SPECIAL FOCUS

Navigating Climate Change

A Brief Summary on Innovative Ocean Solutions

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Abstract

The ocean plays a crucial role in sustaining life on Earth by harbouring a significant portion of biodiversity, regulating the climate, contributing to the economy, and ensuring global food security. Nevertheless, the anticipated rise in worldwide temperatures, in addition to the acidification of the oceans and the elevation of sea levels, presents significant dangers to vital marine ecosystems and the benefits they provide. In spite of the commitments to reduce greenhouse gas (GHG) emissions, as outlined in the Paris Agreement, they are inadequate in restraining the global temperature increase to within +2°C by the year 2100. Hence, there is an immediate requirement for more ambitious measures to reduce GHG emissions. Ocean-based interventions show promise in mitigating the effects of climate change—such as ocean warming, acidification, and sea-level rise—on marine ecosystems. However, there is a lack of guidance in prioritising these interventions, and limited research, development, and deployment have been conducted in this field. This concise article offers an evaluation of ocean-based measures or schemes aimed at lessening climate-related drivers and negative impacts on selected marine ecosystems and their services. The assessment gauges the potential of each measure based on eight factors that encapsulates the environmental, technological, social, and economic criteria. These factors encompass effectiveness, technological readiness, lead time, duration of benefits, co-benefits, disbenefits, cost-effectiveness, and governance implications. The study highlights the significance of considering the ethical, equitable, and governance implications of ocean-based interventions and the associated risks to oceanic life and human populations. Overall, this research illuminates the potential of ocean-based interventions in addressing the consequences of climate change on marine ecosystems and ecosystem services. It emphasises the need for further research, development, and deployment in this realm and underscores the importance of considering the broader implications and risks associated with these interventions.

Introduction

Climate change is a critical and urgent challenge confronting humanity in the 21st century, with far-reaching impacts felt across the globe (Elbasiouny & Elbehiry, 2020). Rising sea levels and increasingly extreme weather events are just a few manifestations of this global crisis. Among the numerous realms profoundly affected by climate change, the world's oceans stand out as a prominent and vulnerable domain. The oceanic environment is grappling with rising temperatures, acidification, and changes in ocean currents, which have profound repercussions for marine ecosystems, fish populations, and the livelihoods of millions of people who depend on the ocean for sustenance (Noor & Das, 2019; Kumar et al., 2021).

Since glaciers and ice sheets are melting, sea levels are increasing. There has been and will be more coastal flooding and erosion.

Therefore, the role of the ocean in both mitigating climate change and adapting to its effects has become increasingly vital.

One remarkable aspect is that the ocean serves as a vast carbon sink, absorbing approximately one-quarter of all carbon dioxide (CO_2) emissions. However, this valuable service comes at a cost, as the absorption of CO_2 contributes to ocean acidification, profoundly impacting marine life.

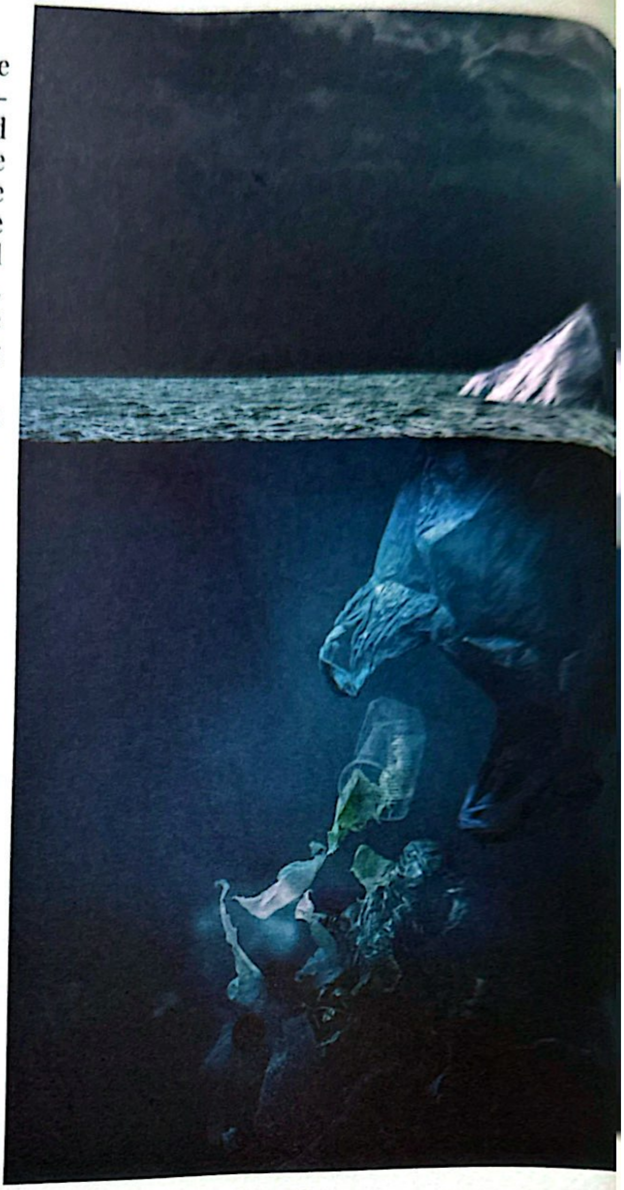
Additionally, the ocean holds significant potential for renewable energy sources such as offshore wind, wave, and tidal power (Masood et al., 2022). Harnessing these resources can help reduce GHG emissions from the energy sector. Furthermore, sustainable ocean-based industries such as aquaculture and biotechnology have the potential to alleviate pressure on land-based resources.

Against this backdrop, this brief article aims to explore innovative solutions that effectively address climate change and its impact on the ocean. While there is no singular solution to the complex challenge of climate change, a combination of innovative, science-based approaches holds promise for both mitigating and adapting to its effects. This article further showcases a diverse array of pioneering solutions tailored to the ocean's unique challenges, encompassing sustainable fisheries, aquaculture, ocean-based renewable energy, blue carbon, and marine biotechnology. Through the examination of case studies and successful projects from around the world, this article vividly illustrates the potential of these solutions in combating climate change. Most crucially, it emphasises the indispen-sable role of collaboration and partnerships in driving forward these oceanic initiatives.

This article also calls for increased investment in research and development of innovative solutions, accompanied by greater financial support from both the public and private sectors to facilitate their implementation.

Furthermore, this brief article underscores the significance of incorporating traditional knowledge and engaging local communities in the formulation and execution of ocean solutions. By doing so, these solutions can achieve heightened effectiveness, sustainability, and equity.

Overall, this brief review makes a significant contribution to the ongoing discourse surrounding climate change and the pivotal role of the ocean in addressing this global challenge. Through its comprehensive overview of innovative ocean solutions, the authors offer a valuable roadmap for policymakers, scientists, and stakeholders to collaboratively pave the way towards a more sustainable and resilient future.



Striking a Balance: Climate Action and Ecosystem Protection

The ability to effectively mitigate climate-related impacts on ecosystems depends on two crucial factors: successfully reducing exposure to warming, acidification, and sea-level rise, and understanding the sensitivity of ecosystems to changes in these drivers. Global solutions provide the most effective approach to reducing exposure to all three drivers, but they often do not specifically address the sensitivity of ecosystems to climate-related changes (Goodwin et al., 2023).

On the other hand, local solutions vary in their effectiveness in mitigating climate-related drivers but primarily focus on addressing non-climatic drivers that impact the health and resilience of coastal ecosystems and marine environments, aiming to minimise the impacts of climate change. Notably, local solutions yield a multitude of co-benefits, such as reducing non-climate stressors that enhance ecosystem resilience against climate change. Among the most impactful measures across ecosystems are vegetation management, hy-

brid approaches, alkalinisation, and renewable energy deployment. Additionally, safeguarding hydrology, restoring ecosystems, and curbing overexploitation rank relatively high in mitigating effects towards mangroves and seagrasses. These actions play a vital role in enhancing the resilience of ecosystems to climate change by addressing non-climatic drivers.

By implementing these local measures, the ability to alleviate the impacts of climate change on ecosystems is strengthened, ensuring their long-term health and sustainability. Although local solutions cannot entirely eradicate all climate-related impacts, they have the capacity to counteract global climate impacts when scaled beyond their current implementation.

The successful implementation of measures that effectively address world climatic factors including alkalinisation along with renewable energy, is anticipated to have positive implications for sensitive ecosystem services (McDonald et al., 2020). However, it is important to acknowledge potential unintended consequences. The addition of non-carbonate alkali elements, for example, while beneficial in some respects, may disrupt biogeochemical processes by releasing mineral constituents like cadmium, nickel, chromium, iron, and silicon.

The emissions have the potential to affect the patterns of primary and secondary production and add to the build-up of contaminants throughout the food chain (de Wit et al., 2022). Consequently, the fishing industry, aquaculture production, and the protective role of coastal habitats may experience adverse consequences.

The Vital Role of Oceans in Addressing Climate Change

Addressing climate change involves four main approaches:

1. reducing atmospheric GHG concentrations,
2. managing solar radiation,
3. protecting biota and ecosystems, and
4. manipulating biological and ecological adaptation.

The first two approaches focus on tackling the global root causes of climate change, while the latter two concentrate on mitigating its local impacts. This section explores the effectiveness of various solutions that can be implemented on a global or local scale, with a particular emphasis on ocean-based strategies. Ocean-based solutions offer promising avenues for climate action. For example, seaweed aquaculture presents an innovative approach to supplementing cattle feed, thereby reducing methane emissions. Additionally, marine-based interventions can help curb emissions of other GHG (Pinnegar et al., 2021). While some of these solutions are still experimental, others have been refined and successfully implemented over several decades. Renewable energy deployment, vegetation management, and the establishment of marine protected areas (MPAs) have notably gained traction on a global scale in recent years.

While local measures are able to mitigate the non-climatic factors and enhance ecosystem resilience in the face of climate change, it is important to recognise their limitations. Implementing protective measures and reducing overexploitation can play a crucial role in supporting high reproductive rates and facilitating the recruitment of juveniles. These actions are particularly important in the aftermath of climate-related mass mortalities, as they can contribute to the recovery of populations (Islam et al., 2020).

These measures offer additional benefits, such as the spill-over effects of MPAs on nearby areas that support shellfish fisheries and aquaculture. Most importantly, these benefits can be achieved with minimal negative impacts on coral reefs and vegetated marine habitats. However, it is important to note that MPAs featuring thermally sensitive corals may still experience greater susceptibility to coral bleaching compared to fished areas, even though protected coral reefs generally have a better chance of recovery.

The ocean plays a vital role in addressing climate change through a range of global and local solutions. By exploring and implementing innovative strategies, we can harness the potential of oceans to mitigate climate impacts, protect ecosystems, and foster resilience in the face of this global challenge. While local solutions have their limitations in directly addressing global warming, acidification, and sea-level rise, they still offer valuable contributions towards mitigating the overall effects.

Scaling up these efforts and implementing them in conjunction with broader global actions can lead us towards a more comprehensive approach to tackling climate change with its effects towards ocean ecosystems. Furthermore, this brief review also provides a valuable resource in the form of Table 1, offering comprehensive insights into the sensitivity of ecosystems and ecosystem services to key ocean drivers.

This analysis encompasses the potential effects of rising sea-level, acidification, and warming in ocean on various systems, providing a comprehensive understanding of their vulnerabilities.

It is crucial to acknowledge that under high CO_2 emission scenarios, low-latitude and tropical MPAs may experience further habitat and species losses, reducing their intended benefits. While local solutions may have limited effectiveness in directly addressing global climate change impacts, they do offer positive effects that could help counteract broader climate impacts within the scope of its present use.

As an example, the cultivation of seaweeds and seagrasses has the capacity to address local ocean acidification by serving as a natural buffer against decreases in seawater pH. This approach not only helps mitigate the negative impacts of acidification but also provides a beneficial effect on reef habitats. (Albright & Cooley, 2019). By recognising these limitations and scaling up efforts, we can work towards a more comprehensive approach to combating climate change and how it affects marine environments.

Table 1 The effect of major ocean factors in marine ecosystem.

System	Ocean Warming	Ocean Acidification	Sea-Level Rise	Factors to Consider
Seagrass habitats	4	4	2	Negative warming effect for tropical and temperate seagrass. Positive effect for higher latitude species. No or stimulating acidification effect for plants; possible negative effect on associated calcareous organisms.
Coral reefs	5	5	4	Ocean warming leads to widespread destruction of coral reef ecosystems through bleaching. Ocean acidification compounds warming's negative impact on reef accretion. Sea-level rise magnifies negative impacts on coastal protection services.
Arctic biota	5	3	3	Arctic ecosystems are rapidly warming, with potential negative impacts on ice-associated biota and key Arctic zooplankton. Freshening and warming affect productivity and polar calcifiers.
Fin fisheries	4	4	3	Warming and changes in oxygen and net primary production (NPP) are dominant factors affecting finfish fisheries. Ocean acidification has moderate impact. Sea-level rise may affect accessibility of coastal fisheries.
Finfish aquaculture	4	4	2	Finfish aquaculture is sensitive to warming, but measures like aeration of water can reduce sensitivity. Ocean acidification has relatively low direct impacts. Sea-level rise has limited impacts on open net cage farming.
Coastal protection	4	5	3	Reefs, saltmarshes, seagrasses, and mangroves provide coastal protection but are vulnerable to climate impacts. Reefs are highly sensitive to warming and acidification. Sea-level rise affects marshes and mangroves.
Shellfish fisheries	4	3	4	Warming and ocean acidification negatively impact shellfishery. Sea-level rise has very low impact.
Mangroves and saltmarshes	2	3	1	Warming can have positive and negative effects. Sea-level rise has a high direct impact on coastal wetland stocks.

* Each number corresponds to a different level of impact, ranging from high impact (5) to very low impact (1). 5: High impact; 4: Moderate impact; 3: Medium impact; 2: Low impact, and 1: Very low impact.

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Assessing the Effectiveness and Duration of Implemented Strategies

Projected outcomes for the year 2100 include a potential decrease in sea surface warming by 2°C, avoidance of sea surface acidification by 0.25 pH units, and a reduction in sea-level rise ranging from 0.26 to 1.1 m. These projections provide insights into the potential effectiveness of global measures in addressing rising of sea-level, acidification, and warming, as well as the anticipated duration of their impact. It is important to note that these projections represent a theoretical maximum that may not be fully achievable, but they serve as illustrations of each approach's potential.

Among the approach considered, alkalinisation and renewable energy have shown the highest theoretical potential to address multiple drivers. Renewable energy sources, including current, wave, and tide, offer an enormous energy potential approximately around 7,000 EJ annually, surpassing future human energy requirements (Wen & Lin, 2022).

By replacing fossil fuels with marine renewables, GHG emissions can be permanently reduced. Large-scale alkalinisation, on the other hand, presents a substantial and permanent intervention by utilising alkaline materials to consume and store CO_2 as dissolved bicarbonate and carbonate ions or precipitated calcium carbonate, thereby neutralising ocean acidity (Hartmann et al., 2023).

Nevertheless, it is important to carefully consider the feasibility and benefits of this approach in light of the associated costs, environmental impacts related to large-scale mining or production of alkaline materials, and potential adverse effects on ecosystems due to trace elements or contaminants associated with alkalinity. Balancing these considerations is crucial to ensure that any implementation of alkalinisation is done in a responsible and sustainable manner, taking into account both the potential benefits and potential risks to the environment.

Hybrid land-ocean methods offer a promising approach to enhance the potential for mitigation by combining ocean and land-based strategies. One example is the utilisation of marine biomass for bioenergy with carbon capture and storage (BECCS) fuel, which helps overcome the limitations of terrestrial fuel capacity due to competition for land, water, and nutrients (Zahed et al., 2021). This process involves converting CO_2 emissions from land-based biomass energy into ocean alkalinity, which can then be stored in the ocean. This innovative approach significantly expands the capacity for CO_2 storage, contributing to the overall efforts to mitigate climate change.

By utilising marine resources in this manner, we can optimise the potential of both land and ocean ecosystems to sequester and store CO_2, thereby reducing GHG emissions and addressing the challenges posed by global warming and counteract ocean acidification, surpassing the capabilities of conventional carbon capture and storage (CCS) approaches. However, further research is needed to comprehensively explore a range of alternatives, including their costs, benefits, and trade-offs.

Iron fertilisation, for instance, has a global limit on deployment at around 70 Pg C due to other limitations related to nutrients or light when marine algae reach optimal iron levels. Strategies involving vegetation have limited capacity to mitigate global-scale warming, acidification, and sea-level rise due to the constrained availability of vegetated habitats worldwide.

Nevertheless, there is some potential for expansion through seaweed aquaculture. Local measures, while less effective in addressing these issues on a global scale, can be highly effective in mitigating local ocean acidification through pollution reduction and alkalinisation, as well as relative sea-level rise through actions such as vegetation restoration, protection, hydrology restoration, relocation, and reef restoration. The duration of effects varies significantly among different approaches, with renewable energy and protection measures capable of achieving permanent effects.

Fertilisation, however, has finite duration effects, while techniques like albedo enhancement and cloud brightening exhibit short-lived effects (Gray, 2021). By capturing and storing CO_2 for extended or permanent periods, alkalinisation and hybrid methods such as converting CO_2 to ocean alkalinity or marine BECCS can have long-lasting effects (Michaga et al., 2022). It is crucial to highlight that when these schemes are abruptly terminated, they tend to lose most of their benefits.

This termination can have a significant impact, as it is projected to accelerate the rate of temperature changes in both the ocean and the land, reaching unprecedented speeds. Therefore, careful consideration must be given to the long-term sustainability and management of these schemes to ensure their effectiveness and minimise any adverse effects on climate and ecosystems.

In conclusion, assessing the effectiveness and duration of implemented strategies provides valuable insights into the potential impact of global measures on addressing climate-related challenges in the ocean. While renewable energy, alkalinisation, and hybrid land-ocean methods offer significant potential, continued research and analysis are crucial for a comprehensive understanding of alternative approaches, their associated costs, benefits, and trade-offs.

Future Course of Action

Over the past 20 years, there has been a rapid increase in the adoption and testing of renewable energy, vegetation, eliminating overexploitation, and protection measures. However, the current deployment scale of these solutions is insufficient to effectively address the drivers and impacts of climate change.

Immediate and decisive action is essential to substantially enhance research, testing, and implementation efforts, in order to fully unlock the potential of global measures such as renewable energy, alkalinisation, and hybrid approaches. This urgency arises from the imminent threats posed by climate change to the sustainability of our oceans. It is crucial to recognise that there is a time lag of several decades before these global measures can fully manifest their effectiveness.

Consequently, there is a high likelihood of substantial increases in climate-related impacts on ocean ecosystems and services, which will undermine the capacity of ecosystems to offer localised solutions. It is evident that relying solely on conventional marine management strategies will be insufficient in adequately mitigating climate change and its associated impacts.

Therefore, it is imperative to adopt a proactive and comprehensive approach that encompasses a range of innovative and sustainable measures to address the challenges ahead. Therefore, there is a pressing need to accelerate research and deployment of alternative solutions, which will present challenges to the capacity of science, policy, and decision-making in evaluating and implementing these measures.

It is crucial to prioritise the development of policies and allocate funding towards research into new or emerging ocean and climate management options. This is essential in order to overcome the constraints faced in implementing enhanced action plans, which are influenced by uncertainties in key non-climatic variables such as socioeconomic conditions and their impact on fossil fuel markets and renewa[ble] energy. In light of this, it is imperative to consi[der] a wider range of measures, including large-sc[ale] seaweed aquaculture or abiotic methods of C[O2] removal from seawater.

Both the marine policy and science com[m]unities must recognise the uncertainties a[nd] limitations of existing climate and oce[an] management options. They should focus [on] prioritising the development of promising sol[u]tions, such as renewable energy sources a[nd] scalable local actions, to address the challeng[es] posed by climate change and ensure a sustainab[le] future for our oceans.

Furthermore, it is important to recognise th[at] new or emerging measures that are not current[ly] part of marine management practices may pro[ve] to be cost-effective, socially acceptable, an[d] environmentally sustainable through furth[er] research and testing. Embracing innovation an[d] exploring unconventional approaches will b[e] instrumental in addressing the complex challenges posed by climate change in the ocean. MIMA

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