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Role of Phytoplankton and water bodies in Decarbonizing Coastal areas: A case of Digha, West Bengal.

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Abstract - *Over centuries, human settlements have evolved from largely self-sufficient systems to highly resource-dependent urban centers reliant on extensive hinterlands for food, energy, and materials. Contemporary urbanization, particularly in coastal regions, has significantly intensified carbon emissions due to population concentration, fossil-fuel-based energy consumption, infrastructure expansion, and land-use transformation. Coastal towns, however, possess unique ecological assets—such as oceans, estuaries, wetlands, and phytoplankton-rich water bodies—that function as natural carbon sinks and can play a decisive role in climate change mitigation. This paper examines the role of oceans and phytoplankton in carbon sequestration and explores their potential integration into urban decarburization strategies. Using the coastal town of Digha, West Bengal, as a representative case, the study proposes a conceptual model approach that links coastal ecology, water bodies, phytoplankton dynamics, and urban planning interventions to reduce greenhouse gas (GHG) emissions. The research synthesizes climate science, urbanization trends, and ecological processes to demonstrate how coastal urban systems can transition from being net carbon emitters to carbon-mitigating landscapes. The study argues that integrating marine ecological processes into urban planning frameworks is essential for achieving long-term coastal sustainability and climate resilience.*

Key Words: **Coastal Decarbonisation; Phytoplankton; Carbon Sequestration; Coastal Urban Planning; Digha; Climate Change; Water Bodies**

1. INTRODUCTION

Climate change is a long-term shift in atmospheric conditions occurring worldwide. For thousands of years, the Earth's climate has remained relatively stable. Temperatures, rainfall, the length of the seasons, and other environmental factors have sustained humans, animals, and plants. This stability has existed due to the greenhouse effect. Urban areas account for more than 70% of CO2 emissions from burning fossil fuels. Urban expansion in tropics is responsible for 5% of the annual emissions from land use change. Urban residents currently control ~22 (12–40)% of the land carbon uptake (112 PgC/yr) and ~24 (15–39)% of the carbon emissions (117 PgC/year) from land globally. Urbanization resulted in the creation of new carbon pools on land such as buildings (~6.7 PgC) and landfills (~30 PgC).

Since the Industrial Revolution from the mid-18th to the mid-19th centuries, the greenhouse effect has intensified as human activities have increased the amount of carbon dioxide in the atmosphere by 30 percent, nitrous oxide by 15 percent, and methane by 100 percent. These increases have had a direct impact on climate, and average global temperatures have risen significantly. In fact, temperatures have increased by 0.74°C in the last 100 years, mostly because of the intensification of human activities like urbanization, combustion of fossil fuels and use of cars.

2 EFFECT OF URBANIZATION IN CARBON RELEASE

With the rapid development of economic globalization and foreign trade, remarkable achievements have been made. Urbanization is considered to be a process during which most of the working population changes from farmers to a non-rural population, increasing the urban population. Urbanization is becoming the most important human social change globally, especially in developing countries. The technological explosion that was the Industrial Revolution led to a momentous increase in the process of urbanization. Larger populations in small areas meant that the new factories could draw on a big pool of workers and that the larger labor force could be ever more specialized. Manufacturing Production in India averaged 5.86 percent from 2006 until 2023, reaching an all-time high of 196.00 percent in April of 2021 and a record low of -66.60 percent in April of 2020.

3. PAST TREND ANALYSIS OF GHG EMISSION

The greenhouse effect is a natural process that warms the Earth’s surface and makes life on Earth possible. Greenhouse gases are types of gases which change how much heat is absorbed by Earth’s atmosphere. Greenhouse gases in our atmosphere act like the glass in a greenhouse, letting light through but stopping heat from escaping. Energy from the Sun reaching Earth's atmosphere passes through the air and clouds to the surface, where it is absorbed and then radiated

upward in the form of infrared heat. About 90% of this heat is then absorbed by the greenhouse gases and radiated back toward the surface. This natural greenhouse effect means that Earth has an average temperature of 15°C. Without it, Earth's average temperature would be about −18°C (well below the freezing point of water).

Human activity has rapidly increased the emission of greenhouse gases to the atmosphere. Since the start of the Industrial Revolution, in about 1750, human activities such as burning fossil fuels, including coal and oil, have increased greenhouse gas concentrations in our atmosphere. This process is called the 'enhanced' greenhouse effect', and it is warming our planet. In fact, Earth's average surface temperature rose about 1.18 °C from the late 1800s to 2020. The current warming trend is different because it is clearly the result of human activities since the mid-1800s, and is proceeding at a rate not seen over many recent millennia. It is undeniable that human activities have produced the atmospheric gases that have trapped more of the Sun's energy in the Earth system. This extra energy has warmed the atmosphere, ocean, and land, and Wide-spread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred.

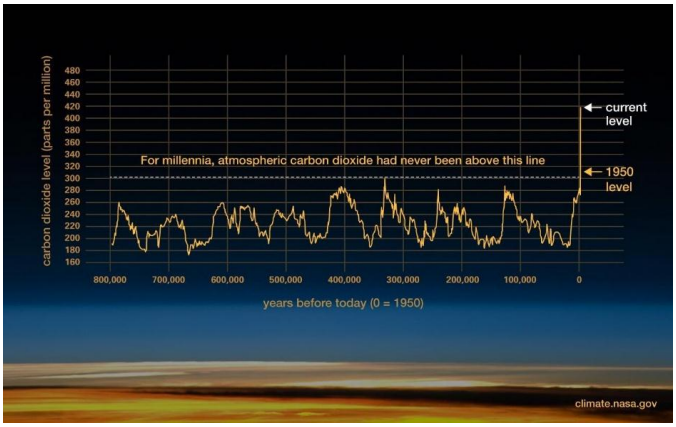

Fig -1: Atmospheric Carbon Dioxide level vs timeline

4. PRESENT TREND OF GHG EMISSION

Since the middle of the 20th century, annual emissions from burning fossil fuels have increased every decade, from an average of 3 billion tons of carbon (11 billion tons of carbon dioxide) a year in the 1960s to 9.5 billion tons of carbon (35 tons of carbon dioxide) per year in the 2010s As per the World Economic Forum, energy, transport and building infrastructures are gradually becoming greener: There are more electric vehicles on city streets, better water treatment and recycling schemes, and more solar panels on rooftops around the globe. According to International Energy Agency estimates, renewables like solar and wind are set to become the largest source of electricity generation worldwide by 2025, supplying one-third of the world's electricity and ending coal's decades-long dominance of the global power mix.

But with climate change accelerating, we need more comprehensive decarburization actions on three fronts. First, we need even more energy to come from renewable sources. Second, we need more cars, heating and other activity to be powered by clean electricity. Third, we need everything from factories, to office buildings, homes, transport systems and consumer devices to become more energy-efficient. This third lever might not as headline-grabbing as the rise of solar panels or electric vehicles. But it is a big piece of the decarburization puzzle, with an even larger potential enabled by digital technologies.

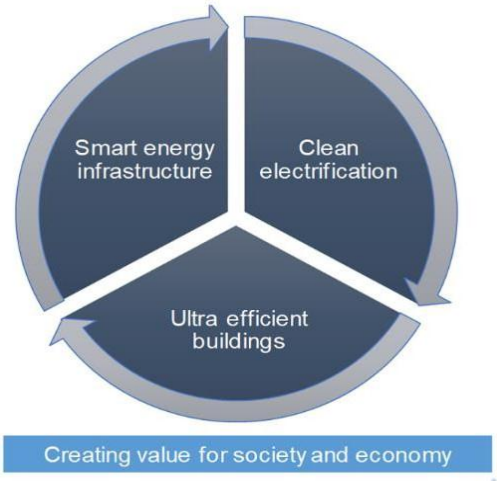

Fig -2: Value for society and economy

Integration of energy, buildings and mobility requires cross-cutting industry collaboration, ranging from utilities and real estate, to technology companies and financial institutions. City- and state-level administration can enable and facilitate such collaboration through public-private cooperation. The public sector can drive on governance, policy and licensing, while the private sector provides agility, technology and resources. This cooperation can share and balance risks and liability between stakeholders for mutual gains and value creation for the broader community.

5. CASE OF OCEANS AS THE NATURAL CARBON SINKS

The ocean acts as a "carbon sink" and absorbs about 31% of the CO2 emissions released into the atmosphere according to a study published by NOAA and international partners in Science. As atmospheric CO2 levels increase, so do the CO2 levels in the ocean. When CO2 is absorbed by seawater, a series of chemical reactions occur causing the seawater to become more acidic. This phenomenon is commonly referred to as ocean acidification.

Ocean acidification threatens the fundamental chemical balance of ocean and coastal waters across the globe. Ocean

acidification can create conditions that eat away at the minerals used by oysters, clams, shrimp, coral reefs, and other marine life to build their shells and skeletons. Human health is also a concern, as lab studies have shown that many harmful algal species produce more toxins and bloom faster in acidified waters.

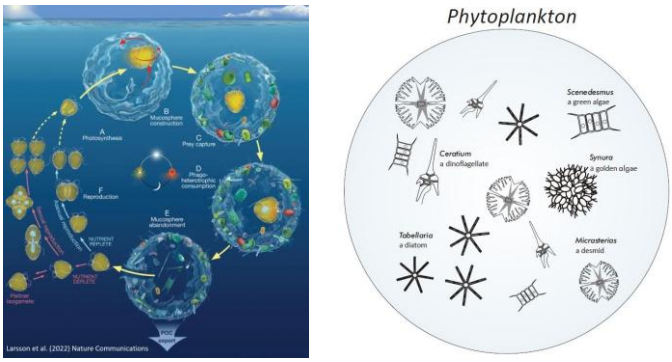

Fig -3: (a) Phytoplankton cycle (b) Phytoplankton types

The ocean plays a critical role in carbon sequestration. Phytoplankton, which live on the warm, light-filled surface, suck carbon dioxide out of the atmosphere for food. They also need nutrients such as phosphorus and nitrogen from colder, heavier, saltier water that upwells into warmer layers. When phytoplankton die, they sink, bringing some of the carbon and other nutrients they consumed with them back to the ocean depths. On the other hand, additional atmospheric input of inorganic nitrogen has increased significantly to a level where it is already higher than the natural nitrogen supply in the North Atlantic Ocean basin. The effects of eutrophication vary from increased growth of phytoplankton, benthos and fish to changed species composition at moderate eutrophication. At severe eutrophication, the effects vary from blooms of nuisance-causing or toxic algae to mass growth of certain species and mortality of others, and ultimately to anoxic conditions and mass mortality (fishkills). An algal biomass related phenomenon such as oxygen depletion of the water column and consequent mortality of animals can be prevented by a general reduction of nutrient discharges.

6. CASE OF OCEANS AS NATURAL CARBON SINKS: THE COASTAL CONTEXT OF DIGHA

Digha is a rapidly urbanizing coastal town and a major tourist destination in West Bengal. The town has experienced increasing carbon emissions associated with tourism-driven infrastructure expansion, rising vehicular movement, higher energy demand, and intensified solid and liquid waste generation. Concurrently, Digha is endowed with significant coastal and marine ecological assets, including nearshore waters, estuarine systems, and productive marine ecosystems.

This case examines Digha's coastal and marine environment as a natural carbon sink, focusing on the interaction between urban development patterns, coastal water bodies, and marine ecological processes. Rather than framing an intervention, the study analyzes existing and potential ecological functions that influence carbon regulation within the coastal system.

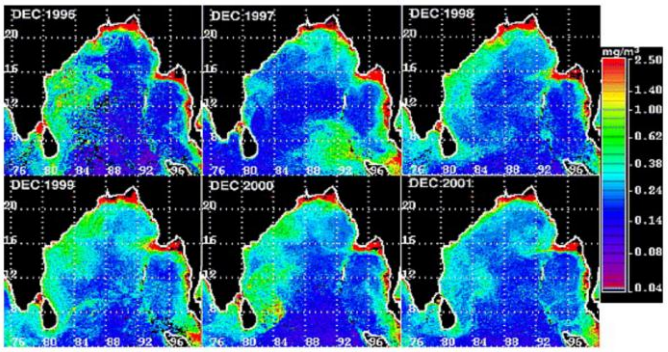

Fig -4: Bay of Bengal Phytoplankton traces

As stated by Vinayachandran, P. N., and Simi Mathe, Satellite derived chlorophyll a imageries shows presence of phytoplankton bloom in the Bay of Bengal during the northeast monsoon (November–February) and the mechanisms that can upwell nutrients to sustain the bloom are investigated using sea level anomalies and winds. OCTS and SeaWiFS chlorophyll a images show that there is a phytoplankton bloom in the southwestern part of the bay during November–January. A concentration of the bloom can be as high as 2 mg m−3 compared to near zero value before the bloom. Through the above imagery, concentration of chlorophyll is found to be high in the study region of Digha.

6.1. ANALYTICAL FRAMEWORK FOR THE STUDY

The assessment of coastal carbon dynamics in Digha is structured through an integrated analytical framework that examines coastal ecology, nutrient flows, urban systems, and governance mechanisms influencing natural carbon sequestration. The framework relies exclusively on secondary data sources, including reports from the Intergovernmental Panel on Climate Change (IPCC), National Centre for Coastal Research (NCCR), India, Central Pollution Control Board (CPCB), West Bengal Pollution Control Board (WBPCB), Food and Agriculture Organization (FAO), NASA MODIS satellite products, and peer-reviewed coastal and marine science literature.

i. Coastal Water Body Conservation Status

Digha's coastal environment comprises nearshore marine waters of the Bay of Bengal, sandy intertidal beaches, seasonal wetlands, and estuarine influences linked to the Hooghly–Subarnarekha river system. According to shoreline change assessments conducted by the National Centre for Coastal Research (NCCR, Ministry of Earth Sciences, Government of India), several stretches of the West Bengal

coast exhibit erosion rates ranging from 0.3 to 1.2 m per year, driven by sea-level rise, altered sediment transport, and coastal infrastructure development.

The IPCC Sixth Assessment Report (AR6) and FAO blue carbon studies identify coastal and nearshore ecosystems as highly efficient natural carbon sinks, with carbon burial rates significantly exceeding those of terrestrial ecosystems. Coastal wetlands globally sequester approximately 2–4 tonnes of carbon per hectare per year, while Indian coastal wetland sediments store between 150–400 tonnes of carbon per hectare (FAO, 2018; IPCC, 2022). Although Digha lacks extensive mangrove forests comparable to the Sundarbans, its shallow continental shelf and nearshore sediments function as important carbon storage zones through organic matter deposition. Reports by the Ministry of Environment, Forest and Climate Change (MoEFCC) indicate that tourism infrastructure expansion, shoreline armoring, and beach modification have increased ecological stress on these systems, potentially reducing their long-term carbon sequestration efficiency.

ii. Nutrient Dynamics and Phytoplankton Sensitivity

Phytoplankton productivity in coastal waters is regulated by nutrient availability, light penetration, and water temperature. Secondary water quality data from the Central Pollution Control Board (CPCB) and West Bengal Pollution Control Board (WBPCB) indicate that municipal wastewater discharge and surface runoff contribute significant nitrogen (N) and phosphorus (P) loads to coastal waters along the Digha coastline. According to the IPCC AR6 Working Group I and FAO marine productivity assessments, coastal waters contribute nearly 20–30% of global marine primary productivity, despite covering only about 7% of ocean surface area, due to higher nutrient availability. Satellite-derived chlorophyll-a data from NASA's MODIS-Aqua mission show elevated chlorophyll concentrations in the northern Bay of Bengal, including the Digha coastal zone, particularly during post-monsoon and winter seasons. Typical chlorophyll-a values range between 1–10 mg/m^3, compared to <0.5 mg/m^3 in oligotrophic open-ocean regions. Peer-reviewed studies published in journals such as Nature Geoscience and Global Biogeochemical Cycles report that only 10–15% of phytoplankton-fixed carbon is exported to deeper waters through the Biological Carbon Pump (BCP). Excessive nutrient loading, as highlighted by UNEP coastal eutrophication reports, can lead to hypoxia and harmful algal blooms, thereby reducing net carbon sequestration efficiency.

iii. Blue–Green Infrastructure Linkages

Blue–green infrastructure (BGI) includes urban ponds, drainage channels, wetlands, vegetated buffers, and coastal water bodies that regulate nutrient and carbon flows. Urban water studies by NIUA (National Institute of Urban Affairs) and UN-Habitat highlight that traditional Indian coastal towns historically relied on interconnected ponds and canals to filter sediments and nutrients before discharge into the sea. Secondary data from FAO wetland management studies and UNEP coastal ecosystem reports indicate that constructed wetlands and vegetated drainage systems can reduce nutrient loads by 30–70%, while sequestering approximately 1–3 tonnes of carbon per hectare per year through biomass growth and sediment accumulation.
In Digha, municipal reports (LUDCP) and regional planning documents indicate fragmented drainage systems with direct discharge points into nearshore waters. The absence of continuous inland–coastal blue–green linkages reduces nutrient buffering capacity, resulting in episodic nutrient surges into coastal waters, particularly during monsoon rainfall and peak tourist seasons.

iv. Coastal Urban Form and Emission Patterns

Tourism-driven urbanization strongly influences coastal carbon dynamics through indirect emission pathways. According to West Bengal Tourism Department statistics, Digha experiences seasonal population surges of three to five times its resident population during peak tourism periods. Transport sector emissions—primarily from private vehicles, buses, and diesel generators—are identified by the India GHG Program and IPCC urban emissions assessments as dominant emission sources in coastal tourist towns.
Studies by UN Tourism and IEA (International Energy Agency) suggest that transport and accommodation energy use account for 60–70% of total tourism-related emissions in coastal destinations. Dispersed urban form and automobile-dependent tourism infrastructure increase per-capita emissions, indirectly increasing atmospheric CO_2 available for air–sea gas exchange.

While coastal waters can absorb a portion of atmospheric CO_2, the IPCC AR6 notes that oceanic carbon uptake efficiency is constrained by rising water temperatures, pollution, and declining ecosystem health.

v. Monitoring and Governance Mechanisms

Monitoring of coastal carbon-related processes is primarily supported by remote sensing and secondary observational datasets. Satellite platforms such as NASA MODIS, ESA Sentinel-3, and USGS Landsat provide spatial data on chlorophyll-a concentration, sea surface temperature (SST), turbidity, and shoreline change, widely used in Indian coastal studies.
Institutional governance involves the West Bengal Coastal Zone Management Authority (WBCZMA), MoEFCC, local municipalities, pollution control boards, and tourism authorities. Reviews by OECD coastal governance studies and UNEP integrated coastal management reports indicate that fragmented institutional responsibilities often limit coordinated monitoring of emissions, water quality, and marine ecosystem productivity.

The absence of an integrated coastal carbon accounting framework restricts the ability to quantitatively assess the role of coastal waters as natural carbon sinks within urban planning and climate action strategies.
Based on secondary data from IPCC, NCCR, CPCB, FAO, NASA, UNEP, and national planning agencies, Digha's coastal system can be understood as a coupled urban–marine carbon system. While biophysical conditions such as shallow waters and high nutrient availability favor phytoplankton-driven carbon uptake, anthropogenic pressures, urban form, and governance fragmentation significantly influence the effectiveness and stability of this natural carbon sink.

7. INTERNATIONAL CASE COMPARISONS

7.1. GLOBAL COASTAL DECARBONIZATION PRACTICES

Across the world, coastal cities are increasingly integrating marine and coastal ecosystems into their decarburization strategies, recognizing the role of "blue carbon" systems in climate mitigation.

Rotterdam, Netherlands, represents a leading example where blue carbon integration is aligned with port-led decarburization. Through large-scale coastal wetland restoration and nutrient-controlled estuarine management, the city has enhanced natural carbon sinks while simultaneously reducing industrial and shipping-related emissions. Importantly, Rotterdam has institutionalized carbon accounting for marine ecosystems, allowing blue carbon sequestration to be formally incorporated into its climate action plans and long-term sustainability frameworks.

A densely built port city (325.8 km^2) that has invested heavily in climate-resilient infrastructure: e.g. 130,000 m^2 of green roofs are already installed, plus large storm water storage (e.g. a 10,000 m^3 cistern). Its coastal land use includes recently created wetlands: the Rijnhaven area will feature an 18-hectare tidal park (0.18 km^2). The North Sea temperate waters have moderate phytoplankton uptake (~500 mg C/m^2/day ≈180 g/yr) due to cooler, nutrient-rich conditions.

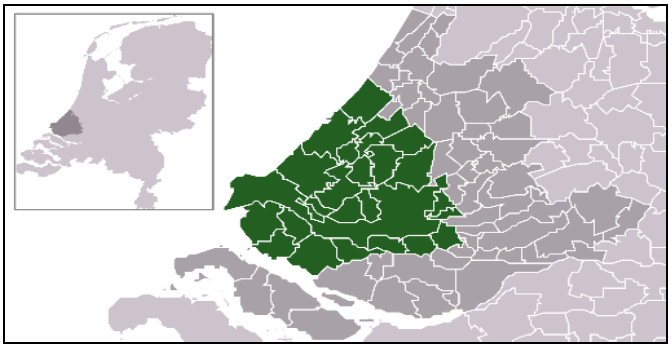

Fig -5: Location map of Rotterdam, Netherlands

In Qingdao, China, coastal decarburization has been pursued through marine ecological engineering, with a strong emphasis on optimizing phytoplankton productivity without triggering ecological imbalance. By regulating nutrient inflows from coastal wastewater and carefully managing estuarine conditions, Qingdao has enhanced biological carbon uptake while avoiding eutrophication and harmful algal blooms. This approach demonstrates how controlled nutrient management can leverage phytoplankton as a carbon sink while maintaining marine ecosystem health, offering a technically calibrated model for rapidly urbanizing coastal regions.

Fig -6: Location map of Qingdao, China

A major port-industrial metropolis with ~9.5 M residents. Its Yellow/East China Sea shelf waters are biologically productive (order ~1 g C/m^2/day). Urbanization has surged: impervious (built) area grew by +140.6 km^2 (≈9% increase) from 1970–2020. Qingdao has introduced coastal restoration efforts (marine ranching, aquaculture upgrades), but still has very high urban land-use (≈77% urbanized). No significant mangrove or seagrass reserves remain within the city's footprint.

Sydney, Australia adopts a coastal ecosystem-based management approach that emphasizes synergistic interactions between seagrass meadows and phytoplankton systems. By implementing urban runoff filtration measures prior to marine discharge, the city has reduced excess nutrient loading while supporting balanced primary productivity. These interventions have resulted in measurable gains in marine carbon sequestration, illustrating how integrated land–sea planning and ecological infrastructure can contribute effectively to coastal decarburization goals. Greater Sydney spans 12,368.7 km^2(pop. 5.3 M). Its coastal Tasman Sea waters have average NPP on the order of 200–300 mg C/m^2/day (~70–110 g/m^2/yr), with the Australian EEZ mean of 606 mg/d (≈221 g/yr). Sydney has adopted strict storm water pollution targets (e.g. 45% nitrogen removal, 60%

phosphorus removal) via green infrastructure and runoff filtration. Nearly 12,369 km^2 of the region includes substantial protected coastal wetlands and waterways (seagrass beds, mangroves, tidal marshes).

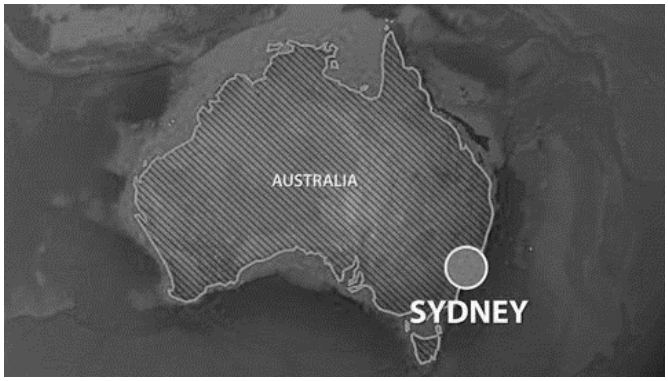

Fig -6: Location map of Sydney, Australia

Table -1: Marine Carbon Sink & Phytoplankton Response

	Marine Carbon Sink & Phytoplankton Response			
Indicator	**Digha, India**	**Rotterdam, NL**	**Qingdao, China**	**Sydney, Australia**
Mean coastal NPP (mg $C/m^2/day$)	1,800–2,400 (monsoon peak); ~900 annual avg	400–600	900–1,400	500–800
Annual phytoplankton carbon fixation (g $C/m^2/yr$)	300–700	150–220	330–510	180–290
CO_2 equivalent sequestration (t $CO_2/km^2/yr$)*	1,100–2,600	550–800	1,200–1,900	650–1,050
Risk of eutrophication / HAB	High (uncontrolled nutrient inflow)	Low–Moderate	Moderate (actively managed)	Low
Nutrient regulation (N, P)	Minimal / informal	Strict EU WFD limits	Controlled discharge thresholds	Enforced urban runoff limits

***Converted using 1 g C ≈ 3.67 g CO_2**

Table 1 indicates that Digha records the highest seasonal phytoplankton productivity among the four cases, largely driven by monsoonal nutrient enrichment. However, the lack of nutrient regulation increases the risk of eutrophication, limiting the proportion of fixed carbon that contributes to long-term sequestration. Rotterdam and Sydney exhibit lower phytoplankton productivity, yet achieve more stable carbon sink performance due to controlled nutrient inputs and balanced primary productivity. Qingdao demonstrates an intermediate condition, where relatively high productivity is actively managed to enhance biological carbon uptake while avoiding ecological imbalance. The comparison underscores that regulated nutrient dynamics are critical for converting phytoplankton productivity into effective carbon sequestration.

Table -2: Urban & Coastal Infrastructure Supporting Carbon Regulation

	Urban & Coastal Infrastructure Supporting Carbon Regulation			
Indicator	**Digha, India**	**Rotterdam, NL**	**Qingdao, China**	**Sydney, Australia**
Coastal wastewater treated (%)	<40%	>99%	~95%	>98%
Dedicated green–blue infrastructure investment	<1% of urban capex	15–20%	8–12%	12–18%
Stormwater nutrient removal efficiency	<10%	60–80%	50–65%	45% N, 60% P
Port/industrial decarbonization linkage	Absent	Strong	Moderate	Moderate
Nature-based coastal defenses	Minimal	Extensive	Selective	Extensive

Table 2 highlights the decisive role of urban infrastructure in mediating marine carbon processes. Digha's limited wastewater treatment coverage and negligible green–blue infrastructure result in uncontrolled nutrient discharge, undermining carbon sink stability. In contrast, Rotterdam and Sydney allocate substantial investment toward nature-based and hybrid infrastructure, enabling effective storm water nutrient removal and controlled land–sea exchanges. Qingdao relies on large-scale engineered wastewater and coastal management systems, achieving relatively high treatment efficiency despite rapid urban growth. The findings indicate that infrastructure-driven nutrient control is essential for sustaining phytoplankton-based carbon sinks in urban coastal environments.

Table -3: Land Use & Coastal Ecological Structure

	Land Use & Coastal Ecological Structure			
Indicator	**Digha, India**	**Rotterdam, NL**	**Qingdao, China**	**Sydney, Australia**
Urbanized coastal zone (%)	~65–70%	>90%	~75–80%	~45–50%
Mangrove / saltmarsh area (km^2)	~3	~2–4 (restored tidal wetlands)	~0	>50 (metro region)
Seagrass meadows (km^2)	Negligible	Minimal	Minimal	>1,800 (regional)
Net blue-carbon habitat change (last 20 yrs)	Negative	Positive	Slight positive	Positive
Coastal land-use control	Weak	Strong statutory zoning	Strong but growth-driven	Strong environmental regulation

The land-use comparison in Table 3 reveals sharp contrasts in blue-carbon capacity across the case studies. Digha's highly urbanized coastline and near-total loss of mangrove and wetland systems severely constrain long-term carbon storage potential. Rotterdam compensates for dense urban development through targeted wetland and tidal restoration, creating localized but functionally significant carbon sinks. Sydney benefits from extensive seagrass meadows and coastal wetlands, which provide stable carbon burial and regulate phytoplankton dynamics. Qingdao shows moderate ecological buffering, with controlled coastal development limiting further habitat loss. These patterns demonstrate the importance of preserving and restoring coastal ecosystems to stabilize marine carbon sequestration.

Table -4: Governance, Accounting & Climate Integration

	Governance, Accounting & Climate Integration			
Indicator	**Digha, India**	**Rotterdam, NL**	**Qingdao, China**	**Sydney, Australia**
Urbanized coastal zone (%)	~65–70%	>90%	~75–80%	~45–50%
Mangrove / saltmarsh area (km^2)	~3	~2–4 (restored tidal wetlands)	~0	>50 (metro region)
Seagrass meadows (km^2)	Negligible	Minimal	Minimal	>1,800 (regional)
Net blue-carbon habitat change (last 20 yrs)	Negative	Positive	Slight positive	Positive
Coastal land-use control	Weak	Strong statutory zoning	Strong but growth-driven	Strong environmental regulation

The governance comparison in Table 4 illustrates that institutional frameworks strongly influence the effectiveness of coastal carbon sinks. Rotterdam is the only case where marine carbon sequestration is formally integrated into climate action plans through accounting and monitoring mechanisms. Sydney and Qingdao show partial integration, with environmental performance targets supporting coastal decarburization but without comprehensive blue-carbon accounting. Digha lacks formal recognition of marine carbon processes within urban planning, resulting in fragmented and reactive management. The comparative analysis underscores that biological productivity alone is insufficient for effective coastal decarburization. Cities such as Rotterdam and Sydney demonstrate that governance, infrastructure, and land-use control are decisive in converting marine ecological processes into durable climate benefits. For towns like Digha, the priority is not to increase phytoplankton productivity, but to stabilize and govern it through wastewater control, coastal habitat restoration, and institutional carbon accounting.

This framing positions phytoplankton not merely as a natural phenomenon, but as an urban-regulated carbon infrastructure, capable of contributing meaningfully to coastal climate mitigation when embedded within integrated land–sea planning systems.

8. RECOMMENDATIONS FOR COASTAL DECARBONIZATION IN DIGHA

Based on the analytical framework, international comparisons, and the specific ecological and urban conditions of Digha, the following recommendations are proposed to enhance the town's capacity to transition from a carbon-emitting coastal settlement to a regulated, carbon-mitigating coastal system. These recommendations do not advocate artificial enhancement of phytoplankton productivity, but rather emphasize governance, infrastructure, and spatial planning interventions that stabilize and optimize existing marine carbon sink functions.

8.1. REGULATED NUTRIENT MANAGEMENT AS A CARBON STRATEGY

Digha's high phytoplankton productivity is primarily driven by monsoonal nutrient inflows, but the absence of nutrient regulation increases the risk of eutrophication and limits long-term carbon sequestration efficiency. A priority recommendation is the systematic regulation of nitrogen and phosphorus discharges through:

- Expansion of municipal wastewater treatment coverage to at least 80–90%, with tertiary nutrient removal standards aligned with coastal sensitivity.
- Decentralized wastewater treatment systems (DEWATS) for hotels, resorts, and seasonal tourism clusters.
- Regulation of storm water outfalls through sedimentation ponds and constructed wetlands to dampen nutrient surges during monsoon and peak tourist seasons.

Such measures would shift nutrient delivery from episodic and uncontrolled loading to moderated inflows that support stable phytoplankton productivity and improve the effectiveness of the biological carbon pump.

8.2. BLUE–GREEN INFRASTRUCTURE INTEGRATION WITHIN URBAN FORM

Digha requires a spatial restructuring of its inland–coastal water system to function as a nutrient and carbon buffer. The integration of blue–green infrastructure should be institutionalized through:

- Restoration and interconnection of urban ponds, drainage channels, and seasonal wetlands to form continuous inland–coastal ecological corridors.
- Mandatory vegetated buffers along drains and canals discharging into the sea.
- Incorporation of constructed wetlands within tourism infrastructure zones as multifunctional landscape elements for wastewater polishing, carbon sequestration, and climate adaptation.

These interventions can reduce nutrient loads by 30–70% while simultaneously creating minor but cumulative terrestrial carbon sinks within the urban fabric.

8.3. COASTAL HABITAT RESTORATION AND SEDIMENT CARBON PROTECTION

Although Digha lacks extensive mangrove systems, its shallow nearshore sediments play a significant role in organic carbon burial. Planning controls should therefore prioritize:

- Protection of intertidal zones and nearshore sediments from excessive shoreline armoring and beach modification.
- Pilot restoration of salt-tolerant marshes and dune–wetland interfaces where geomorphologic ally feasible.
- Restriction of further hard engineering along erosion-prone stretches, favoring hybrid nature-based coastal defenses.

Stabilizing these sedimentary environments enhances long-term carbon storage while improving coastal resilience to sea-level rise.

8.4. TOURISM AND TRANSPORT EMISSION MANAGEMENT

Given that tourism-related transport and accommodation account for a dominant share of emissions in Digha, decarburization strategies must complement marine carbon sinks by reducing upstream emissions. Key measures include:

- Promotion of low-emission mobility options such as electric shuttle services, pedestrianized beach zones, and seasonal traffic restrictions.
- Energy-efficiency standards and renewable energy integration for hotels and tourism facilities.
- Alignment of tourism carrying-capacity assessments with coastal ecological thresholds.

Reducing atmospheric CO_2 concentrations locally improves the net effectiveness of oceanic carbon uptake while addressing the root sources of emissions.

8.5. INSTITUTIONAL INTEGRATION AND BLUE CARBON ACCOUNTING

The most critical recommendation for Digha is institutional rather than ecological. Marine and coastal carbon processes must be formally embedded within urban planning and climate governance through:

- Inclusion of coastal and marine carbon sinks within municipal and state-level climate action plans.
- Development of a basic monitoring, reporting, and verification (MRV) framework using satellite-derived chlorophyll-a, sea surface temperature, and water quality indicators.
- Strengthening coordination between WBCZMA, municipal authorities, pollution control boards, and tourism agencies under an integrated coastal carbon management framework.

9. CONCLUSION

Coastal towns occupy a strategic position in the global response to climate change. While urbanization intensifies emissions, marine ecosystems—particularly phytoplankton-rich coastal waters—offer powerful yet underutilized mechanisms for carbon sequestration. This study demonstrates that integrating marine ecological processes into urban planning frameworks can transform coastal settlements from carbon-intensive growth centers into climate-regulating systems.

The proposed model for Digha illustrates a replicable approach that aligns urban development with marine carbon dynamics through planning, infrastructure, and governance interventions. Such integration is essential for achieving long-term sustainability, resilience, and decarburization across India's extensive and vulnerable coastline.

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