastructure damage occurs, there are both direct and indirect socio-economic effects. Large coastal cities, colonial states, and SIDS are identified as highly vulnerable, with projections indicating severe to catastrophic impacts by the end of the century [29]. Urgent action for coastal restoration and adaptation strategies is imperative.

Adapting to the imminent challenge of permanent coastal flooding, particularly affecting both large low-lying land areas and small islands, is crucial due to the potential displacement of millions from SLR and its impacts [30]. However, there is ongoing controversy surrounding the application of existing models for projecting SLR effects and assessing vulnerability, given significant variations across spatial scales and scenarios [31]. Addressing SLR requires a combined approach of large-scale climate mitigation and local adaptation, posing a complex and costly challenge, especially for low-income countries and SIDS constrained by limited resources [32,33]. SIDS and colonial island states, often lacking socio-economic and technical capabilities, face vulnerabilities exacerbated by governance issues, colonial legacies, neocolonial policies, debt burdens, health and racial disparities, and environmental injustices [34]. This review explores opportunities for tropical SIDS and colonial island states to adapt to the escalating threats of SLR and climate change, recognizing the numerous constraints they encounter. Colonial island states are considered part of SIDS in this context due to their high vulnerability to climate-related disasters and the imperative need for coastal restoration strategies [1,2].

The socio-economic consequences of SLR and anticipated increases in wave energy, runup, and storm surge burden many developing countries and SIDS. Global projections indicate a 48% increase in affected land area, 52% in population, and 46% in assets at risk of coastal flooding by 2100, putting approximately 34 million residents in SIDS at risk [35]. The tropics face substantial (>2×) increases in extreme flooding frequency by 2050 with just a 10–20 cm SLR, impacting economic development and habitability in low-lying areas [36]. Protecting developed coastal zones is recognized as a cost-effective response [37], but resource limitations and political/logistical challenges in low-income countries pose significant obstacles. Failure to timely implement adaptation strategies could lead to escalating risks, higher management costs, and greater proportional damage to gross domestic productivity (GDP) in these countries compared to wealthier counterparts, considering projected increases in SLR, stronger hurricanes, and storm surge impacts [38–43]. While in the long term, the cost of adaptation is generally lower than inaction, it remains unaffordable for many low-income countries and most SIDS [44,45]. Therefore, urgent exploration and implementation of cost-effective coastal ecological restoration are necessary to address these inevitable changes.

This review aims to (1) identify the primary obstacles and opportunities for SIDS and colonial states in implementing low-tech, low-cost green or green/gray restoration strategies to mitigate the increasing threats of SLR, storm surge, and climate change; (2) discuss tailored restoration strategies designed for small island scenarios, considering the unique challenges they face; (3) explore strategies to address financial challenges and opportunities specific to SIDS; (4) examine best management practices (BMPs) for ecological restoration within each coastal scenario, emphasizing the ecological benefits that extend beyond coastal protection; (5) delve into the socio-economic benefits and emphasize the importance of implementing a successful coastal restoration public policy, identifying it as a top priority for islands; and (6) address the interconnectedness of ecological restoration, coastal engineering, community-based engagement, participatory ocean economy, equity, and sustainable development within the context of SIDS and colonial states, taking into account their major constraints.

2. Projected Impacts of Climate Change and SLR: The Need for Timely Action in Islands

The anticipated impacts of climate change and SLR in SIDS present significant and worrisome challenges. The cumulative effects of climate change [46,47], SLR [21,48], intensified wave patterns [49–54], and heightened hurricane activities [18,19,55–62] could lead to irreversible consequences for SIDS by the end of the century, including increased coastal flooding and storm surges [62–65] (Figure 2). These conditions have already heightened the frequency and severity of disasters in coastal communities, resulting in adverse socio-economic repercussions [64,65]. Compounded effects, such as the degradation of coral reefs, seagrass communities, and mangrove habitats due to recurrent extreme events, further amplify the risks. The loss of wave energy attenuation from coral [66–68] and seagrass decline [69,70] may expose coastlines and infrastructure to increased wave energy, height, and runup in the long term [71]. These factors, coupled with the limited geographic size, resource constraints, and socio-economic and political limitations of SIDS, could lead to catastrophic impacts.

Some of the consequences of climate change and SLR on SIDS include the following listed below.

2.1. Increased Coastal Erosion

Rising sea levels contribute to amplified shoreline erosion [72–74], leading to the depletion of vital green infrastructure, including sand beaches [75,76] and sand dunes [77]. Human interventions, such as coastal and watershed modifications, can exacerbate this erosion by altering coastal hydrodynamics and sediment dynamics [78]. Additionally, SLR induces more frequent and intense wave action, causing further erosion and infrastructure damage along the coast. The anticipated future intensification of hurricanes is expected to alter wave climates, increasing the frequency of extreme wave action and swells, thereby heightening the vulnerability of coastal infrastructure and communities.

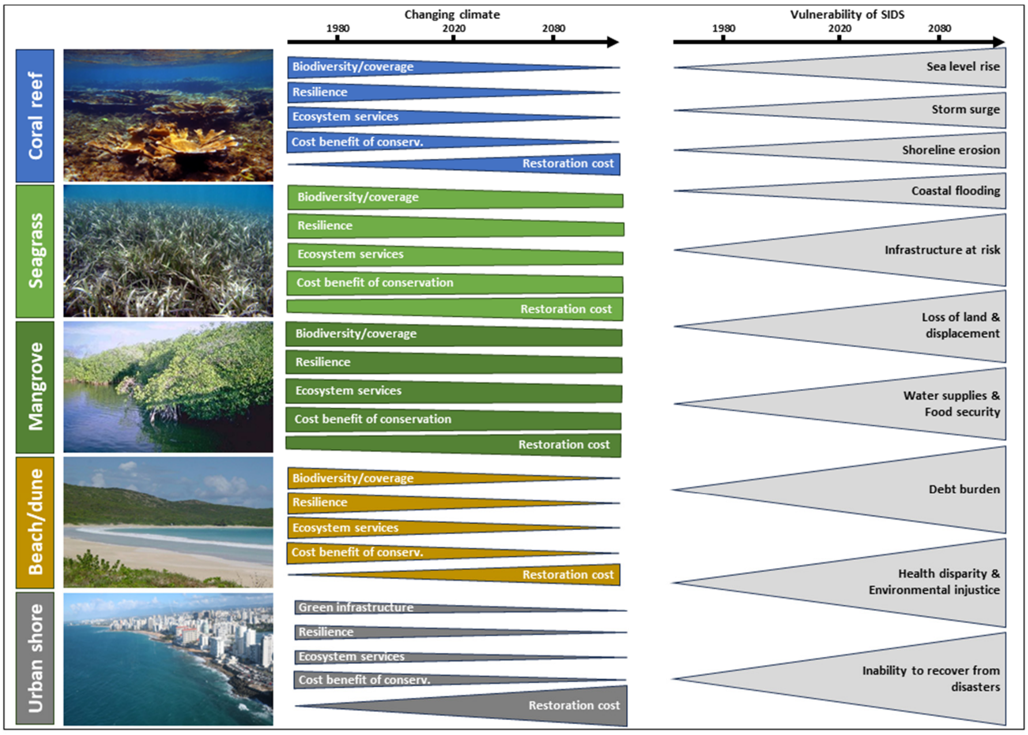

Figure 2. Conceptual diagram of the most common consequences of climate change impacts on coral reefs, seagrass meadows, mangroves, sand beaches/dunes, and urban shorelines in small island developing states (SIDS). Declining ecological condition of coastal ecosystems will result in a net long-term loss of their ecological persistence, resilience, ecosystem services, benefits, and socio-economic values. Consequently, restoration cost is projected to increase. Social vulnerability will increase as a function of increased risks of exposure to climate change impacts and the chronic degradation of coastal ecosystems. Figure adapted from Unsworth et al. [79].

2.2. Loss of Land and Displacement

Small island nations, characterized by a significant proportion of low-lying coastal areas, face heightened vulnerability to SLR and storm surge events [78]. The escalating sea levels pose the imminent threat of losing land mass and wetlands, leading to the displacement of populations and the destruction of homes and critical infrastructure [80,81]. This predicament carries dire socio-economic consequences [82,83]. Earlier modeling by the Intergovernmental Panel on Climate Change (IPCC) strongly indicates a high-confidence projection of adverse impacts on these islands. These include a decrease in the resilience of coastal systems to cope with natural climate variability, an adversely affected natural capability to adapt to changes in climate, sea level, and human activities, and an increased hazard potential for coastal populations, infrastructure, and investment [84]. Factors such as explosive population growth, unsustainable development, and coastal pollution may exacerbate these impacts [85]. The ongoing coastal effects, including land submergence, shoreline erosion, increased storm flooding, high water tables, and reduced fresh water supply on SIDS, will worsen these problems. These changes render the small islands less habitable for humans, leading to potential off-island migration [86,87].

2.3. Saltwater Intrusion

The rising sea levels present a risk of saltwater intrusion into freshwater sources, encompassing groundwater reserves and agricultural lands. This intrusion poses threats to various aspects, including the contamination of drinking water supplies [88,89], adverse effects on agricultural productivity, and harm to ecosystems [90]. The potential long-term consequences are paramount, impacting SIDS in terms of food security, sovereignty, and public health [46,91,92], thereby adversely affecting the habitability of these islands. SIDS face particular vulnerability due to limited land availability, insularity, susceptibility to extreme events, and integration into global markets. This vulnerability exposes them to the compounding effects of global environmental and economic change processes, which could further magnify the repercussions of declining food security and sovereignty [93].

2.4. Increased Frequency and Intensity of Storms

Climate change contributes to the heightened frequency and severity of tropical storms and hurricanes [20,94]. There is even a projected increase in the frequency of sequential impacts by major hurricanes [95]. Small islands are particularly vulnerable to the destructive impacts of these extreme weather events, which include strong winds, storm surges, and heavy rainfall. The consequences encompass flooding, extensive shoreline erosion, and damage to infrastructure and communities [96,97]. Any increase in the frequency and/or severity of hurricanes has the potential to exacerbate vulnerabilities, leading to severe damage and prolonged disruption of essential services. This, in turn, can result in a wide range of public health consequences [98].

2.5. Coral Reef Degradation

Coral reefs, crucial for marine life habitats and coastal erosion protection, face high vulnerability to climate change impacts. Elevated ocean temperatures [99–105], ocean acidification [106–108], and SLR contribute to coral bleaching, leading to coral mortality. The most significant damage occurs on shallow coral reefs [109]. This vulnerability is particularly alarming for Caribbean shallow reef systems, which exhibit limited natural recovery from sexual coral larval recruitment [110–112]. Strong hurricanes further exacerbate the situation by causing substantial mechanical damage, including colony fragmentation, dislodgment, and the physical disruption of coral reef frameworks [113–115]. The resulting loss not only impacts marine biodiversity but also diminishes the natural protection that coral reefs provide to small islands against wave action and storm surges, primarily due to reef flattening.

2.6. Threats to Biodiversity and Ecosystems

Small tropical islands typically host unique and delicate ecosystems that sustain many plant and animal species. The impacts of climate change and SLR can disrupt these ecosystems, resulting in the loss of biodiversity and the potential extinction of endemic species [116–119]. Such disruptions affect multiple ecological processes and compromise the normal functioning of these ecosystems.

2.7. Economic Impacts

The impacts of climate change and SLR pose severe economic consequences for SIDS [120,121]. These islands heavily depend on sectors such as tourism, agriculture, and fisheries, all of which are susceptible to disruptions caused by climate change [122]. The resulting damage to infrastructure [123,124], loss of coastal land [125], depletion of freshwater supply [126,127], and declines in natural resources [128] can lead to economic instability and impede sustainable development. Additionally, the colonial legacies, neo-colonial policies, debt burden, health disparities, and environmental injustice prevalent in most SIDS may disproportionately amplify human vulnerability and the economic impacts of climate change and SLR.

These impacts vary based on geographical location, socio-economic vulnerability, numerous socio-political constraints, and the adaptive capacity of each small tropical island (Figure 3). Despite this variability, climate change and SLR present substantial challenges to the sustainability and well-being of these islands and their communities, necessitating the implementation of low-tech, low-cost adaptive strategies. Given the acknowledged political and socio-economic obstacles, a critical question arises: How can SIDS effectively address the projected impacts of climate change and SLR?

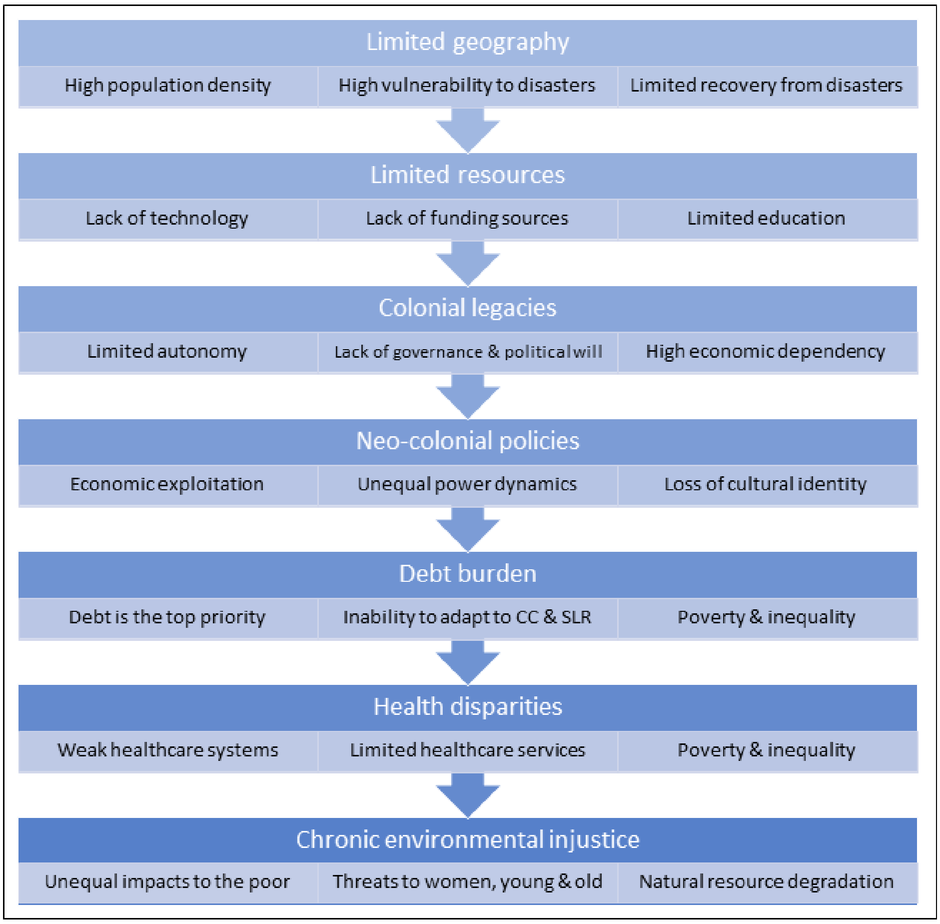

Figure 3. Conceptual diagram of the most common political and socio-economic obstacles and challenges faced by small island developing states (SIDS) that might limit their ability to adapt to and mitigate projected impacts of climate change and SLR.

3. An Overview of Obstacles and Roadblocks to Climate Change and SLR Adaptation in SIDS

Socio-economic and socio-political challenges pose substantial constraints for SIDS in effectively adapting to climate change and SLR. These hindrances encompass colonial legacies, neocolonial policies, environmental injustice, overwhelming debt burdens, and health disparities. Recognizing the interplay between these constraints and the pressing need for swift, cost-effective coastal restoration strategies is crucial for addressing the urgency of the situation in SIDS.

3.1. The Impact of Colonial Legacies

Colonial legacies exert a complex and multifaceted influence on climate change adaptation in SIDS. This term refers to the historical and structural impacts left by former colonial powers on societies and institutions in SIDS, potentially heightening vulnerability to disasters and impeding the ability to adapt to projected climate change impacts [129,130]. In this context, colonial legacies serve as a political framework affecting SIDS governed by invasive colonial rulers. This influence can perpetuate outdated political practices, weaken government structures, hinder governance, impede economic development, and contribute to unsustainable practices, permanent environmental degradation, and recurring instances of social and environmental injustice, thereby limiting adaptation capabilities [128].

The effects of colonial legacies on climate change adaptation efforts are nuanced, presenting both positive and negative outcomes. The outcome hinges on the existing political and socio-economic relationship with former colonial powers and factors like governance strength and resource availability. These factors, in turn, can elevate human vulnerability [129] and significantly curtail the ability of SIDS to adapt to climate change and SLR. Key considerations associated with colonial legacies include the following listed below.

3.1.1. Economic Dependency

Numerous SIDS, once exploited economically by colonial powers, grapple with a legacy of economic dependence [131]. This dependency poses a challenge to investing in climate change adaptation measures [132], as limited resources are often directed towards addressing other pressing issues [133].

3.1.2. Institutional Weaknesses

Colonial rule has frequently bequeathed SIDS with a legacy of weak institutions and governance structures. These institutions often suffer from a shortage of human and economic resources or exhibit asymmetrical governance arrangements [134]. These weaknesses hinder effective decision making and policy implementation for climate change adaptation [135]. The combination of limited capacity, bureaucratic inefficiencies, and corruption can further impede progress in addressing climate-related challenges.

3.1.3. Limited Autonomy

SIDS commonly inherited governance systems and legal frameworks established during the colonial era, impacting their political and economic sovereignty. These structures may not be well suited for addressing contemporary climate change issues [136]. Furthermore, SIDS often grapple with limited autonomy and encounter challenges in making independent decisions, as their policies can still be influenced by former colonial powers, evident in aspects such as globalization [136] and cultural loss [137]. This influence may be exacerbated by inadequate education systems [138], impeding the provision of trained personnel and technology necessary to support adaptation efforts.

3.1.4. Land Tenure and Resource Management

Colonial powers frequently introduced land tenure systems and resource management practices that may not align with the evolving requirements of climate change adaptation or the genuine needs of SIDS [139]. These systems can curtail local communities' control over their resources and hinder the implementation of sustainable land and resource management practices that align with real needs, thereby increasing vulnerability to climate change [140].

3.1.5. Disrupted Traditional Knowledge

Colonialism has disrupted and devalued community-based participation in decision-making processes and eroded traditional knowledge systems and communication practices that have enabled local communities to adapt to their environments and cope with disasters for centuries [141]. The failure to integrate local traditional knowledge and practices has diminished the resilience of SIDS in the face of climate change [142,143]. Community-based participation is crucial for fostering community stewardship, integrating all societal actors, adopting a democratic decision-making strategy, ensuring a fair, participatory economy, and facilitating consensus solutions to climate change adaptation.

3.1.6. Unequal Burdens

Colonial legacies have contributed to global inequalities, rendering SIDS more vulnerable to the impacts of climate change and leading to discrimination against climate refugees [144]. Despite their minimal contributions to global greenhouse gas emissions, small islands face higher risks and have limited resources and capacity to cope with rising sea levels, extreme weather events, and other climate-related challenges. Disasters tend to be more destructive and prolonged in small islands due to heightened vulnerabilities, lack of preparation for such impacts, increased exposure of disadvantaged groups to adverse effects, greater susceptibility to climate change damage, and reduced ability to cope and recover [145]. Some countries are up to 15 times more vulnerable to natural hazards than less vulnerable ones [146]. This underscores the critical need to develop and implement low-tech, low-cost strategies tailored for SIDS to cope with climate change and SLR.

Despite formidable challenges, SIDS are not passive victims. They have demonstrated resilience in the face of multifaceted adversities and have actively advocated for their unique climate change adaptation needs. The support of international cooperation, financial assistance, and capacity-building initiatives, including coastal ecosystem restoration, is vital to helping SIDS overcome their diverse range of challenges.

3.2. The Impact of Neocolonial Policies

Neocolonial policies significantly affect the climate change adaptation capacity of SIDS and can potentially limit their ability to restore affected coastal resources. Neocolonialism refers to the ongoing economic and political influence exerted by former colonial powers or other dominant global actors on developing countries. Due to the colonial history of many island nations, they heavily rely on external funding sources to adapt to climate change and SLR. This dependence perpetuates colonial subordination by undermining the sovereignty of small island states over their resource management and adaptation strategies [132]. Key obstacles imposed by neocolonial policies include the following list.

3.2.1. Intrinsic Vulnerability of SIDS

SIDS face intrinsic vulnerabilities to natural disasters, climate change, and SLR due to their small size, limited resources, and intense land use. Insularity and remoteness result in high external transportation costs, limited access to goods, food security concerns, and governance challenges. Additional factors include small interiors, large coastal zones, limited disaster mitigation ability, demographic challenges, and economic factors such as dependence on external finance and neocolonial policies. These factors collectively amplify the challenges and vulnerabilities faced by SIDS [123].

3.2.2. Economic Exploitation

Neocolonial policies can perpetuate economic exploitation in SIDS [147], intensifying the challenges they encounter in adapting to climate change. Exploitative trade practices, unequal resource extraction, and unfavorable economic agreements can impede the ability of SIDS to allocate resources for climate change adaptation measures.

3.2.3. Debt Burden

Neocolonial policies can contribute to unsustainable debt accumulation in SIDS [148], especially when compounded by recurrent disasters [149]. Structural adjustment programs imposed by international financial institutions may prioritize debt repayment over investments in coastal restoration and climate change adaptation. For instance, the Commonwealth of Puerto Rico faces such challenges, where a Fiscal Control Board, imposed by a U.S. President's executive order, prioritizes debt repayment to Wall Street investors over education, public health, infrastructure maintenance, natural resource management, and adaptation efforts to climate change and SLR. This situation leaves SIDS with insufficient financial resources to implement vital adaptation measures [148].

3.2.4. Limited Access to Technology

Neocolonial policies may hinder SIDS' access to crucial technology and innovation for effective climate change adaptation [150]. Challenges such as intellectual property rights, high costs, and limited technology transfer can impede the acquisition of climate-resilient technologies, posing difficulties for SIDS in building adaptive capacity.

3.2.5. Unequal Power Dynamics

Neocolonial policies often perpetuate unequal power dynamics between dominant global actors and SIDS, impeding islands from shaping international climate change agendas, accessing financial resources, and influencing decision-making processes. These imbalances hinder effective adaptation planning and impede the implementation of locally appropriate strategies based on local needs and realities, including coastal restoration.

3.2.6. Loss of Cultural Identity and Values

Neocolonial policies may erode cultural identity, values, and traditional knowledge in SIDS [151]. As global economic and cultural influences penetrate, vital practices and knowledge systems for climate change and SLR adaptation may be devalued or displaced. This loss of cultural identity can further diminish the resilience of SIDS communities in the face of projected climate change and SLR impacts.

3.2.7. Limited Policy Autonomy

Neocolonial policies may limit the policy autonomy of SIDS in addressing climate change and SLR adaptation. Foreign aid or loans often come with conditions imposing specific policy choices that are not aligned with the unique needs and contexts of SIDS. This constraint hinders the development of locally relevant adaptation strategies and impedes progress in building resilience.

Addressing neocolonial impacts involves challenging power imbalances perpetuating inequalities. Empowering SIDS in climate negotiations, promoting fair trade, facilitating technology transfer and capacity building, respecting local values and traditional knowledge, and fostering respectful partnerships are vital for enhancing opportunities for coastal restoration and climate change and SLR adaptation in SIDS.

3.3. The Impact of Environmental Injustice

Environmental injustice has profound implications for climate change adaptation in SIDS and other low-income countries [152]. This term denotes the uneven distribution of environmental burdens and benefits, disproportionately affecting marginalized communities. Key impacts of environmental injustice on climate change adaptation in SIDS include the following list.

3.3.1. Unequal Vulnerability

Environmental injustice worsens the vulnerability of marginalized communities in SIDS to climate change impacts. Typically residing in coastal or low-lying areas, these communities are at increased risk from SLR, extreme weather events, and coastal erosion. They often lack the resources, infrastructure, and institutional support necessary for effective adaptation. Additionally, rising inequality, coastal racialization, and limited recovery capacity from disasters pose significant obstacles to adaptation [153].

3.3.2. Limited Access to Resources

Marginalized communities in SIDS frequently encounter restricted access to essential resources for climate change adaptation and restoration projects. These limitations extend to land, clean water, healthcare, education, economic opportunities, and technology. Insufficient access to these resources impedes their capacity to invest in adaptive measures, such as constructing climate-resilient infrastructure or diversifying livelihoods.

3.3.3. Displacement and Forced Relocation

Climate change impacts, including SLR and intensifying storms, can result in the displacement of communities in SIDS. Environmental injustice and racialization compound this displacement, as marginalized communities are frequently sidelined in decision-making processes concerning relocation. Moreover, they are more prone to encountering insufficient support and resources during the relocation, leading to disruptions in social cohesion, cultural heritage, and heightened social and economic inequalities due to migration.

3.3.4. Health Disparities

Environmental injustice amplifies health disparities in SIDS, particularly affecting marginalized communities. Factors such as poverty, restricted access to healthcare, and exposure to environmental hazards make these communities more vulnerable to adverse health effects from climate change impacts. This enhanced vulnerability includes increased incidences of vector-borne diseases, food insecurity, waterborne illnesses, and mental health challenges, further impairing their livelihoods [46].

3.3.5. Limited Participation and Representation

Environmental injustice, coupled with other types of roadblocks, exacerbates marginalization by restricting community participation and representation in climate change adaptation decision-making processes. This exclusion denies these communities opportunities to contribute their knowledge, perspectives, and needs to adaptation strategies, leading to less effective and equitable solutions.

Addressing environmental injustice for effective adaptation to climate change and SLR in SIDS is crucial. This entails promoting inclusive and participatory approaches that prioritize the needs and rights of marginalized communities. Ensuring their meaningful involvement in decision making, providing access to resources and support for adaptation measures, and recognizing and valuing their traditional knowledge and practices are key components. Additionally, addressing underlying social and economic inequalities is essential to build resilience and promote equitable adaptation outcomes in SIDS.

3.4. The Impact of Debt Burden

Debt burden significantly impacts climate change adaptation in SIDS, often in combination with degraded environmental conditions and increasing disasters [148,154,155]. High levels of debt in small islands can hinder their ability to allocate resources and implement effective adaptation measures, leading to various consequences.

3.4.1. Limited Financial Resources

High levels of debt restrict the financial resources available for ecological restoration and climate change adaptation in SIDS. Debt servicing, including interest payments, often consumes a significant portion of the national budget, leaving limited funds for investments in adaptation projects, infrastructure, capacity building, and research and development. These impositions are often the result of neocolonial policies.

3.4.2. Reduced Fiscal Space

The debt burden reduces the fiscal space of SIDS, limiting their ability to mobilize domestic resources for restoration or adaptation. Governments are compelled to prioritize debt repayment over climate change adaptation, resulting in underfunding or delayed implementation of critical adaptation initiatives.

3.4.3. Lack of Access to International Financing

The debt burden can hinder SIDS' access to international financing mechanisms for climate change adaptation, especially for colonial states like Puerto Rico. Concerns about the ability of highly indebted countries to repay additional loans may limit the availability of international climate finance, including grants, concessional loans, and climate funds.

3.4.4. Constraints on Policy Flexibility

High levels of debt can impose constraints on policy flexibility for climate change adaptation. Structural adjustment programs imposed by international financial institutions may require austerity measures, including budget cuts and public sector retrenchment. These measures can limit the capacity of SIDS to develop and implement comprehensive adaptation strategies.

3.4.5. Weakened Governance and Institutions

The debt burden can weaken governance structures and institutions in SIDS due to severely restricted budgets and reduced human resources. Governments may face pressure to prioritize short-term economic stability over long-term adaptation planning, leading to weakened regulatory frameworks, inadequate enforcement, and diminished institutional capacity to address climate change challenges effectively.

3.4.6. Increased Vulnerability

The debt burden can exacerbate the vulnerability of SIDS to climate change impacts. Limited financial resources can hinder investments in adaptive infrastructure, early warning systems, disaster preparedness, and disaster response ability. As a result, SIDS are less able to cope with the adverse effects of climate change, including SLR, extreme weather events, and long-term ecosystem degradation.

Addressing the impact of the debt burden on climate change adaptation in SIDS requires a multi-faceted approach. This might include promoting debt relief initiatives, such as debt restructuring, debt forgiveness, or debt-for-climate swaps, tailored to the unique circumstances of highly vulnerable countries. Enhancing international climate finance flows, improving access to concessional financing, and providing technical assistance and capacity-building support are also crucial to assisting SIDS in overcoming financial constraints and implementing effective coastal restoration and climate change adaptation measures.

3.5. The Compounded Impact of Health Disparities

Health disparities in SIDS pose challenges for climate change adaptation. Residents of these islands often face a substantial burden of health conditions, creating additional complexities for addressing climate change and SLR [156,157]. These disparities manifest as unequal access to healthcare, divergent health outcomes, and varying vulnerabilities across populations, all of which may strain the limited budgets and priorities of SIDS. The consequences of these health disparities compound the challenges associated with climate change adaptation in SIDS.

3.5.1. Differential Health Impacts

Health disparities within SIDS worsen the disparate effects of climate change on the most vulnerable populations. Groups like the elderly, children, pregnant women, individuals with pre-existing health conditions, and marginalized communities are particularly susceptible to the health impacts of climate change. These effects encompass a higher occurrence of vector-borne diseases, heat-related illnesses, respiratory problems from air pollution, mental health issues, and malnutrition [46].

3.5.2. Unequal Access to Healthcare

Health disparities in SIDS lead to uneven access to healthcare services. Marginalized populations, residing in remote or socioeconomically disadvantaged areas, encounter obstacles such as limited healthcare facilities, shortages of healthcare personnel, and affordability concerns. This restricted access hampers their capacity to prevent, mitigate, and address health impacts associated with climate change.

3.5.3. Reduced Adaptation Capacity

Health disparities in SIDS diminish the adaptive capacity of populations with poor health outcomes and limited healthcare access. Such populations are less resilient and struggle to cope with the health effects of climate change. This impedes their active participation in climate change adaptation and reduces overall adaptive capacity.

3.5.4. Inequitable Distribution of Resources

Health disparities in SIDS are closely linked to socioeconomic inequalities, with marginalized populations often lacking the resources needed for effective adaptation. This includes limited access to clean water, sanitation, healthcare facilities, and preventive services. The unequal distribution of resources undermines the ability of disadvantaged communities to adapt to climate change impacts and exacerbates existing health disparities.

3.5.5. Intersecting Vulnerabilities

Health disparities in SIDS intersect with other vulnerabilities, including socioeconomic status, gender, age, and ethnicity, intensifying challenges for specific population groups. For instance, women and children may face distinct health risks and burdens during climate-related disasters. Considering intersectional vulnerabilities is crucial in developing climate change adaptation strategies for equitable and effective responses.

Addressing health disparities is crucial for equitable and effective climate change adaptation in SIDS. It involves integrating health considerations into adaptation planning, strengthening healthcare systems, and improving access to quality healthcare services for marginalized populations. Additionally, enhancing health surveillance systems, promoting community-based approaches, and addressing social determinants of health, such as poverty and inequality, are vital for building resilience and reducing health disparities in the face of climate change.

4. An Overview of Coastal Restoration Strategies for SIDS in the Context of Climate Change and SLR Mitigation

Urgent and cost-effective climate change and SLR mitigation, as well as coastal restoration strategies, are imperative for SIDS. These may involve a mix of multidisciplinary adaptation strategies and targeted restoration efforts, emphasizing green infrastructure, integrating green–hybrid–gray infrastructure, beach renourishment, and implementing low-cost coastal ecosystem engineering strategies.

4.1. SLR and Climate Change Mitigation Strategies

Given the characteristics that contribute to SIDS' persistent vulnerability to climate change and SLR, limited recovery ability from disasters, and narrow capacity to mitigate and adapt, it is crucial to explore their options. While SIDS have various alternatives to address coastal threats, there are inherent tradeoffs. Mitigation strategies can be broadly classified into several categories.

4.1.1. Adaptation and Land-Use Planning

Land-use planning tools play a crucial role in climate change mitigation [158,159]. Small islands can employ strategies that account for SLR and shifting climate patterns. This involves avoiding construction in high-risk zones, relocating vulnerable infrastructure inland, setting up coastal setbacks to safeguard against SLR and erosion impacts [160], and promoting sustainable land use practices. Nevertheless, the geographic constraints of many low-lying islands and atolls can pose challenges to implementing such strategies.

4.1.2. Coastal Protection and Engineering

Deploying coastal protection measures, including sea walls, breakwaters, and artificial reefs, is instrumental in mitigating storm surge and SLR impacts while minimizing erosion [161]. These structures serve as effective physical barriers against wave action and storm surges, safeguarding coastal communities and infrastructure. However, prioritizing the rehabilitation, expansion, and preservation of natural coastal barriers, such as coral reefs, seagrasses, mangroves, sand beaches, dunes, salt marshes, and other coastal wetlands, is equally crucial. This approach enhances protection against erosion and flooding while maintaining the integrity of the coastal ecosystem [162].

4.1.3. Ecosystem-Based Approaches

Preserving and revitalizing natural ecosystems, including mangroves, coral reefs, and seagrass beds, offers a sustainable approach to mitigating the long-term effects of SLR and climate change. These ecosystems serve as natural buffers, absorbing wave energy, mitigating erosion, and serving as vital nurseries for marine life. Prioritizing conservation and restoration initiatives contributes to the resilience of these ecosystems. Importantly, the incorporation of natural resource conservation into land-use planning is crucial for a comprehensive and effective strategy [163].

4.1.4. Sustainable Water Management

Ensuring sustainable water management practices is vital for small islands grappling with saltwater intrusion and freshwater scarcity as indirect impacts of SLR. Recurrent droughts and rising sea levels contribute to the infiltration of underground aquifers and surface water sources with saline, leading to chronic water scarcity [164] and shortages [165]. Addressing these challenges requires the implementation of water management policies, best practices, and tools to safeguard water security and achieve sustainable development in SIDS amidst climate change and other stressors. Enhancing functional governance [166] is crucial for effective water resource management. Strategies include rainwater harvesting, water conservation measures, and the establishment of desalination facilities to ensure a reliable freshwater supply.

4.1.5. Renewable Energy Adoption

SIDS often depend on fossil fuel energy [167], and the shift to renewable sources faces economic challenges [168,169]. However, transitioning to renewable energy, including solar and wind power, is crucial for reducing reliance on fossil fuels and curbing greenhouse gas emissions. To achieve this, small islands can invest in renewable energy infrastructure, advocate for energy efficiency, and establish local clean energy systems to minimize their carbon footprint.

4.1.6. Community Engagement and Education

Community awareness and engagement are vital for successful climate change mitigation in small islands. Educating residents on climate change risks, encouraging sustainable practices, and actively involving local communities in decision-making processes are key steps. This approach not only enhances resilience and adaptation but also fosters natural resource stewardship.

4.1.7. International Cooperation and Support

Small islands often depend on international support, financing, and cooperation to implement effective climate change mitigation strategies. Collaborative efforts, including partnerships with international organizations, neighboring countries, or private sectors, can enhance access to funding, technical expertise, and knowledge sharing.

Mitigation strategies for small islands should be customized to their unique characteristics, vulnerabilities, and socio-economic context, considering local contexts and available resources. This approach promotes stronger community integration and the development of locally tailored strategies, including the restoration of coastal green infrastructure.

4.2. Coastal Green Infrastructure Restoration

Coastal green infrastructure restoration is vital for biodiversity recovery, human health, and mitigating SLR, storm surge, and coastal erosion impacts [170]. With multiple benefits and lower costs [171], it aligns with abiotic, ecological, and social goals [172]. Possible strategies include the following listed below.

4.2.1. Mangrove Restoration and Conservation

Restoring and conserving mangrove ecosystems is highly effective in stabilizing shorelines, providing marine habitat, and acting as a natural barrier against erosion, storm surges, and water pollution [173].

4.2.2. Coral Reef Protection and Restoration

Protecting existing coral reefs from destructive activities and implementing restoration programs are paramount for maintaining healthy coral reefs. These ecosystems act as natural breakwaters, absorbing wave energy and reducing erosion. Restoration efforts can enhance resilience, protective capacity, and community involvement [174,175].

4.2.3. Beach Nourishment and Sand Dune Restoration

Beach nourishment, involving the addition of sand to eroded beaches and dune restoration, focusing on rebuilding sand dune systems, serves as natural buffers against waves and storm surges. These strategies provide multiple benefits, including habitat for wildlife, support for biodiversity, and contributions to socio-economic development through tourism and recreational activities. Integrating both approaches is valuable for the geomorphological and ecological restoration of dynamic beach systems [176].

4.2.4. Living Shorelines

Living shorelines utilize natural materials like oyster reefs, salt marshes, seagrass meadows, and mangroves to protect muddy shorelines and wetlands from erosion, rehabilitating ecosystem functions [177,178]. These coastal wetlands offer habitat for diverse marine species, stabilize sediments, reduce wave energy and sediment loss, and support the rehabilitation of crucial essential fish habitats and nursery grounds. Successful community-based efforts have demonstrated the effectiveness of restoring living shorelines for enhanced natural protection against storm surges [179].

4.2.5. Green Roofs, Green Walls, and Permeable Surfaces

Green roofs, green walls on buildings [180,181], and the use of permeable surfaces in urban areas [182,183] aid in absorbing rainwater, minimizing runoff, and mitigating flooding. These approaches offer added insulation, decrease energy consumption, and contribute to urban greening, becoming increasingly crucial for lessening the impact of urban stormwater runoff on coastal waters and supporting ecological restoration success.

4.2.6. Stormwater Management

Deploying green stormwater management strategies, such as constructing rain gardens, bioswales, and retention ponds, aids in capturing and filtering stormwater runoff [184,185]. These initiatives alleviate stress on drainage systems, mitigate erosion, and enhance water quality in watersheds and coastal waters.

4.2.7. Reforestation and Native Vegetation Restoration

Planting native trees and vegetation along coastlines and in upland areas is instrumental in stabilizing soils, preventing erosion, and enhancing biodiversity. Native vegetation also plays a crucial role in capturing carbon dioxide, mitigating climate-related impacts on hydrological cycles in watersheds, shielding coastal areas from intensified storms, and providing habitat to reduce the risk of species extinctions under projected climate change [186].

4.2.8. Integrated Coastal Zone Management

Implementing integrated coastal zone management approaches can coordinate efforts and balance the interests of various societal sectors in coastal areas by promoting stakeholder integration and participation [187]. This involves considering the ecological, social, and economic aspects of coastal development to ensure sustainable and resilient practices. Successful integration of science, conservation-oriented policies, marine spatial planning, climate change adaptation policies, and effective public participation is crucial for improving the outcomes of such efforts [188].

4.2.9. Education and Community Involvement

Raising awareness among local communities about coastal green infrastructure and involving stakeholders in planning and implementation can enhance the long-term success of strategies. Public engagement is imperative for addressing power dynamics, preventing negative livelihood impacts [189], and bridging gaps between the community and academia [190]. Incorporating cultural practices into ecological restoration efforts improves community-based stewardship and integration [191]. One notable case study of community engagement in active coastal ecological restoration is the Community-based Coral

Aquaculture and Reef Rehabilitation Program initiated by Sociedad Ambiente Marino (SAM) in Culebra Island, Puerto Rico, in 2003 [174,175]. This project employs extensive community-based citizen science integration and participatory programs, resulting in numerous volunteers, trained students, and the recruitment of the next generation of restoration practitioners. It has successfully restored over 200,000 coral colonies of various species and has spurred the creation of jobs in ecological restoration and a notable increase in nature-based tourism activities on restored sites.

Choosing and implementing coastal green infrastructure strategies for small tropical islands must account for their unique ecological and socio-economic characteristics. Customized approaches and integrating local knowledge are essential for effective resilience and adaptation. Considering the present and projected mounting threats of SLR and climate change on SIDS, a combination of green and gray infrastructure should be implemented to minimize the growing impacts of SLR, storm surge, and coastal erosion.

4.3. Integration of Green–Hybrid–Gray Coastal Infrastructure

Increasing threats of SLR, storm surge, and coastal erosion pose a global challenge to the vulnerability of coastal infrastructure and settlements in SIDS. To address this, rapid mitigation solutions are necessary, and integrating green and gray coastal infrastructure is a promising approach. Green and hybrid infrastructure, known for climate change mitigation, offer lower maintenance costs and enhanced resilience compared to gray infrastructure (Figure 4) [192]. These strategies contribute to coastal erosion control, land formation, and watershed-scale improvements in water conservation, reducing runoff impacts and enhancing coastal water quality [193].

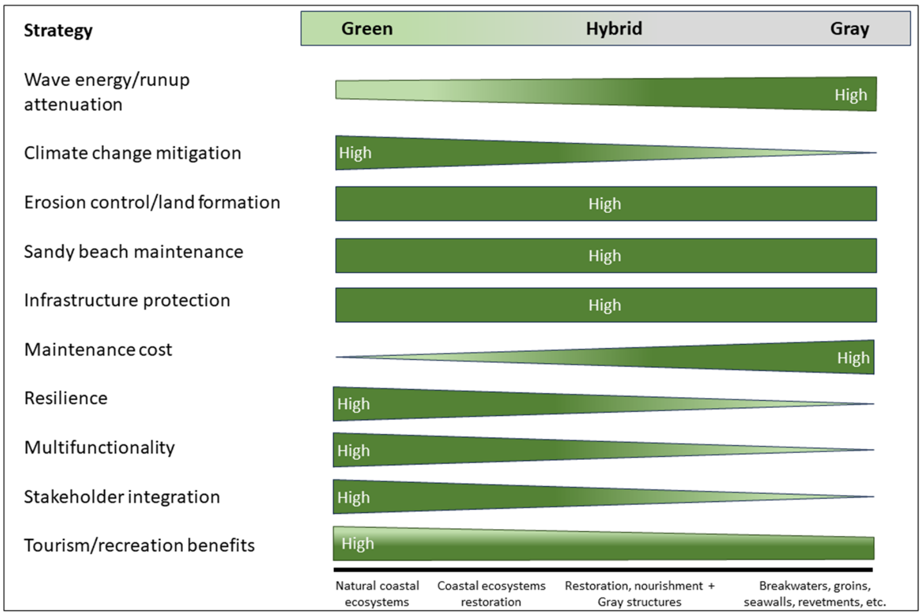

Figure 4. Conceptual diagram of the most common co-benefits of green, hybrid (green/gray), and gray coastal infrastructure, beyond their original functionality protecting coastlines and built infrastructure. *Green infrastructure* refers to coral reefs, seagrass meadows, mangroves, salt flats, tidal marshes, wetlands, oyster reefs, sandy beaches, and sand dunes. *Coastal ecosystem restoration* refers to any activity involving natural habitat enhancement with specific objectives of protecting the shoreline and numerous co-benefits (i.e., biodiversity enhancement, depleted species recovery, fisheries management, enhanced essential fish habitats, etc.). *Hybrid infrastructure* refers to the incorporation of coastal reengineering (i.e., artificial reefs, living shorelines, submerged breakwaters, groins, beach renourishment) that promotes shoreline protection and/or beach stabilization, but can also promote biodiversity enhancement. *Gray infrastructure* refers to building any hardened artificial structure along or adjacent to the shoreline to protect infrastructure and life from disasters. Figure adapted from Kuwae and Crook [192].

Some potential examples of green–hybrid–gray infrastructure that could be integrated into the restoration of urban coastal areas facing increasing flooding risks include the following strategies.

4.3.1. Sea Walls and Revetments

Constructing sea walls and revetments serves as crucial physical barriers against wave energy and erosion, especially when shoreline erosion poses a significant threat to essential infrastructure [194]. Typically made of concrete, rock, or other durable materials, these structures are designed to safeguard vulnerable coastlines. However, it is important to note that they can contribute to accelerated erosion on adjacent beaches [195]. To mitigate such negative impacts, these structures could be combined with complementary measures, such as artificial reefs, coral reef restoration, restored living coastlines, or other green strategies aimed at reducing wave energy and runup impacts.

4.3.2. Breakwaters and Groins

Breakwaters, as detached offshore structures, effectively diminish wave force before they reach the shore and generally result in fewer erosion problems compared to groins [196]. Groins, constructed perpendicular to the shoreline, are designed to trap sand and stabilize beaches. While both measures effectively reduce erosion and preserve beach profiles, they can often contribute to increased erosion on downstream shorelines [197].

4.3.3. Gabions and Geotextiles

Gabions, wire mesh baskets filled with stones, and geotextiles, permeable fabrics on slopes or shorelines, stabilize soils and prevent erosion by absorbing wave energy and reducing sediment movement [198,199]. However, gabions are susceptible to rapid corrosion, potentially losing effectiveness over a relatively short term.

4.3.4. Dredging and Sediment Management

Regular maintenance dredging of bays, inlets, tidal channels, and waterways can manage sediment buildup and preserve navigational channels. While proper sediment management can replenish eroded areas and beaches, dredging is a costly and environmentally impactful solution [200–202].

4.3.5. Coastal Reclamation and Land Reengineering

In some cases, land reclamation may create or expand land areas, involving filling coastal regions with materials like soil, sand, or rock to address infrastructure threats from wave action or to expand land surface for coastal development. However, coastal reclamation leads to the permanent loss of crucial natural habitats, including wetlands and seagrasses [203,204].

Combining green and gray infrastructure is often recommended for a holistic and sustainable approach to coastal resilience. While gray infrastructure offers immediate protection, it may have adverse environmental impacts and limited long-term resilience. Customizing the blend of green and gray infrastructure to the specific conditions and needs of each small island is crucial for an effective strategy.

4.4. Beach Renourishment as a Tool to Stabilize Shoreline Dynamics

Beach renourishment, a coastal management practice involving adding sand or sediment to eroded beaches, is crucial for stabilizing urban beach systems and protecting coastal infrastructure from wave action and flooding. It enhances recreational values [205] but requires careful implementation. Improper practices may alter natural beach dynamics [206] and impact adjacent coral reefs [207]. To minimize adverse effects, strategies like using compatible sand materials and considering proximity to coral reefs must be employed. Some recommended strategies to achieve this include the following examples.

4.4.1. Sediment Selection

Selecting sediment for beach renourishment must prioritize matching native beach material characteristics, minimizing negative effects on adjacent coral reefs and seagrasses. Additionally, sediment should be free from contaminants to prevent harm to marine ecosystems during the renourishment process.

4.4.2. Timing and Seasonality

To minimize impacts on corals and seagrasses, timing beach renourishment activities to avoid peak reproductive or spawning periods is essential. Implementing standard turbidity barriers during the process can further reduce potential disturbances to these sensitive marine organisms.

4.4.3. Monitoring and Assessment

Thorough environmental monitoring before, during, and after beach renourishment projects is crucial. Assessing the health and distribution of nearby corals and seagrass meadows helps determine potential impacts, allowing for adaptive management and mitigation measures if necessary.

4.4.4. Sediment Placement Techniques

Methods used to distribute renourished sediment can influence impacts on adjacent coral reefs and seagrasses. Employing techniques that minimize sedimentation and turbidity, such as careful placement and controlled spreading of sediment, or conducting renourishment projects during low-wind conditions can help reduce smothering and sedimentation effects on nearby marine ecosystems.

4.4.5. Designing Setbacks and Buffers

Designing setbacks and buffers between the renourished beach and sensitive marine habitats can minimize impacts, allowing for natural transition zones, such as shallow subtidal areas or seagrass meadows, to act as protective buffers to preserve intertidal and shallow water biodiversity and maintain ecological connectivity among different habitats.

4.4.6. Stakeholder Engagement and Communication

Engaging with local communities, conservation organizations, private businesses, academia, and other relevant stakeholders throughout the planning and implementation of beach renourishment projects is essential. This collaboration can ensure that the concerns and knowledge of the local community and conservation experts are considered, leading to more environmentally sensitive practices.

4.4.7. Ecosystem Restoration and Conservation

Implementing concurrent measures for the restoration and conservation of adjacent coral reefs and seagrasses can help offset potential impacts from beach renourishment. Supporting efforts to enhance these ecosystems' health through habitat restoration, coral propagation, and seagrass conservation promotes overall recovery and reduces coastal vulnerability.

By employing such integrated strategies, beach renourishment projects can minimize adverse impacts, preserving the ecological integrity of coastal ecosystems. A comprehensive understanding of the local ecological context and regular monitoring are crucial components for effective beach renourishment management and adaptive strategies for SIDS.

4.5. An emergent Toolbox: Integrated Coastal Ecosystem Engineering Strategies

Ecosystem engineering strategies, falling under the umbrella of nature-based solutions (NBS), aim to utilize natural resources to address critical issues such as climate change impacts and water pollution management [208]. Coastal ecosystem engineering can reduce wave energy and runup in tropical islands, involving the modification or creation of natural ecosystems for protective functions against waves, storm surges, and disaster prevention [209]. These strategies integrate green–hybrid–gray approaches, utilizing ecosystem engineering species or adjusting hard substrates to enhance ecological functioning and reduce wave energy [210–212]. Effective ecosystem engineering approaches include the following strategies.

4.5.1. Mangrove Forests

Mangroves are highly effective in reducing wave energy and protecting against storm surges. Their dense root systems and above-ground structures act as natural barriers, dissipating wave energy and reducing the height and force of waves reaching the shore. Restoring and conserving mangrove forests and building new mangrove fringes along coastlines can help minimize wave energy and runup, providing numerous ecological benefits [213,214].

4.5.2. Coral Reefs

Healthy coral reefs can also reduce wave energy, as the complex structure, including living coral organisms and the calcium carbonate framework, acts as a natural breakwater. This dissipates wave energy and reduces wave height. Protecting and restoring coral reefs is crucial for maintaining their wave attenuation capabilities. Incorporating novel engineering approaches to coral propagation and restoration (i.e., larger, multi-species in situ and land-based nurseries, coral micro-fragmentation, larval rearing, gene banking, cryopreservation) has led to important tools for increasing the spatial scale of interventions [215,216].

4.5.3. Seagrass Meadows

Seagrass meadows contribute to reducing wave energy and offering protection against coastal erosion. The dense underwater vegetation dissipates wave energy by creating friction and turbulence, thereby decreasing the force of waves reaching the shoreline. Conserving and restoring seagrass beds are essential for wave attenuation and the rehabilitation of various ecological functions [217–219].

4.5.4. Oyster Reefs and Mussel Banks

Oyster reefs function as natural breakwaters, diminishing wave energy and safeguarding coastlines. The rough surfaces of oyster shells and the intricate structure of reef formations dissipate and attenuate wave energy. The restoration and conservation of oyster reefs can effectively mitigate wave impacts, emphasizing the importance of ecosystem engineering strategies that foster self-facilitating feedback processes and community integration for enhanced success and improved stewardship [220,221].

4.5.5. Artificial Reef Structures

Artificial reef structures, like submerged breakwaters or offshore reefs, mimic natural reefs and offer wave attenuation benefits. Crafted from materials such as concrete or rock, these structures reduce wave energy, protecting coastlines [222,223]. Simultaneously, artificial reefs deliver diverse ecological, recreational, and socio-economic advantages [224].

4.5.6. Wetlands and Salt Marshes

Wetlands and salt marshes serve as natural buffers against waves and storm surges. The vegetation and intricate root systems dissipate wave energy, lowering wave height. Conserving and restoring these coastal wetland ecosystems contribute to wave attenuation, coastal protection, and significant habitat enhancement supporting biodiversity [225,226].

4.5.7. Dunes and Beach Vegetation

Building and enhancing natural sand dunes along the shoreline, coupled with planting beach vegetation, reduces wave runup effects. Dunes act as natural barriers, absorbing and dissipating wave penetration inland. Vegetation stabilizes the dune structure, offers additional erosion protection, and rehabilitates natural habitats for wildlife [227].

4.5.8. Urban Shorelines

Urbanized coastal areas often feature gray structures like seawalls, breakwaters, groins, and jetties, leading to significant degradation of coastal natural ecosystems. Embracing ecological engineering approaches and implementing environmental policies that integrate coastal protection, climate change adaptation, and SLR mitigation with enhanced ecological benefits have become common practices [228]. This approach promotes more sustainable development in the urbanized seascapes of SIDS.

The effectiveness of ecosystem engineering strategies relies on factors like local coastal conditions, ecosystem health, and wave intensity. Successful implementation requires a thorough understanding of the specific context, consultation with coastal management and ecology experts, and meaningful integration of community stakeholders.

5. Challenging Financing Strategies: The Integration of the Private Sector

Adapting to climate change and SLR in SIDS creates challenges in securing appropriate financing. Factors such as debt burden, unequal power dynamics, limited policy autonomy, and economic exploitation exacerbate funding constraints. SIDS often lack fiscal space, struggle with limited access to international financing, and face challenges in decision making. Public budgets are restricted, necessitating external funding sources. Public–private partnerships, involving active participation from businesses, especially in tourism and other sectors, can enhance support for green/gray restoration strategies, mitigating SLR and chronic coastal erosion impacts (Figure 5).

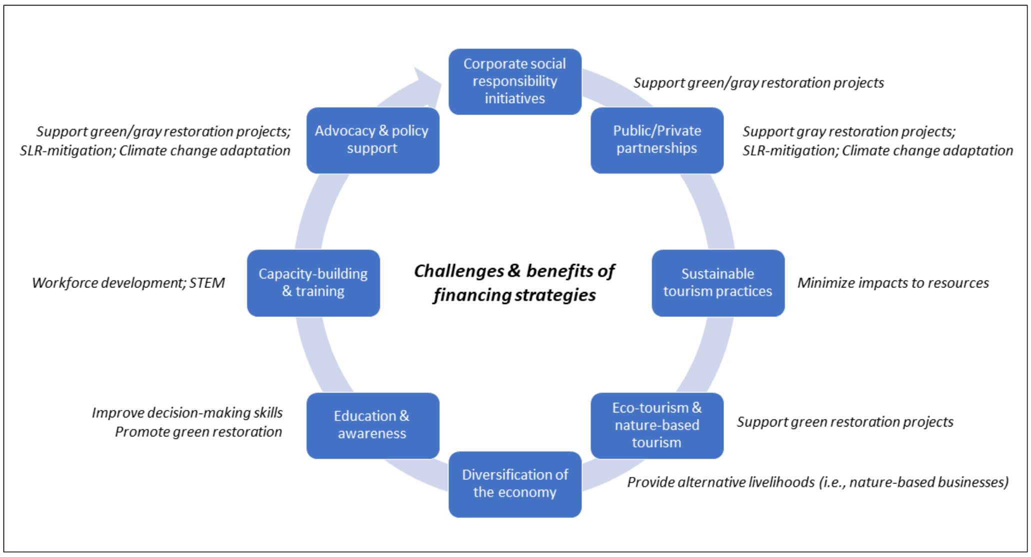

Figure 5. Conceptual model of challenges and benefits of alternative financing strategies to implement green/gray coastal restoration in SIDS.

Some potential financing strategies might include the following approaches.

5.1. *Corporate Social Responsibility (CSR) Initiatives*

Tourism businesses and other industries can contribute to sustainable development by engaging in CSR activities. These activities may involve funding or actively participating in projects related to the restoration of coral reefs, seagrasses, mangroves, and sand dunes, as well as initiatives such as beach nourishment and other measures to enhance coastal resilience. Such engagement not only benefits the environment but also aligns with the goals of responsible and sustainable business practices.

5.2. *Public–Private Partnerships*

Public–private collaborations offer a valuable opportunity to combine resources and expertise for the implementation of green infrastructure projects. Through partnerships between private businesses, local governments, conservation organizations, and community groups, initiatives aimed at enhancing coastal resilience can receive crucial funding and support. This collaborative approach fosters shared responsibility and ensures a more comprehensive and effective response to the challenges posed by climate change and SLR.

5.3. Sustainable Tourism Practices

The tourism industry in SIDS has the potential to adopt sustainable practices that mitigate its environmental impact and enhance coastal resilience. Key initiatives involve responsible waste management, eliminating single-use plastics, reducing energy and water consumption, endorsing local conservation efforts, and fostering awareness among tourists about the significance of protecting and restoring coastal ecosystems. By embracing these sustainable measures, the tourism sector can play a pivotal role in safeguarding the environment and contributing to the long-term health of coastal regions.

5.4. Eco-Tourism and Nature-Based Tourism

Encouraging eco-tourism and nature-based tourism activities that showcase the natural beauty and ecological significance of coastal areas can yield economic benefits while promoting environmental stewardship. These activities have the potential to generate funds for green infrastructure projects, providing incentives for their development and upkeep, all while involving and benefiting local communities.

5.5. Diversification of the Economy

Small islands heavily dependent on tourism can explore opportunities to diversify their economies and reduce reliance on a single sector. Supporting the growth of sustainable industries, including renewable energy, sustainable agriculture, eco-friendly manufacturing, and low-impact tourism, can create new sources of income while minimizing environmental impacts.

5.6. Education and Awareness

Private businesses, especially in the tourism industry, can play a crucial role in educating tourists about the importance of coastal resilience and the value of green infrastructure. Establishing visitor centers, offering guided tours, and providing informational materials can be effective ways to raise awareness about the impacts of climate change, the significance of coastal ecosystems, and the importance of adopting sustainable practices.

5.7. Capacity Building and Training

Implementing training programs and capacity-building initiatives for local communities and tourism stakeholders is crucial to enhance their understanding of green infrastructure and empower them to actively participate in its development and maintenance. These programs should focus on skills development in areas such as coastal management, sustainable tourism practices, and ecosystem restoration.

5.8. Advocacy and Policy Support

The tourism industry can leverage its influence to advocate for policies and regulations that prioritize the protection and development of green infrastructure. Collaborating with government bodies, industry associations, academia, and environmental organizations is essential to actively shape policies that foster sustainable development and investment in coastal resilience.

Aligning their operations and activities with green infrastructure development goals allows the tourism industry and other sectors of SIDS' economies to contribute to the long-term sustainability and resilience of small islands facing threats from climate change, SLR, and coastal erosion. This strategy must prioritize the restoration of three critical coastal ecosystems: coral reefs, seagrasses, and mangroves.

6. An Overview of Best Management Practices for Coastal Restoration in SIDS

Several best management practices (BMPs) for coastal restoration in SIDS encompass a range of ecosystems, including coral reefs, seagrass meadows, mangroves, urban coastal habitats, and strategies tailored for wave energy and runup attenuation.

6.1. Coral Reef Restoration Best Management Practices

Coral reef restoration is a specialized field aimed at rehabilitating and enhancing damaged coral reef ecosystems [229,230]. It serves as a critical tool for the restoration of declining coral species [231], the rehabilitation of degraded ecosystems [232], and the recovery of fish assemblages [233]. While it has not been widely tested for its impact on reducing wave energy and runup due to logistical and scale limitations, scaling up restoration efforts for coastal protection necessitates the integration of coastal engineering, hydrodynamics, and ecology across various spatial scales [234]. This approach should also encompass coastal zone management, climate change adaptation and mitigation, and the implementation of a comprehensive national coastal ecosystem restoration plan. Such a plan should include a list of best management practices (BMPs) to enhance success (Figure 6), considering the crucial wave attenuation roles of shallow coral reefs [71,235,236].

Some important BMPs for successful coral reef restoration include the following strategies.

6.1.1. Site Selection and Assessment

The success of coral reef restoration hinges on meticulous site selection. A comprehensive preliminary assessment of potential restoration sites is essential, considering factors like water quality, sediment dynamics, substrate suitability, coral recruitment potential, and proximity to healthy source coral populations. Evaluating both the ecological and physical characteristics of the site, along with its connectivity potential, is crucial in determining its suitability for restoration efforts and the likelihood of enhancing coral demographic performance [237,238].

6.1.2. Collaboration and Partnerships

Effective coral reef restoration frequently relies on collaboration among diverse stakeholders, including scientists, local communities, government agencies, NGOs, dive operators, hotels, and other private businesses. Nurturing partnerships and involving stakeholders throughout the entire restoration process is crucial to fostering shared knowledge, resources, and support.

6.1.3. Monitoring and Evaluation

A comprehensive monitoring and evaluation program is essential for assessing the progress and effectiveness of coral reef restoration initiatives. Regular monitoring should encompass key parameters such as coral growth, survivorship, recruitment, and overall ecosystem health [239]. Additionally, monitoring water physico-chemical parameters, including turbidity, transparency, solid suspended materials, sedimentation, nutrient concentration, dissolved oxygen concentration, temperature, and salinity, is crucial. This information guides adaptive management strategies and informs future restoration endeavors.

6.1.4. Genetic Diversity and Local Adaptation

Recent developments in coral reef restoration science highlight the significance of restoring genetic diversity and employing assisted evolution techniques. These techniques include selective breeding, assisted gene flow, conditioning or epigenetic programming, and manipulating the coral microbiome to enhance the environmental stress tolerance of corals and improve the success of future restoration efforts [240]. It is crucial to use locally sourced coral colonies or fragments to encourage local adaptation and genetic resilience. Additionally, considering the diversity of coral species and genetic connectivity between populations is essential when selecting corals for restoration. Understanding oceanographic dynamics is also critical in choosing restoration locations to promote enhanced genetic diversity and improve genetic connectivity.

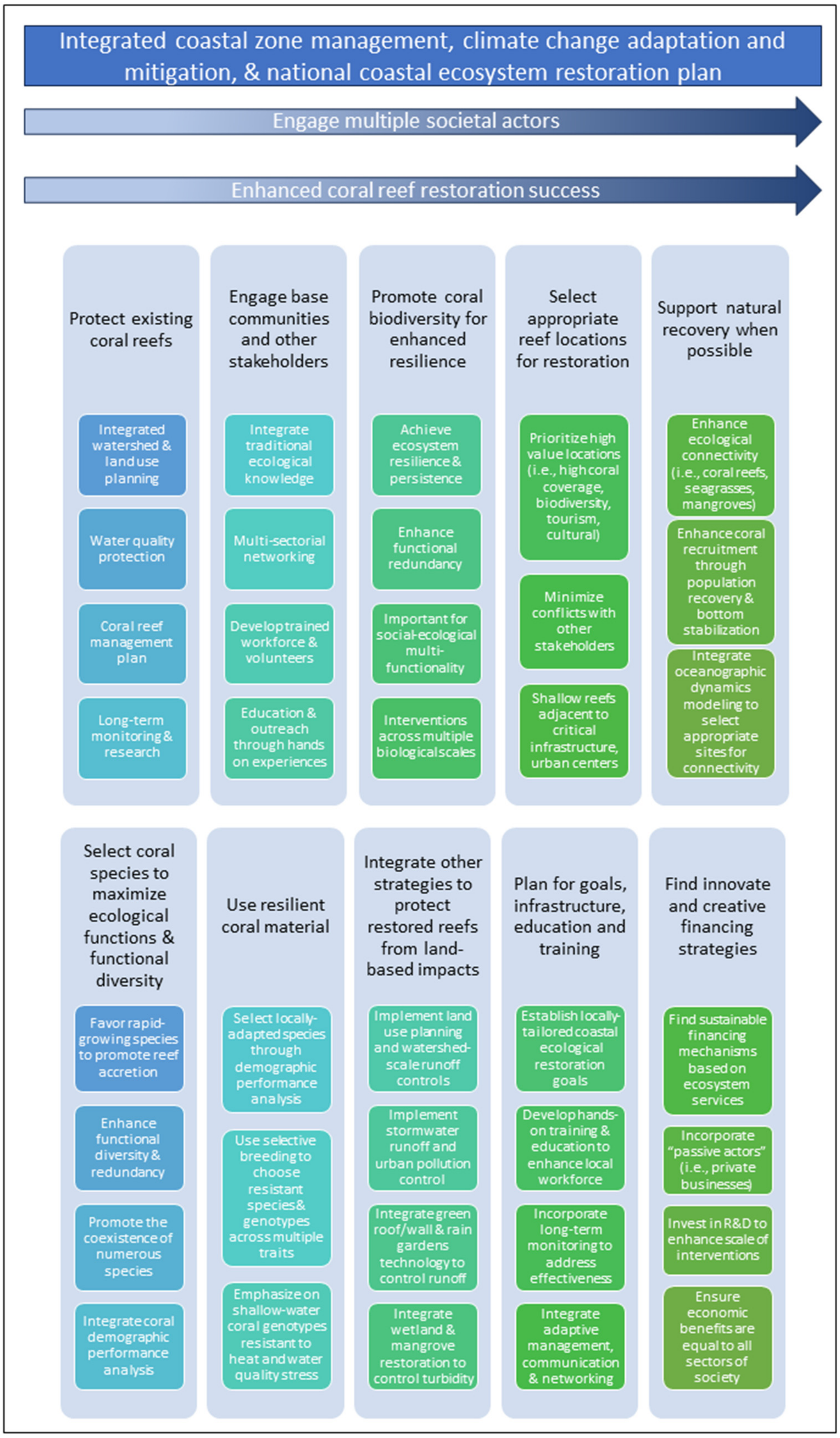

Figure 6. Conceptual integration of critical planning and implementation steps necessary to achieve successful coral reef ecological restoration in SIDS. These actions should be implemented within a larger framework that should integrate coastal zone management, climate change adaptation and mitigation, and the incorporation of a national coastal ecosystem restoration plan. Figure adapted from Quigley et al. [241].

6.1.5. Coral Propagation and Nursery Techniques

Utilize coral propagation techniques, including coral fragmentation and micro-fragmentation, along with a combination of field methods [242], to generate numerous coral colonies for restoration purposes. Establish coral nurseries to grow and acclimate coral fragments before deploying them onto restoration sites. The choice between onshore and offshore nurseries should be based on local conditions, available resources, and specific project requirements.

6.1.6. Out-Planting Strategies

Thorough planning and meticulous execution of out-planting techniques are essential for the success of coral reef restoration. Ensure secure attachment of coral fragments to the substrate, considering factors such as substrate stability, water flow, sediment bedload, potential competition from other reef species, and predation risks. Maintain appropriate spacing and densities to optimize growth and minimize inter-coral competition. Avoid substrates dominated by turf, macroalgae, sponges, and fire coral. The potential integration of emerging technologies, such as 3D-printed coral colonies (if economically feasible), has shown promise in promoting enhanced fish recruitment, thereby supporting the survival and growth of out-planted corals [243].

6.1.7. Coral Disease and Predation Management

Implement strategies to mitigate the risk of coral diseases and predation on restored corals. Establish quarantine measures and treat coral fragments if needed to prevent the introduction or spread of coral diseases. Employ physical or chemical deterrents, such as predator exclusion devices or antifouling coatings, to safeguard out-planted corals.

6.1.8. Community Involvement and Education

Involve and engage local communities actively in coral reef restoration initiatives. Educate them about the significance of coral reefs, their contribution to livelihoods, and the advantages of restoration efforts. Encourage sustainable practices, including responsible fishing and pollution reduction, to contribute to the enduring well-being of restored coral reefs.

6.1.9. Long-Term Management and Protection

Develop comprehensive, long-term management plans for restored coral reefs, incorporating strategies to safeguard them against human-induced threats like destructive fishing practices, pollution, and climate change stressors. Implement effective regulations, zoning practices, and enforcement mechanisms to ensure the sustained health and resilience of the restored reefs.

6.1.10. Adaptive Management and Knowledge Sharing

Adapt management strategies based on monitoring data and scientific research findings. Foster knowledge exchange and collaboration within the scientific and restoration community to share lessons learned and BMPs, thereby continually refining restoration techniques and bolstering the success of future projects [174,175].

Coral reef restoration is a dynamic and evolving field, and these BMPs should be adapted to local conditions and specific project goals. Collaboration, adaptive management, and ongoing research are essential for ensuring the long-term success of coral reef restoration efforts. Critical concerns in SIDS include increasing restoration efficiency, scaling up larval-based efforts, ensuring restoration aligns with population genetics management, adopting a holistic approach, promoting standardized terms and metrics, and supporting practitioners in diverse geographic locations, including SIDS [244].

6.2. Seagrass Restoration Best Management Practices

Seagrass restoration endeavors to rehabilitate and enhance degraded or lost seagrass meadows [245], playing a crucial role in preserving ecosystem services [246]. These efforts have become essential for seagrass conservation [247,248], with notable advancements made in recent years to enhance the success and scalability of interventions [249]. BMPs for seagrass restoration include the following approaches.

6.2.1. Site Selection and Assessment

Thoroughly assessing potential restoration sites is crucial to determine their suitability for seagrass restoration. Factors such as water quality, sediment characteristics, light availability, and historical seagrass presence should be considered. This comprehensive evaluation of the site's ecological and physical characteristics is essential to ensure the success of restoration efforts [217].

6.2.2. Seed Collection and Propagation

Identify local seagrass species and collect seeds or propagules from healthy populations in nearby areas. Establish seagrass nurseries to propagate and grow these seeds or propagules before out-planting them onto restoration sites, especially if managing seagrass genetic diversity is a concern. Optimize nursery conditions, including light, temperature, and nutrient levels, to promote healthy growth.

6.2.3. Seeding and Out-Planting Techniques

Implement suitable seeding and out-planting techniques based on the selected seagrass species and site conditions. This may involve directly seeding seagrass seeds or transplanting seedlings or adult shoots onto the restoration site. Ensure proper anchoring and placement of seagrass material to promote successful establishment.

6.2.4. Monitoring and Evaluation

Implementing a thorough monitoring and evaluation program is crucial to assessing the progress and effectiveness of seagrass restoration efforts. Regularly monitor key parameters such as seagrass density, shoot growth, survival rates, and sediment characteristics. Evaluate the response of the restored seagrass meadows by comparing them to reference sites or nearby healthy meadows. Additionally, quantify the impacts on associated fauna within the seagrass ecosystem.

6.2.5. Water Quality Management

Optimizing water quality conditions is essential for supporting seagrass growth and survival. Minimize sedimentation and nutrient inputs that can negatively impact seagrass health. Implement effective measures to reduce pollution sources, including addressing agricultural runoff, wastewater discharge, and coastal development impacts.

6.2.6. Habitat Protection and Management

Safeguarding restored seagrass habitats is crucial, necessitating protection from destructive activities like recreational navigation, anchoring, trampling, bottom trawling, and dredging. Establishing marine protected areas or implementing zoning regulations is essential to prevent damage to seagrass meadows. Continuous monitoring and management of human activities are imperative to mitigate potential risks to the restored areas.

6.2.7. Community Involvement and Education

Incorporating local communities into seagrass restoration efforts is essential. Providing education about the ecological significance of seagrass meadows, their contribution to supporting fisheries, and the advantage of restoration is crucial. Promoting sustainable practices, such as responsible boating and fishing, helps protect the restored seagrass habitats and ensures community involvement in their preservation.

6.2.8. Sediment Stabilization and Erosion Control

To ensure the stability of sediments and prevent erosion in and around restored seagrass areas, it is essential to implement measures such as establishing vegetative buffers, managing coastal development responsibly, and reducing land-based sources of sediment runoff. These actions contribute to the long-term success and resilience of seagrass restoration efforts.

6.2.9. Long-Term Management and Adaptive Strategies

Establishing long-term management plans for restored seagrass meadows is crucial for their ongoing health and resilience. These plans should incorporate regular monitoring, adaptive management, and maintenance activities. Additionally, it is important to protect against invasive species, such as the Indian Ocean sea vine (*Halophila stipulacea*) on Caribbean seagrasses [250]. Continuous assessment and adaptation of restoration strategies based on monitoring data and scientific research findings are essential components of effective seagrass conservation.

6.2.10. Collaboration and Knowledge Sharing

Encouraging collaboration among scientists, restoration practitioners, and stakeholders is essential for the success of seagrass restoration initiatives. This collaborative approach facilitates the sharing of knowledge, experiences, and BMPs for seagrass restoration. By exchanging lessons learned and research findings, the collective understanding of restoration techniques can be improved, leading to greater success in future projects.

Successful seagrass restoration demands meticulous planning, considering site-specific factors and continuous monitoring. Quantifying the demographic performance of restored seagrass is crucial, with BMPs needing customization for the specific conditions and goals of each restoration project in SIDS. Collaboration, adaptive management, and stakeholder engagement emerge as vital elements for ensuring the sustained success of seagrass restoration initiatives.

6.3. Mangrove Restoration Best Management Practices

Mangrove restoration endeavors to rehabilitate and enhance degraded or lost mangrove ecosystems, restoring their vital ecosystem processes [251]. Various restoration strategies and approaches are employed based on specific project objectives [252]. Key BMPs for mangrove restoration include the following approaches.

6.3.1. Site Selection and Assessment

The initial step in mangrove restoration involves a comprehensive assessment of potential sites to ascertain their suitability. Considerations such as hydrology, sediment characteristics, salinity levels, and proximity to healthy mangrove populations are crucial factors. This thorough evaluation of the site's ecological and physical characteristics is essential to ensure the success of restoration efforts.

6.3.2. Native Species Selection

Identify and use native mangrove species that are appropriate for the specific site conditions. Select mangrove species that are naturally found in the area or have historically occurred there. Using native species ensures better adaptation to local conditions and enhances the ecological integrity of the restored mangrove ecosystem.

6.3.3. Propagation and Planting Techniques

For effective mangrove restoration, it is imperative to employ suitable propagation and planting techniques [252]. This encompasses methods such as collecting and germinating mangrove propagules or cultivating mangrove seedlings in nurseries. Planting techniques may involve the direct placement of propagules or seedlings in favorable substrate conditions, considering proper spacing and orientation. The spatial configuration can vary based on the project's objectives and location.

6.3.4. Hydrological Restoration

In certain situations, particularly after significant mechanical disturbances like hurricanes or human-driven impacts, restoring or emulating natural hydrological conditions becomes crucial to support mangrove growth. Ensuring that tidal flows, freshwater inputs, and drainage patterns are conducive to mangrove ecosystems is vital. Hydrological restoration may entail reinstating or constructing channels, tidal creeks, or hydrological connections to facilitate proper water exchange [253,254].

6.3.5. Sediment Stabilization

Implementing measures to stabilize sediments and prevent erosion in and around restored mangrove areas is crucial. Mangrove roots and vegetation play a vital role in trapping sediments, mitigating coastal erosion, and contributing to land building [255]. Additionally, mangroves capture organic carbon in their soils, helping to maintain coastal water quality [256]. Restoration efforts can enhance sediment and nutrient trapping by promoting natural mangrove recruitment, especially when incorporating appropriate engineering techniques such as designed mangrove patches.

6.3.6. Monitoring and Evaluation

Implementing a comprehensive monitoring and evaluation program is essential to assess the progress and effectiveness of mangrove restoration efforts [257]. Regularly monitoring parameters such as mangrove density, height, canopy cover, growth and survival rates, and biodiversity is crucial. This helps assess the response of the restored mangrove ecosystem and allows for comparisons with reference sites or nearby healthy mangroves.

6.3.7. Community Involvement and Education

Engaging and involving local communities in mangrove restoration efforts is crucial. Educating communities about the ecological importance of mangroves, their role in coastal protection, and the benefits of restoration is key. Encouraging community stewardship and promoting sustainable practices, such as responsible fishing and mangrove conservation, fosters a sense of ownership and ensures the long-term success of restoration initiatives.

6.3.8. Habitat Protection and Management

Protecting restored mangrove habitats is essential to their long-term success. Preventing destructive activities such as illegal logging, aquaculture, overfishing, and land-use conversion is crucial. Establishing protected areas or implementing zoning regulations can help prevent encroachment and damage to mangrove ecosystems. Collaborating with local authorities and stakeholders to enforce protection measures ensures the continued health and resilience of restored mangrove habitats.

6.3.9. Climate Change Resilience

When planning mangrove restoration projects, it is crucial to consider the potential impacts of climate change on the ecosystems. Designing projects with future climate scenarios in mind, including projected SLR and increased storm frequency, is essential. To enhance the resilience of restored mangroves, incorporate measures such as creating diverse age and species structures. Additionally, implementing coastal protection measures, such as combining artificial reefs and coral reef restoration, can further contribute to the overall resilience of the ecosystem.

6.3.10. Collaboration and Knowledge Sharing

Collaboration among scientists, restoration practitioners, private businesses, and stakeholders is essential for successful mangrove restoration. By fostering partnerships and sharing knowledge, experiences, and BMPs, the collective effort can leverage resources and expertise. Engaging with local communities, NGOs, and government agencies further enhances support for mangrove restoration initiatives, ensuring a more comprehensive and effective approach.

Mangrove restoration demands meticulous planning, site-specific considerations, and sustained management. A comprehensive, long-term strategy should encompass the restoration of other natural coastal systems like coral reefs and seagrasses. BMPs must be customized to the unique conditions and goals of each restoration project, especially in SIDS and urban coastal habitats. Successful outcomes hinge on collaboration, adaptive management, and active engagement with stakeholders for enduring success.

6.4. Urban Coastal Habitats Restoration Best Management Practices

Revitalizing urban coastlines poses a multifaceted challenge, requiring the rehabilitation and enhancement of chronically degraded or damaged coastal habitats within urban environments. Often confronted with adverse environmental conditions and notable obstacles, urban coastal restoration plays a vital role in reclaiming impaired ecological functions and processes [258–260]. BMPs for coastal habitat restoration include the following strategies.

6.4.1. Integrated Coastal Management

Embrace an integrated approach to coastal management that encompasses the ecological, social, and economic dimensions of the urban coastline. Develop comprehensive management plans addressing concerns like coastal erosion, water quality, habitat loss, and recreational requirements. Incorporate principles of sustainability and resilience to ensure a holistic and enduring strategy.

6.4.2. Stakeholder Engagement and Collaboration

Involve and engage local communities, government bodies, NGOs, businesses, and other stakeholders in the restoration process. Foster collaboration to incorporate diverse perspectives and secure support, resources, and expertise for restoration projects. Encourage participation through public consultations, workshops, partnerships, and hands-on involvement in the restoration efforts.

6.4.3. Ecological Assessment and Planning

Perform ecological assessments to comprehend the present conditions and ecological dynamics of the urban coastline. Identify crucial ecological features like wetlands, dunes, or mangroves, and evaluate their ecological functions and values. Utilize this information to guide restoration planning and prioritize areas for intervention.

6.4.4. Green Infrastructure and Nature-Based Solutions

Integrate green infrastructure and nature-based solutions into urban coastline restoration. Employ techniques like green roofs, permeable pavements, rain gardens, and bioswales to manage stormwater runoff and enhance water quality. Include the restoration of natural habitats such as dunes, wetlands, oyster reefs, coral reefs, seagrass meadows, and mangroves to improve biodiversity, wave energy attenuation, shoreline stabilization, and flood resilience.

6.4.5. Erosion and Sediment Management

Implementing erosion and sediment management measures is essential to protect and restore urban coastlines. Utilize strategies like beach nourishment, sediment bypassing, groins, breakwaters, and soft engineering techniques such as vegetated dunes or bioengineering. It is crucial to deploy appropriate erosion control structures while maintaining the natural sediment transport processes.

6.4.6. Water Quality Improvement

Implementing measures to enhance water quality along the urban coastline is crucial. Minimize pollutant inputs from urban runoff by advocating BMPs, including reducing impervious surfaces, adopting green infrastructure, and installing stormwater treatment systems. Monitor and manage land-based sources of pollution to safeguard both human health and the ecological integrity of the coastal ecosystem [261,262].

6.4.7. Habitat Restoration and Creation

Enhance biodiversity and ecological functions along the urban coastline by restoring or creating habitats. This may include the restoration of adjacent coral reefs, seagrass meadows, mangroves, wetlands, or salt marshes. Additionally, consider the creation of artificial habitats such as oyster reefs or submerged breakwaters. Consider habitat connectivity and ecological corridors to facilitate wildlife movement [263].

6.4.8. Public Access and Recreation

Design restored urban coastlines with public access and recreational opportunities in mind. Create trails, boardwalks, or viewing platforms to enable people to enjoy and learn about the restored coastal areas. Ensure accessibility for diverse user groups while preserving the ecological integrity of the restored habitats.

6.4.9. Education and Awareness

Promote education and awareness programs to engage the public and stakeholders in the importance of urban coastline restoration. Conduct outreach activities, interpretive signage, and educational programs to raise awareness about the ecological, social, and economic benefits of restored coastlines. Encourage community stewardship and participation in ongoing monitoring and maintenance efforts.

6.4.10. Long-Term Monitoring and Adaptive Management

Establish long-term monitoring programs to assess the success and effectiveness of urban coastline restoration projects [264]. Regularly monitor ecological indicators, water quality parameters, and coastal processes to evaluate the outcomes of restoration efforts. Use the monitoring data to adapt management strategies, make informed decisions, and guide future restoration projects.

These BMPs for urban coastline restoration should be tailored to the specific context, challenges, and opportunities of each urban coastal area, especially in SIDS. Collaboration, adaptive management, and engagement with stakeholders are also crucial for the successful restoration of urban environments.

6.5. Wave Energy and Runup Attenuation Best Management Practices

Reducing wave energy and mitigating wave runup are fundamental considerations in SIDS, especially with projected SLR and increasing storm intensities. Coral reefs traditionally act as the primary defense against wave action. Unfortunately, chronic environmental degradation and coral decline have led to reef flattening [66,67,265], compromising their ability to attenuate wave energy. Key BMPs for wave energy and runup attenuation include the following approaches.

6.5.1. Natural and Nature-Based Features

Restore natural and nature-based features to attenuate wave energy and runup [234]. These features encompass coral reefs, submerged or emergent vegetation (such as seagrasses, mangroves, and salt marshes), dune systems, and wetlands. These elements play a crucial role in dissipating wave energy, lowering wave height, and trapping sediment, thereby offering effective coastal protection.

6.5.2. Beach Nourishment and Sediment Management

Implement beach nourishment projects to restore and widen beaches. Proper sediment management is vital for maintaining the protective function of the beach [176,266]. Regularly monitor sediment movement patterns, identify potential sources of sediment, and implement strategies to ensure a sustainable sediment supply.

6.5.3. Submerged Breakwaters and Groins

Install submerged breakwaters and groins strategically along the coastline to attenuate wave energy [267]. Breakwaters are offshore structures that reduce wave height by dissipating and reflecting wave energy. Groins are perpendicular structures extending from the shoreline that trap sediment and help build up beaches, reducing wave runup.

6.5.4. Seawalls and Revetments

Seawalls and revetments are commonly used coastal defense structures as a last alternative when shoreline erosion becomes critical [268,269]. However, they can reflect wave energy and cause increased erosion in adjacent areas [178]. When using these structures, careful design and consideration should be given to minimize wave reflection and maintain natural sediment longshore transport processes.

6.5.5. Offshore Artificial Reefs and Submerged Structures

Construct offshore artificial reefs or submerged structures to break waves before they reach the shoreline. These structures can be designed to dissipate wave energy and reduce wave height [270–272]. They also create habitats for marine organisms and support biodiversity and can be combined with coral transplanting to the submerged structures [273,274].

6.5.6. Coastal Setbacks and Land-Use Planning

Implement coastal setback regulations and land-use planning strategies to ensure appropriate development setbacks from the shoreline. This approach helps protect coastal areas from erosion, maintains natural shoreline dynamics, and allows for the establishment of natural buffers such as dunes or wetlands [159]. However, this could have severe geographic constraints in SIDS with limited surface area and may result in impairing coastal development on a large proportional land surface.

6.5.7. Living Shorelines

Use living shoreline approaches, which involve the strategic placement of native vegetation (i.e., mangroves), oyster reefs, or other natural materials to protect the shoreline [275,276]. Living shorelines provide wave attenuation, erosion control, and habitat enhancement, while also promoting natural ecosystem processes, including recovering depleted biodiversity.

6.5.8. Coastal Vegetation and Dune Restoration

Restore and maintain coastal vegetation, including dune systems, to attenuate wave energy and stabilize sediments [277,278]. Native vegetation, such as beach grasses and shrubs, can provide effective wave runup attenuation during storm events and/or winter swells, and help trap sand, contributing to dune formation and stability. It also provides habitat for numerous species.

6.5.9. Coastal Monitoring and Adaptive Management

Establish long-term monitoring programs to assess the effectiveness of wave energy and runup attenuation measures. Regularly monitor wave conditions, beach profiles, sediment movement, ecological parameters, and the structural integrity of built structures. Monitoring data should be used to evaluate the performance of the implemented measures and make necessary adjustments through adaptive management.

6.5.10. Public Education and Awareness

Promote public education and awareness about the importance of wave energy and runup attenuation for coastal resilience. This might include hands-on experiences (i.e., through sand dune vegetation, mangrove, or coral reef restoration). Engage communities through outreach programs, interpretive signage, and educational campaigns to foster understanding and stewardship of coastal protection measures.

It is crucial to consider site-specific conditions, environmental factors, and local regulations when implementing wave energy and runup attenuation measures. Integrated coastal management approaches that incorporate natural and nature-based solutions often provide more sustainable and ecologically beneficial outcomes, particularly if local communities and other stakeholders are involved. Additionally, it is paramount to consider the benefits of any coastal habitat restoration activity beyond the protection of shorelines from wave action and erosion.

7. Beyond Shoreline Protection: Ecological Benefits from Coastal Ecological Restoration

There are numerous ecological benefits from coastal ecological restoration of coral reefs, seagrass meadows, and mangroves that further magnify the benefits that restoration provides for coastal protection.

7.1. Coral Reefs

Coral reef restoration can have numerous ecological impacts that can result in significant habitat enhancement and biodiversity recovery (Figure 7). Restoration outcomes include also numerous socio-economic benefits that improve livelihoods and well-being of local communities. Some of the ecological impacts include the following list.

Figure 7. Model of numerous benefits derived from the ecological restoration of coral reef, seagrass, and mangrove ecosystems. Enhancing the scale of restoration interventions, as well as the diversity of restored ecosystems, will improve obtained benefits to society, including socio-economic resilience, improved livelihood and well-being, job opportunities, and other cultural benefits.

7.1.1. Habitat Improvement and Restoration of Critical Ecological Processes

Coral reef restoration seeks to rehabilitate habitats damaged by hurricanes, mass coral mortality events, or human activities. Successful restoration enhances habitat complexity, creating niches for diverse organisms and bolstering coral reef ecosystem resilience [241,279,280]. It improves substrate availability for coral settlement, facilitating the growth of new colonies, and contributes to natural reef accretion and carbon sequestration.

7.1.2. Biodiversity Enhancement

Restored coral reefs contribute to increased biodiversity by offering habitats for a diverse array of species [281,282]. Healthy coral reefs are recognized for their abundant fish, invertebrates, and other marine organisms. Successful restoration aids in the recovery and preservation of diverse coral reef ecosystems, supporting essential biogeochemical and geo-ecological processes such as herbivory, nutrient connectivity, and sediment movement.

7.1.3. Ecological Connectivity

Coral reef restoration enhances ecological connectivity among reefs and associated habitats, such as seagrasses and mangroves. Restoring and connecting fragmented reef habitats facilitates the movement of organisms, including coral larvae and other marine species, promoting genetic diversity and population resilience [283,284].

7.1.4. Ecosystem Functioning

Restored coral reefs enhance ecosystem functioning, including nutrient cycling, energy flow, and trophic interactions, while also providing critical services such as fish production, coastal protection, and shoreline stabilization [285,286]. Restoration efforts aimed at improving reef structure and diversity are key to sustaining or restoring these vital ecosystem functions.

7.1.5. Enhanced Resilience to Disturbance

Coral reef restoration enhances the resilience of coral ecosystems by reinstating crucial ecological processes and bolstering overall reef health and stability. Restored reefs demonstrate the potential to endure and recover from environmental stressors like coral bleaching, disease outbreaks, and physical disturbances. Moreover, restoration efforts can boost the adaptive capacity of coral reefs to face future challenges, including impacts from climate change [287,288].

7.1.6. Habitat Availability and Complexity

Coral reef restoration can significantly impact fish assemblages, thereby supporting biodiversity and artisanal fisheries. By restoring the physical structure and complexity of reefs, restoration efforts provide additional habitat for fish communities. Restored coral reefs offer suitable shelter, feeding grounds, and breeding sites for various fish species. This increased habitat availability can lead to higher fish densities and greater diversity [289,290].

7.1.7. Fish Recruitment and Nursery Habitats

Healthy coral reefs play a vital role as crucial nursery areas for many fish species [291]. Successful restoration efforts that restore coral cover and structural complexity can improve the availability of nursery habitats. This enhancement promotes fish recruitment and sustains the early life stages of various fish species.

7.1.8. Associated Species Diversity and Abundance

Coral reefs are known for their rich diversity and abundance of fish species [292,293]. Successful coral reef restoration efforts can play a vital role in the recovery and maintenance of species diversity and abundance within fish communities. Restored reefs offer a range of niches, resources, and ecological functions that support various fish functional groups, including herbivores, carnivores, and planktivores.

7.1.9. Trophic Interactions and Food Webs

Coral reef restoration can trigger cascading effects on trophic interactions and food webs within fish communities. Healthy coral reefs sustain intricate trophic relationships, with different fish species occupying diverse trophic levels [294]. Restoration initiatives fostering coral recovery and bolstering overall reef health can facilitate the functioning of food webs and bolster fish populations across various trophic levels. This enhances biodiversity and boosts net coastal productivity.

7.1.10. Fish Assemblage Composition and Biomass

Coral reef restoration can shape the composition and biomass of fish assemblages by furnishing habitats suited to specific species. Restored reefs may draw and sustain particular fish species closely tied to healthy coral ecosystems, potentially altering the relative abundance and distribution of fish species within the restored area.

7.1.11. Improved Population Dynamics

Coral reef restoration can improve connectivity among various reef areas, facilitating the movement of fish larvae and adults. Restored reefs can serve as stepping-stones or corridors, aiding fish dispersal and gene flow through restored corridors. This connectivity is vital for preserving genetic diversity, population resilience, and the exchange of individuals among reef systems. Enhanced connectivity fosters population movement, energy flow, and increased coastal productivity.

7.1.12. Response to Disturbances

Coral reef restoration enhances the resilience of fish communities by bolstering reefs' capacity to rebound from disturbances. Restored reefs can serve as refuges for fish populations during or after events like coral bleaching, storms, or pollution incidents. With healthy coral cover and complex habitat structures, fish gain heightened protection and access to resources, aiding their ability to withstand and recover from disturbances.

7.1.13. Potential for Unintended Impacts

Coral reef restoration, aimed at improving reef health, can inadvertently lead to potential adverse ecological impacts. For instance, if restoration involves transplanting corals from different locations, there is a risk of introducing genetic traits not naturally suited to the local environmental conditions. This could affect local adaptation and genetic diversity. Moreover, restoration methods like coral gardening or transplantation may cause localized physical impacts on the substrate or adjacent benthic communities. Therefore, minimizing or avoiding impacts on habitats such as seagrasses from coral nursery installation and operation is crucial.

The ecological impacts of coral reef restoration on ecosystem health and fish communities can vary depending on several factors, including the specific restoration techniques employed, the scale and spatial extent of restoration, the characteristics of local fish populations, and the broader ecological context of the reef ecosystem. Continuous monitoring and research are essential to assess the long-term effects of restoration efforts on fish communities and to inform adaptive management strategies.

To ensure the ecological success of coral reef restoration, it is vital to consider the specific ecological needs of the target reef, use native and locally sourced coral species, and employ best management practices (BMPs) for restoration techniques. Monitoring and adaptive management are essential for assessing the long-term ecological impacts of restoration efforts and making necessary adjustments to maintain the ecological integrity and sustainability of restored coral reef ecosystems.

7.2. Seagrass Meadows

Seagrass restoration offers broader ecological benefits beyond wave action mitigation for SIDS, enhancing the overall health of interconnected coastal ecosystems (Figure 7). Key impacts include the list below.

7.2.1. Habitat Provision

Seagrass restoration fosters vital habitats for diverse marine organisms, acting as nurseries that offer shelter, food, and protection to numerous fish species, invertebrates, and young organisms. This restoration promotes connectivity with coral reefs and other associated ecosystems [295], bolstering habitat availability and boosting biodiversity and the abundance of commercially valuable marine life.

7.2.2. Improved Water Quality

Seagrasses are instrumental in enhancing water quality by capturing sediment, reducing turbidity, and improving water clarity [296]. Restored seagrass meadows aid in sediment stabilization, erosion reduction, and nutrient and pollutant filtration, leading to improved water quality. This fosters favorable conditions for adjacent coral reefs and fish populations, thereby enhancing overall productivity.

7.2.3. Carbon Sequestration

Seagrasses act as highly effective carbon sinks and can sequester and store substantial amounts of carbon dioxide (CO_2) from the atmosphere [297–299]. Restoration efforts aimed at seagrass meadows enhance their carbon sequestration capacity, aiding in the mitigation of climate change impacts. With seagrass meadows capable of sequestering carbon at rates surpassing those of terrestrial forests, they play a crucial role in global carbon budgets [300].

7.2.4. Enhanced Biodiversity and Species Richness

Seagrass restoration fosters enhanced biodiversity and species richness within coastal ecosystems. Seagrass meadows offer microhabitats for a diverse array of organisms, including fish, invertebrates, and macroalgae [301,302]. Notably, seagrass restoration exerts significant impacts on fish communities by furnishing crucial nursery areas, foraging grounds, and shelter for numerous commercially valuable fish species. This support for the recruitment, growth, and survival of juvenile fish enhances their diversity and abundance, thus bolstering ecosystem resilience and functionality.

7.2.5. Food Resources

Seagrass meadows offer a rich variety of food resources for fish, encompassing microorganisms, invertebrates, and detritus. Through seagrass restoration, the availability of these food sources is augmented, fostering productivity and foraging opportunities for fish communities. Consequently, this augmentation can yield amplified fish biomass and diversity within restored seagrass areas, potentially prompting fish spillover effects to adjacent grounds.

7.2.6. Trophic Interactions

Seagrass restoration plays a pivotal role in shaping trophic interactions within fish communities. These habitats provide a diverse array of prey species, including small invertebrates and zooplankton, which serve as vital food sources for fish. Consequently, the restoration of seagrass habitats amplifies the overall productivity of the ecosystem, fostering intricate trophic interactions that benefit fish populations across various trophic levels.

7.2.7. Shelter and Protection

Seagrass meadows serve as crucial shelters and sanctuaries for fish, especially small or cryptic species. The dense blades of seagrass offer effective cover from predators, thereby lowering predation pressure on fish populations. Restoring seagrass habitats expands the availability of natural protected areas within coastal ecosystems, nurturing fish communities and fortifying their population resilience.

7.2.8. Ecological Connectivity and Migration

Seagrass restoration plays a fundamental role in strengthening connectivity among various coastal habitats, fostering fish migration across ecosystems. Fish species dependent on seagrass for feeding or reproduction can move between restored seagrass meadows and adjacent habitats like coral reefs or mangroves. This connectivity is instrumental in preserving genetic diversity, fortifying population resilience, and enabling the exchange of individuals among diverse habitats.

7.2.9. Nutrient Cycling and Productivity

Seagrass meadows are essential for nutrient cycling in coastal ecosystems [303,304]. They efficiently uptake and recycle nutrients like nitrogen and phosphorus from the water column and sediments, thereby fostering nutrient balance and mitigating eutrophication risks. Restored seagrass beds amplify primary productivity, furnishing food and energy for diverse organisms within the ecosystem.

7.2.10. Erosion Control and Shoreline Stability

Seagrasses support extensive root systems that effectively stabilize sediments, safeguarding coastlines against erosion. Restored seagrass meadows offer natural coastal protection by diminishing wave energy and capturing sediments, thus ensuring shoreline stability, and safeguarding adjacent habitats like beaches, mangroves, and coral reefs.

7.2.11. Enhanced Ecosystem Services and Social–Ecological Resilience

Seagrass restoration offers numerous ecosystem services, ranging from supporting fisheries to providing recreational opportunities and shoreline protection. Vibrant seagrass ecosystems serve as crucial fish habitats, supporting productive fisheries, while also catering to recreational activities like snorkeling, diving, and boating. By restoring seagrass habitats, these ecosystem functions are bolstered, fortifying the resilience of fish communities against environmental fluctuations. Moreover, seagrass meadows play a pivotal role in shoreline protection, mitigating the impact of storm surges, erosion, and SLR, thereby enhancing the socio-economic resilience of coastal communities.

It is important to acknowledge the variability in the success and ecological impacts of seagrass restoration, influenced by factors like seagrass species, restoration methods, site conditions, and ongoing management. Similarly, fish community responses to seagrass restoration are influenced by factors such as fish species diversity, habitat condition, and habitat connectivity. Thus, continuous monitoring of fish populations and assessing long-term ecological impacts are essential for informed management decisions and adaptive restoration strategies, guiding future restoration endeavors.

7.3. Mangroves

Mangrove restoration is vital for SIDS, offering ecological benefits beyond coastal protection (Figure 6). It enhances coastal ecosystem health and functioning, particularly by supporting fish communities through habitat provision, food resources, and shelter. Key ecological impacts of mangrove restoration include the following list.

7.3.1. Habitat Provision

Restoring mangrove forests enhances habitat availability, offering shelter, breeding sites, and foraging grounds for a diverse array of organisms such as fish, birds, crustaceans, and reptiles [305]. This fosters increased biodiversity and fish abundance within the restored areas.

7.3.2. Food Resources

Mangroves play a crucial role in the productivity and food web dynamics of SIDS coastal ecosystems [306]. They supply organic matter, leaf litter, detritus, and microorganisms, serving as vital food sources for numerous fish species. Restoring mangroves amplifies the availability of these food resources, bolstering the feeding and foraging activities of fish communities. Additionally, mangroves offer shelter and sustenance to fish assemblages during and after disturbances, facilitating their recovery and survival. Consequently, this can result in heightened fish biomass and enhanced conditions of fish populations.

7.3.3. Nursery Function

Mangroves serve as fundamental nursery habitats for a wide array of fish species, including those of commercial and ecological significance [307,308]. The intricate root systems, mangrove prop roots, and shallow water areas offer shelter and protection for juvenile fish during their early life stages. Restoring mangroves amplifies the availability of these nursery habitats, fostering the growth, survival, and recruitment of juvenile fish populations.

7.3.4. Spawning and Breeding Grounds

Many fish species depend on mangroves as their main spawning and breeding grounds [309]. Mangrove forests provide sheltered areas, calm waters, and suitable substrate essential for fish reproduction. By restoring mangroves, the availability and quality of these spawning and breeding grounds are enhanced, creating optimal conditions for reproductive activities. Consequently, this contributes to the persistence and abundance of fish populations.

7.3.5. Trophic Interactions

Mangroves are pivotal in facilitating trophic interactions within fish communities. They offer habitats and food resources for a range of prey species, including crustaceans, mollusks, and insects, which are crucial prey for fish. Restoring mangroves augments the overall productivity and complexity of the food web, fostering diverse trophic interactions and sustaining fish populations across various trophic levels.

7.3.6. Ecological Connectivity and Migration

Restoring mangrove forests can improve connectivity among diverse coastal habitats, aiding fish migration. Mangroves serve as transitional zones between marine and terrestrial environments, linking estuaries, seagrass beds, coral reefs, and open ocean areas [310]. This connectivity facilitates the movement of fish species between habitats, fostering genetic exchange, energy flow, and population connectivity. Ultimately, it promotes resilience in fish communities.

7.3.7. Enhanced Response to Disturbances

Mangrove restoration bolsters the resilience of fish communities amidst various disturbances like storms, pollution, and climate change impacts. Robust mangrove forests serve as buffers, mitigating storm surge impacts, capturing sediment, and filtering pollutants. Restored mangroves offer sheltered zones and food resources that sustain fish populations during and after disturbances, facilitating their recovery and survival.

7.3.8. Coastal Protection

Mangroves function as a natural barrier against coastal erosion and storm surges [311], constituting a critical natural line of defense in SIDS. Their dense root systems effectively stabilize sediments and diminish wave energy, shielding shorelines and adjacent habitats from erosion and storm-related harm. By restoring mangroves, shoreline stability is reinforced, averting land loss and safeguarding neighboring coastal communities from the adverse effects of storms and SLR.

7.3.9. Water Quality Improvement

Mangroves are vital for enhancing coastal water quality. Their roots and associated microorganisms act as natural filters, trapping sediments, nutrients, and pollutants, thereby reducing turbidity and improving water clarity. Restoration of mangroves can effectively mitigate nutrient pollution and enhance water quality, fostering more favorable conditions for marine life, including fish and other organisms, and enhancing their role in coastal protection wave runup penetration.

7.3.10. Carbon Sequestration

Mangroves are exceptionally effective at sequestering and storing carbon dioxide from the atmosphere [312,313]. With their dense vegetation and organic-rich soils, they can accumulate substantial amounts of carbon over time. By restoring mangrove forests, their capacity for carbon sequestration is enhanced, thereby aiding in the mitigation of climate change impacts through the reduction of greenhouse gases.

7.3.11. Nutrient Cycling

Mangroves actively participate in nutrient cycling within coastal ecosystems by absorbing and recycling nutrients like nitrogen and phosphorus from their surroundings. This process prevents excessive nutrient runoff and eutrophication. Through mangrove restoration, the nutrient balance is preserved, thereby enhancing the productivity and health of coastal ecosystems.

7.3.12. Biodiversity Conservation

Mangrove forests are acknowledged as biodiversity hotspots, hosting a diverse array of species, including numerous rare and endangered ones [314,315]. Restoring mangroves plays a pivotal role in ensuring the survival of a wide range of plant and animal species. Furthermore, mangrove restoration efforts can aid in the recovery and persistence of threatened and migratory species.

7.3.13. Terrestrial–Marine Connectivity

Restoring mangrove forests improves connectivity and interaction among various coastal habitats. Acting as transition zones between land and sea, mangroves link terrestrial, estuarine, and marine ecosystems. This connectivity enables the movement of organisms, including fish and invertebrates, between habitats, fostering genetic exchange and bolstering population resilience.

7.3.14. Enhance Ecosystem Services

Mangrove restoration offers a variety of valuable ecosystem services. These encompass supporting fisheries through vital fish nursery areas, supplying timber and non-timber forest products, and providing opportunities for eco-tourism [316,317]. Additionally, mangroves contribute to shoreline stabilization, carbon sequestration, and water purification, benefiting both local communities and the broader environment in SIDS.

The benefits of mangrove restoration are crucial for safeguarding coastal settlements against rising shoreline erosion, intense wave action, and SLR. When combined with other green infrastructure restoration efforts, it offers significant long-term adaptive advantages for SIDS.

8. Socio-Economic Impacts of Coastal Green Infrastructure Restoration in SIDS

Coastal green infrastructure restoration can yield substantial economic impacts extending beyond wave and runup attenuation and coastal erosion mitigation, benefiting both local communities and the broader economy (Figure 8). Key economic impacts are numerous.

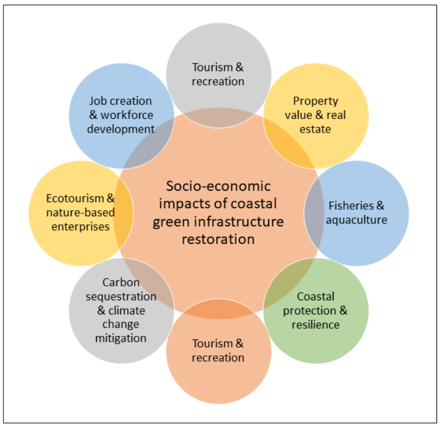

Figure 8. Conceptual array of socio-economic benefits derived from the ecological restoration of the coastal green infrastructure in SIDS.

8.1. Tourism and Recreation

Coastal regions featuring restored green infrastructure, including beaches, dunes, mangroves, seagrass meadows, and coral reefs, often attract tourists and recreationists. These rejuvenated natural areas offer scenic beauty and a variety of recreational opportunities such as swimming, snorkeling, SCUBA diving, kayaking, boating, and wildlife viewing, thereby enhancing the allure of coastal destinations. The uptick in tourism and recreational activities can generate revenue for local businesses, including accommodations, restaurants, tour operators, and souvenir shops, consequently fostering job creation and promoting more circular economic growth.

8.2. Property Value and Real Estate

Coastal green infrastructure restoration has the potential to elevate the value of nearby properties. Locations proximate to restored natural areas, such as beaches or mangroves, may witness heightened demand and subsequently higher property prices. This phenomenon can be advantageous for homeowners and real estate markets, resulting in augmented property tax revenue and overall economic value within coastal communities.

8.3. Fisheries and Aquaculture

Restoring coastal green infrastructure, encompassing coral reefs, seagrass meadows, and mangrove forests, can yield favorable impacts on fisheries and aquaculture industries. Seagrass meadows act as crucial fish nursery areas, bolstering both commercial and recreational fish populations. Similarly, mangroves offer habitat for various fish and invertebrate species, including those of commercial value. The restoration of these habitats has the potential to augment fish populations, but also oysters, clams, and other mollusks, thereby benefiting local fishers, seafood markets, and the broader seafood industry.

8.4. Coastal Protection and Resilience

Green infrastructure restoration along coastlines, encompassing dunes, wetlands, and mangroves, offers natural protection against coastal hazards such as storm surges, erosion, and SLR. By diminishing the vulnerability of urban coastal communities and infrastructure to these hazards, coastal green infrastructure restoration can lead to cost savings associated with avoided damages from storms, decreased necessity for expensive engineering structures (e.g., seawalls), and reduced insurance premiums. This enhances the economic resilience of SIDS coastal areas and alleviates the burden on public finances.

8.5. Carbon Sequestration and Climate Change Mitigation

Coastal green infrastructure, including mangroves, salt marshes, and seagrass meadows, plays a vital role in sequestering and storing substantial amounts of CO_2 from the atmosphere. Preserving and restoring these ecosystems can effectively contribute to climate change mitigation efforts in SIDS by offsetting greenhouse gas emissions. Moreover, green infrastructure restoration aids in bolstering the resilience of coastal communities against climate change impacts, such as extreme wave events, SLR, and coastal erosion, thereby yielding long-term cost savings associated with adaptation and disaster response measures.

8.6. Eco-Tourism and Nature-Based Enterprises

Restored coastal green infrastructure offers opportunities for eco-tourism and nature-based enterprises. Various activities such as guided tours, birdwatching, kayaking, snorkeling, and environmental education can be developed around these rejuvenated natural areas. This diversification of local economies not only fosters sustainable tourism practices but also promotes environmental education and awareness within SIDS communities and visitors.

8.7. Job Creation and Workforce Development

The restoration of coastal green infrastructure frequently demands a skilled workforce for tasks ranging from planning and implementation to monitoring and ongoing management. This creates employment opportunities in fields such as ecological restoration, landscaping, habitat monitoring, research, and conservation. Job creation in these sectors not only fosters local economic development but also supports livelihoods and offers training and skill-building opportunities for the workforce.

The economic impacts of coastal green infrastructure restoration can vary based on factors such as location, scale of restoration, local context, and effective management practices. To gain a more comprehensive understanding of the specific economic benefits and tradeoffs associated with these projects, economic assessments such as cost–benefit analyses and economic impact studies are essential. These assessments provide detailed insights into the economic implications of coastal green infrastructure restoration initiatives.

9. The Need for a Successful Coastal Restoration Public Policy

All the discussed coastal restoration strategies can profoundly influence the coastal resilience of SIDS, which refers to the capacity of coastal areas to endure and rebound from both natural and human-induced disturbances. Moreover, they can significantly impact community well-being and social resilience. Access to and involvement with restored natural areas offers recreational and educational opportunities, promotes physical and mental health, and nurtures a sense of pride and stewardship among community members. These social aspects play a pivotal role in enhancing the overall resilience of coastal communities by fostering social cohesion, bolstering community capacity, and advancing long-term sustainability and safety amid the challenges posed by climate change and SLR.

It is important to acknowledge that the effectiveness and impacts of SIDS' coastal green infrastructure restoration on resilience can vary depending on factors such as the specific type and condition of green infrastructure, site-specific characteristics, climate conditions, and the integration of restoration efforts with comprehensive coastal management strategies. Adaptive management, ongoing monitoring, collaboration among stakeholders, and the planning, design, and implementation of successful coastal restoration public policy are vital for ensuring the long-term effectiveness and success of coastal green infrastructure restoration projects, garnering wide public support (Figure 9).

Implementing a successful coastal restoration public policy necessitates careful planning, stakeholder engagement, and effective implementation strategies. Here are some key steps to consider.

9.1. Assess the Current State of the Coast

Perform a comprehensive assessment of coastal regions to pinpoint degraded or vulnerable areas, including eroding shorelines, degraded habitats, and those susceptible to climate change and SLR impacts. This assessment should entail scientific research, data collection, and analysis to grasp the scope of challenges and potential restoration benefits. It should also integrate traditional ecological knowledge, prioritize areas, and develop an operational plan.

9.2. Set Clear Goals and Objectives

Establish precise, measurable, and quantifiable goals and objectives for the coastal restoration policy. Ensure alignment with broader environmental objectives, such as enhancing ecosystem health, promoting biodiversity, safeguarding coastal communities, and fostering sustainable economic development.

9.3. Engage Stakeholders

Involve diverse stakeholders throughout the policy development process, including local communities, government agencies, non-governmental organizations, fishers, academia, industry representatives, and other relevant groups. Stakeholder engagement is crucial for crafting a policy that addresses the varied interests and concerns of those impacted by coastal restoration initiatives. It also offers opportunities for education and outreach, fostering long-term stewardship and support.

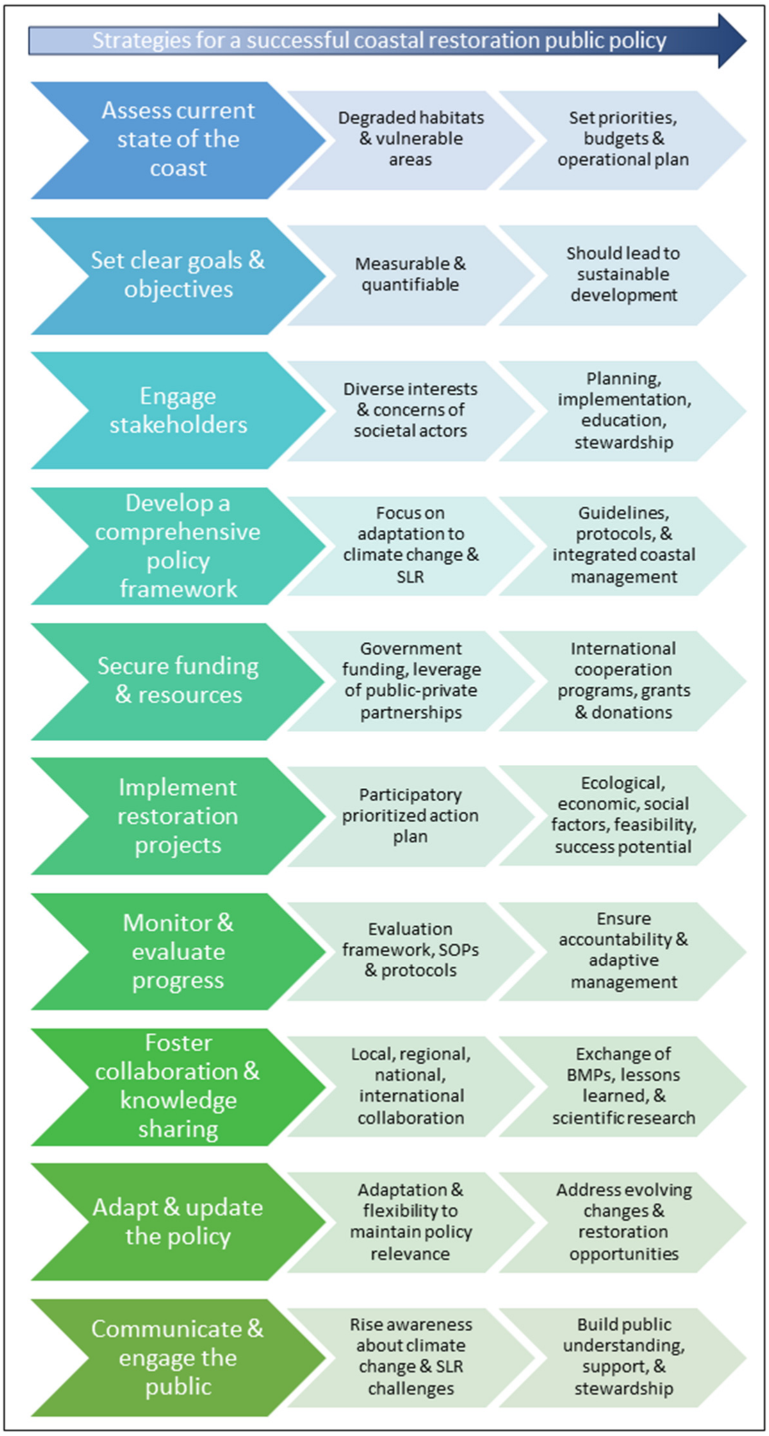

Figure 9. Fundamental steps for the participatory planning, financing, implementation, accountability, and adaptability for the strategic development of a successful coastal restoration public policy for SIDS.

9.4. Develop a Comprehensive Policy Framework

Create a comprehensive policy framework detailing strategies, approaches, and tools for coastal restoration in response to climate change and SLR impacts. This framework should encompass guidelines for project selection, funding mechanisms, regulatory frameworks, and monitoring and evaluation protocols. Additionally, it should address the integration of coastal restoration with broader coastal management strategies and policies.

9.5. Secure Funding and Resources

Identifying and securing sufficient funding and resources for the implementation of the coastal restoration policy is paramount, particularly in SIDS. This entails accessing government funding programs, leveraging public–private partnerships, establishing international cooperation programs, seeking grants and donations, and developing innovative financing mechanisms. It is imperative to ensure that funding adequately covers the costs of restoration projects, monitoring, and long-term maintenance of restoration projects.

9.6. Implement Restoration Projects

Create a participatory prioritized action plan for implementing restoration projects aligned with the goals and objectives of the policy. This plan should consider ecological, economic, and social factors, as well as the feasibility and potential success of each project. It is crucial to involve experts in restoration ecology, engineering, planning, and other relevant fields to ensure effective project design and implementation. Engaging stakeholders will enhance stewardship, support, and educational opportunities.

9.7. Monitor and Evaluate Progress

Set up a monitoring and evaluation framework, along with standard operating procedures (SOPs) and protocols, to evaluate the progress and effectiveness of the coastal restoration policy. Regularly monitor ecological, social, and economic indicators to track the outcomes of restoration projects and make necessary adaptive adjustments to the policy and implementation strategies. Ensure transparency in the monitoring and evaluation process and involve stakeholder engagement to ensure accountability and adaptive management.

9.8. Foster Local, Regional, and International Collaboration and Knowledge Sharing

Promote collaboration and knowledge sharing among stakeholders, non-governmental institutions, government agencies, and academia in coastal restoration efforts. Encourage the exchange of BMPs, lessons learned, and scientific research related to restoration. This collaboration enhances the effectiveness and efficiency of restoration endeavors, minimizes duplication of efforts, facilitates learning from both successful and failed projects, and enables the sharing of lessons with other SIDS.

9.9. Adapt and Update the Policy

Regularly review and update the coastal restoration policy to incorporate new scientific knowledge, emerging BMPs, and changes in environmental and socio-economic conditions. Adaptation and flexibility are crucial to ensure the policy remains relevant and effective in addressing the evolving challenges and opportunities in coastal restoration.

9.10. Communicate and Engage the Public

Create effective communication strategies to raise awareness about the significance and challenges of coastal restoration within the context of climate change adaptation and SLR mitigation. Engage the public in supporting and participating in restoration efforts through public outreach and education programs. These initiatives can enhance understanding, garner support, and foster stewardship for coastal restoration among the public, nurturing a long-term commitment to the policy's objectives.

By adhering to these steps and upholding a dedication to collaboration, adaptive management, and continuous monitoring, a successful coastal restoration public policy can be implemented to restore and safeguard the coastal ecosystems of SIDS. This approach will enhance resilience and ensure the sustainable utilization of coastal resources.

10. Conclusions

The climate crisis poses a critical, life-threatening challenge for many SIDS, exacerbating risks from extreme weather events and SLR. This heightened vulnerability leads to increased coastal erosion, chronic water quality degradation, and declining coastal resources, impacting up to 34–68 million people worldwide. This urgent situation warrants global attention.

Factors such as increasing coastal erosion, chronic water quality degradation, and declining coastal resources can lead to a net loss of ecological persistence, functional services, and ecosystem resilience in critical SIDS coastal habitats. These habitats serve as natural defenses against rising wave energy, runup, and SLR. Additionally, degraded coastal ecosystems contribute to declining biodiversity, fishery yields, and ecological functions, posing threats to the sustainability of natural productivity, ecological connectivity, and socio-economic benefits. Over time, this may compromise the economic value of coastal habitats, food security, and the integrity of built infrastructure and livelihoods. Addressing these challenges requires the implementation of integrated strategies to restore coastal habitats in SIDS. This includes integrated green–grey restoration efforts, engagement of local stakeholders, and the adoption of creative funding strategies and international cooperation.

The current climate crisis is an urgent and life-threatening priority for many SIDS, demanding global attention, prompt responses, and sustained economic support. Intervention strategies must be tailored to the unique circumstances of each SIDS and navigate various critical roadblocks. These challenges include limited socio-economic and technical resources, potential governance and political will constraints, enduring colonial legacies, neocolonial policies, debt burdens, health disparities, equity issues, and environmental injustices. These factors can impede their ability to effectively adapt to and mitigate SLR and climate change threats.

Despite the current threats and potential resource limitations, there is still hope for many SIDS to implement innovative coastal restoration strategies as a means to adapt to increasing climate change and SLR threats. There exist numerous opportunities for success and alternatives that can be customized to the unique reality and needs of each island. However, time is of the essence. It is imperative for developed countries, major greenhouse gas emitters, private businesses, tourism-based industries, and other stakeholders to step up and support coastal adaptation and mitigation strategies for SIDS. International cooperation is crucial to provide support for options available to small islands, with the benefits extending to millions worldwide.

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