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Review

Oceanic Environmental Impact in Seaports

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Abstract: Seaports are gateways that connect a nation to the world economy. With trade by sea increasing due to globalization, the need for the improvement and development of seaports cannot be overlooked. While the development of ports is considered essential for the economic growth and prosperity of a nation, they also result in environmental deterioration that can hurt the future of humanity. The factors that cause such deterioration are many and have been discussed and studied in some detail over the years. Of these, however, studies associated with the environmental impacts of seaports emanating from the oceanfront are limited. It is with this understanding that the current work discusses the physical and biological impacts that occur due to the oceanic environment in seaports, the existing policy provisions, and the possible ways ahead to reduce environmental deterioration and allow their sustainable operation, by means of reviewing published works.

Keywords: sustainability; environmental deterioration; seaports

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1. Introduction

Seaports are among the most significant economic boosters for a nation internationally, regionally, and domestically. Numerous activities, including loading, unloading, storing, and transferring cargo between different transportation modes, result in several economic activities. Centripetal effects of these activities convert the ports into hubs for logistical and industrial activities, which have a domino effect by creating enhanced opportunities and, hence, economic growth. Efimova and Gapochka [1] showed that ports contribute to job creation significantly. They showed that for an increase of 1 million tonnes in turnover at the port of Antwerp of Belgium, the annual number of employees rose by 1285. Mehmood et al. [2] utilized an econometric analysis to prove that, during 2000–2019, 28 countries of the Organization for Economic Co-operation and Development (OECD) relied on their seaports for economic growth. Similarly, Ayesu et al. [3] provided clear evidence that seaport efficiency and trade enhanced the direct welfare outcomes of the people of Africa. Their study showed that increased seaport efficiency triggers positive effects on education, life expectancy, household consumption, and human development, with other positive momentums being multifold. However, the literature suggests that there are additional aspects of port development that need greater attention, especially the environment surrounding these seaports.

During port construction, a study undertaken by Palanques et al. [4] on the massive dumping of dredged material during and after the expansion of the last large port of Barcelona showed that the sediment dumping generated frequent (10–19 h per day), high (>203.2 mg/L), and short (50–90 min) suspended sediment concentration peaks. The unconsolidated sediment left after dumping was resuspended and advected, generating higher ambient suspended sediment concentrations (0.8–15.0 mg/L) than before the dumping (0.4–2.0 mg/L), which lasted for several days. This study highlights that seaports create noticeable environmental impacts during their construction and operations, both physically and biologically. If these environmental impacts remain uncontrolled, they may harm the surrounding terrestrial and marine ecosystems and jeopardize the wellbeing of coastal communities.

Once the port construction is completed, the ports continue to affect their surrounding environment. Žilinskas et al. [5] concluded that dredging of the entrance channel of the Klaipėda Port in Lithuania interrupted the alongshore sediment transport causing shore erosion on the updrift side of the port jetties. This was a result of the change in the wave field caused due to dredging, thereby altering the existing wave refraction pattern, changing the wave height regime, and eventually altering the sedimentation pattern [6]. The port structure in particular can alter the magnitude and direction of water currents differently, depending on the sizes and the permeability of the foundation structures used [7]. Ecologically, water stagnation can happen in certain locations within a port basin, inducing anoxic conditions, leading to low water quality, and killing marine animals [8]. Anton et al. [9], while analyzing the effects of breakwaters that emerged out of water, found that these breakwaters impact zoobenthos by destroying the habitats and benthic populations. In addition, due to reduced penetration of light and reduced oxygen due to sediment suspension, the quantity of phytoplankton was found to have been reduced.

With the known environmental impacts during and after the construction of seaports, it becomes imperative to consider the operations of seaports in a manner that would preserve the environment and ensure sustainability [10] to conform to the Sustainable Development Goals (SDG-2030) given by the United Nations. It is important to realize that increasing the gross domestic product (GDP) or boosting the national economy through the development of seaports without caring for the environment cannot provide sustainability [11]. While seaports are important for the economic growth and development of a nation, the oceanic environmental impacts that they cause are against the ethos of sustainability. This thus necessitates that nations and all stakeholders place greater emphasis on the possible negative impacts of ports' construction and operation to ensure sustainability.

Although there are several publications discussing the impacts of seaports, those focusing on the oceanic environment and their interactions are limited. It is to address this gap that this article provides a holistic picture of the physical and biological impacts that the oceanic environment cause in the seaports, by means of reviewing published works. In doing so, the article aims to create a general awareness amongst the readers about reducing the impact of the oceanic environment and operating seaports sustainably. To do so, we will first discuss the ports and their activities to understand how these activities cause environmental deterioration in the ocean. This will be followed by a detailed discussion of the physical and biological impacts that occur due to the activities happening in the port. Since these impacts are well known, the existing policy provisions will be discussed next. The conclusions will be preceded by analyzing the need for sustainability from ports and providing a possible way ahead to reduce environmental deterioration and to operate the seaports sustainably.

2. Understanding Ports, Port Activities, and Their Correlation with Human Sustenance

Seaports are maritime facilities driven by maritime trade that are created to provide access to the mainland from the seafront. Seaports are usually situated on the seafront or in estuaries, but they can also be found far inland, such as the port of Hamburg and the port of Manchester. The purpose of these ports is to act as entry and exit points for both men and materials during war and in peace. Accordingly, the ports perform the activities of loading, unloading, storage, and transportation of cargo and passengers, and they are considered to be extremely important to the global economy. These activities have an impact on world economics, as they support economic activities both at the port and in the hinterland, along with providing support systems of social and cultural functions by creating jobs and activities. The worldwide importance of ports has been discussed in detail by numerous researchers and needs no further deliberations here [12,13]. Over the years, as maritime trade has flourished, the ports have grown in terms of space occupied, technology used, and activities undertaken, resulting in greater job opportunities and ensuing overpopulation of port cities. This growing population has brought about a wide range of environmental impacts on local ecologies and waterways due to anthropogenic activities conducted on land and in the ocean [14], as shown in Figure 1. The most important of these impacts is the deterioration in water quality caused by dredging, oil spills, effluent discharge, and mindless disposal of solid and liquid pollutants [15]. In addition, activities such as construction and reclamation have created turbidity, changed siltation patterns, caused coastal erosion, impacted marine life due to noise and a lack of carbon sequestration due to ocean acidification, and impacted seaweed growth, to name but a few. Furthermore, activities of cargo handling, transportation, and emissions emanating from ships and industries have adversely impacted the quality of air in ports. Similarly, the impact of climate change has made port infrastructure particularly vulnerable to events such as rising sea levels, cyclones, coastal flooding, and increased precipitation [16]. In places where mangroves have been removed or destroyed to create access for ports, the impact on local marine life is grave and has impacted water quality, reduced the ability to withstand storm surges, and reduced habitats for commercial fishes and seafood [17]. The issue at hand has been compounded further, with modern ports tending to be multimodal hubs that escalate environmental deterioration due to greater demand for water frontage, regular dredging, prolonged usage of pilots, tugboats, and smaller vessels for transshipment using inland waterways, and trucks for hinterland transportation.

Figure 1. Port activities and human sustenance (source: authors).

While trade flourishes and the nation prospers through economic development, the environment is impacted adversely, resulting in both direct and indirect outcomes for human sustenance. With air, water, and land being polluted by port operations and activities, various social, institutional, operational, and land-use, conflicts arise [18]. Such conflicts arise because many gateway ports have become transit hubs and, hence, contribute little to the value chain but excessively to environmental deterioration. Accordingly, these ports are treated by the local population as foreign bodies rather than a driving force for socioeconomic development. Such skewed understanding causes conflict, wherein environmental impacts are disdained without giving due weightage to socioeconomic development. Such an approach impacts seaport governance and port efficiency to increase environmental impacts due to negligence and, hence, needs to be understood and resolved as early as possible.

While regulatory bodies and legal authorities issue guidelines to control environmental impacts, these can be best considered as guidelines, since these bodies have limited enforcement powers. A case in point is the Environmental Protection Agency (EPA), which has issued several regulations regarding where low-emission engines can be manufactured, but cannot enforce the use of such equipment or control the hours of operation, resulting in continued high carbon emissions in ports [19]. Hence, it is important for the authorities to understand the risks and impacts, and to work towards preserving the environment and ensuring sustainability in line with SDG-2030.

It is important to mention that even though the minor ports (especially those in the hinterland) are also considered equal if not greater contributors of pollutants, for this article we limit our discussion to seaports that are subjected to oceanic environmental impacts.

3. Seaports and Their Oceanic Environmental Impacts

One may notice that most of the changes are anthropogenic and have an oceanic impact on both physical and biological environmental aspects. To appreciate these changes better, and to understand the contribution of ports to these oceanic changes, we will discuss the activities and the changes in greater detail.

The environmental facets to be considered with respect to port development that create either physical impacts or biological impacts can be categorized into nine groups for ease of analysis, as shown in Figure 2 [20]. Each of these environmental facets has been discussed by several researchers and will not be deliberated here. Since doing justice to all of the environmental facets discussed in Figure 2 is not feasible in a single research article, we will limit the discussion only to environmental facets emerging from the ocean.

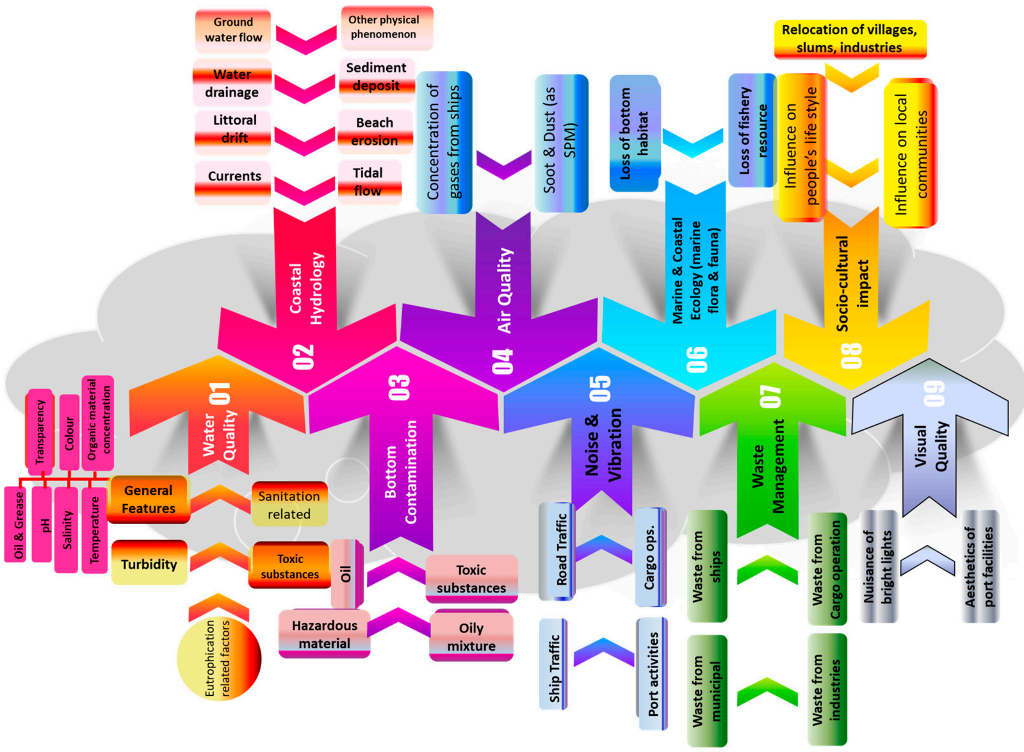

Figure 2. Environmental facets in ports (source: authors).

3.1. Physical Seascape Alterations and Their Impacts

To protect the coastline and manmade structures on the coast, coastal protection structures have been used. However, these structures, which protrude above the ocean, occupy water space and, while providing the required protection, alter the hydrodynamic patterns of the sea waves and currents. This, in turn, alters the water current circulation, resulting in either strong currents or water stagnation. As documented in many studies, the innermost part of port basins often exhibits water stagnation. Cutroneo et al. [21] measured the bottom current within the Port of Genoa, Italy, and found that the current speed in the innermost part of the port was less than 0.05 m/s. Jeong et al. [22] numerically showed that the inner zone of the North Port of Incheon, South Korea, experienced very limited water circulation even during the period with steep hydraulic gradients when the tide was rising or falling. During stagnant water periods, the water was found to have degraded, with increased sediment. Saengsupavanich [8] presented a limited water circulation condition for the Chiang Saen Commercial Port of Thailand, which displayed unsatisfactory water quality within the port basin.

When in the open sea near breakwaters, the water current is altered. The breakwater tends to increase the water current velocity at its tip and decreases it in its lee. Cutroneo et al. [21] showed that the current speed at the tip of the breakwater of the Port of Genoa, Italy, was much stronger than that inside the port basin. Rizwan et al. [23] found that the current speed around the tip of the Kutaraja Port, Indonesia, was very strong (greater than 0.4 m/s), while the current velocity in the breakwater-sheltered zone was less than 0.14 m/s. The increased water current velocity can pose risks to ships entering or leaving the port basins, or to small artisanal fishers navigating in the nearshore area.

Like currents, wave patterns such as wave refraction and diffraction are also altered due to reclaimed areas and breakwaters in the port. Saengsupavanich et al. [24] revealed that, due to breakwaters, the wave height, water flow, and sediment movement get altered. Earlier, Ilic et al. [25] confirmed that the presence of breakwaters could transform waves, especially in shallow-water regions. Prukpitikul et al. [6] showed that a new proposed breakwater at the Sattahip Port, Thailand, changed the existing wave pattern around the port.

Dredging, another necessary activity of most ports, changes seabed bathymetry. This results in altered wave regimes. Iouzzi et al. [26] numerically confirmed that the dredging of the navigation channel of the Mehdia Port, Morocco, led to an increase in wave height in and at the edges of the dredging area, as a result of a sudden increase in the water's depth. The waves propagating across the excavation area refracted toward the areas of shallow water, resulting in increased wave height. Conversely, when the wave regimes (i.e., wave height and wave direction) change along the shoreline, coastline changes follow as a consequence of the modified alongshore sediment transport.

We will now discuss the resulting changes in water quality, sediment quality, and shoreline changes due to the presence of the port structure and alterations of the water current and wave field due to these structures.

3.1.1. Water Quality within the Port Basin

The flushing time, representing the time taken to replace specific water mass in a coastal system, and which is used as a general indicator for this exchange, inevitably increases within the port basin. Sharaan et al. [27] estimated that the flushing time at the innermost part of the El-Burullus Fishing Harbor, Egypt, was 22–25 days, while it was 14–18 days around the port entrance. They showed that when the water is stagnant, the water quality around such zones tends to degrade. Saengsupavanich [8] showed that there was limited water circulation within the Chiang Saen Commercial Port of Thailand, to show that there was unsatisfactory water quality within the port basin. Numerically, Bonamano et al. [28], using the inner part of Civitavecchia Port, Italy, as an example, showed that deterioration in water quality and high concentrations of heavy metals are possible with a decrease in the flushing time.

3.1.2. Sediment Quality within the Port Basin

Limited water circulation around the inner part of the port basin affects sedimentation and sediment quality. Sedimentation at the entrance of the harbor is governed by the exchange of flow, while the sediment transport into the interior of the port is related to the exchange flow caused by the filling and emptying of the tide. Lee et al. [29] concluded that the high siltation at the entrance of the North Port of Incheon, Korea, was attributable to the influx of high-turbidity water, the decrease in current velocity, and the formation of an eddy. Cutroneo et al. [21] found that the coarser sediment tended to accumulate in the inner part of the Port of Genoa, Italy, while the finer sediment was found at the port entrance, where stronger water currents existed. The coarse inland-generated sediments carried into the port basin by rainfall or other anthropogenic activities do not move, because the available shear stress produced by the water current's flow is not enough to initiate sediment resuspension or bed-load movement [30]. Stagnant water flow also limits sediment mixing, resulting in a clear grouping of mineral composition within the port basin [21]. At Civitavecchia Port in Italy, Bonamano et al. [28] found that the sediment enrichment factors (EFs) of trace metals (i.e., how many times the trace metal concentration in the sediment is higher than the background value) were correlated with the flushing time. Their study concluded that the highest EF values of lead, arsenic, and zinc (EF > 40) corresponded to the highest values of the flushing time found in that area. Similarly, Lim et al. [31], who investigated heavy metal concentrations in the Qianzhen Fishing Port in Taiwan, reported that the levels of copper, zinc, lead, chromium, and nickel in the inner part of the port were much higher than those at the port entrance.

The sedimentation and trace metal accumulation within port basins due to limited water exchange eventually affect humans. Large amounts of heavy metals can bioaccumulate in marine bottom-dwellers [32]. Chakraborty et al. [33] showed that the surface sediment quality around the Mongla Port area of Bangladesh was deteriorating, especially with the alarmingly high levels of arsenic, nickel, cadmium, chromium, and Cu, which were considered to be the most concerning pollutants for bottom-dwelling organisms around the area. More specifically, the blood cockle (*Anadara granosa*), which is a favored bivalve mollusk species for many people, is a filter feeder, thus tending to accumulate heavy metals in its tissues. Tu et al. [34] reported that the Vietnamese could experience a carcinogenic risk due to cadmium accumulation in cockles from South Vietnamese coastal waters. Since coastal communities are usually densely situated around ports, and artisanal fishers still fish near the port areas, it is highly possible that the degraded sediment quality and the toxicity of elevated heavy metal concentrations could be transferred to humans and affect human health through the consumption of seafood caught around the ports.

It should be noted that the alteration of the coastline by coastal structures has a direct impact on the movement of sediments and minerals within these confined waters. This, in turn, impacts both the physical and the biological nature of these confined waters. Such changes eventually impact all activities in these areas, leading to undesired outcomes such as diseases, poor water quality, impacts on life forms, and many more that are considered to go against the desired norms of sustainability.

3.1.3. Impact on Coastline

Seaports and reclaimed lands, as well as harbor protection structures such as offshore breakwaters, alter wave patterns approaching the shoreline, changing the alongshore sediment transport rate and affecting neighboring shorelines. When a port breakwater is constructed, a wave-shelter zone is formed on the lee of the structure, inducing longshore sand transport from outside to inside the wave-shelter zone due to the wave diffraction effect. On the other hand, the downdrift coastline can be devastatingly eroded.

Uda [35] presented many case studies in Japan, such as the beach near Kashiwazaki Port in Niigata Prefecture, the coasts adjacent to Ohtsu Fishing Port, and Oharai Port in Ibaraki Prefecture. The studies showed that the shoreline at Oharai Port advanced up to 750 m relative to the original shoreline position before the construction of the port, which is now being used for recreation, but the coast south of the beach has been devastated, and all of the sandy beach has disappeared and been covered by the seawall and concrete armor units. Saengsupavanich et al. [36] illustrated a classic example of one of the biggest ports in Thailand, which created severe downdrift coastal erosion while accreting the updrift beach. Similarly, Nijamir et al. [37] showed that Oluvil Port in Sri Lanka greatly impacted its surrounding shoreline. Since the beginning of the port's construction (2001–2011), the southern part of the port accumulated at a rate of 8 to 13.4 m/year, while the beach erosion in the north was recorded at a level between −10.2 and −5.6 m/year. García-Ayllón et al. [38] firmly supported this finding by showing that every port along the region of Murcia, located on the southeast of the Spanish Mediterranean coast, noticeably changed the coastline in its vicinity. While these examples are not exhaustive, they indicate the possible environmental consequences as a result of changes in wave and water current patterns due to seascape modifications.

3.2. Biological Impacts

The oceans are considered to be rich in marine species. However, to date, only 240,000 species have been identified, with new ones being discovered on a near-daily basis [39]. It has been observed that the interface areas of the marine and terrestrial environments are the richest and the most productive with regard to marine life. These coastal regions act as nurseries for a number of species. If these coastal regions were to degrade, it would have a direct influence on the sustenance of the populations of the species that depend on these nurseries. In addition, vegetated coastal ecosystems such as mangroves, seagrass, plankton, seaweeds, and intertidal marshes, which sequester carbon in marine sediments, would also be impacted [40].

By converting natural coastlines into artificial ones through manmade structures such as ports, dykes, quays, etc., many of which have been built without ecological consideration, the natural habitats of these oceanic spaces are being destroyed. The resulting water contamination due to noise, construction, chemical, pollutants, oil, untreated human waste, and non-native species through ballast water or biofouling on the hulls of ships causes irreversible damage to the coastal ecosystem, affecting both animals and plants.

Before we delve into understanding the impacts of the anthropogenic deterioration of the oceanic environment in ports through the broad headings of deterioration of water quality (due to nutrients, pollutants, and non-native species), noise and vibration, and construction, let us understand the impacts of these environmental factors on marine mammals, turtles, and benthic habitats.

3.2.1. Impacts on Marine Mammals

Human-associated environmental stressors impacting the oceanic space are so closely interconnected that no marine mammal can remain entirely unaffected by them. Being at the top of the food chain, the resulting impact is a cumulative one [41]. If some conservation activity has to be initiated for their protection, an adequate understanding of the behavioral ecology of these species is considered to be essential [42]. Some of these stressors include pollution (e.g., oil, plastics), climate change, noise (human-generated or environment-generated), chemicals, marine debris, shoreline development, ocean acidification, the presence of invasive species, overfishing, habitat loss, and an increasing ocean temperature. These stressors and their impacts on marine mammals have been studied in great detail over the years. However, the cause-and-effect relationship between contaminants and their effects has been demonstrated only by a few studies.

Since the distribution of marine pollutants is not homogeneous and can vary both regionally and temporally, the full environmental impact of the pollutants is difficult to assess. To conduct an assessment of marine pollutants, marine mammals as bioindicators are often used, as they are highly susceptible to changes in the marine environment [43]. Though the impact of climate change is negative, the actual impact remains unconfirmed due to insufficient research and monitoring [44,45]. Similarly, plastic pollution as a stressor has been a reason for physical wounds and entrapment of marine mammals. Other stressors have been found to be equally dangerous for marine mammals.

While the actual impact is unconfirmed, what remains consistent among all stressors is that they cause organ anomalies, impair reproduction and immune functions, and force marine mammals to alter their location.

3.2.2. Impacts on Turtles

Of the known marine species that have survived numerous changes on Earth, turtles are considered to be the most important contributors to the evolution and maintenance of the marine ecosystem and, hence, merit a special mention. The origins of these turtles can be traced to those of the dinosaurs. They play an important role in maintaining the health of the oceans. By eating a variety of other organisms, they regulate them, provide habitats for many marine organisms, provide food sources for other organisms (especially in their early life stages), and provide beach nutrition.

In the last 200 years, their survival has been greatly impacted by anthropogenic activities. Activities on beaches such as beach armoring eliminate their nesting habitat, beach nourishment deteriorates the nesting habitat, human presence and beach cleaning by vehicles crush developing eggs, and artificial lighting causes high nesting mortality [46]. In addition, other anthropogenic activities such as illegal harvesting, poaching, coastal boating, noise due to construction, pollution by solid waste, oil, and chemicals, the presence of plastics, and fishing impact the health and mortality of these turtles. Climate change, on the other hand, is likely to impact their migration patterns, thereby exposing them to new predators. The threat is so enormous that it is expected that, by 2050, sea turtle nesting areas will be 100% flooded and their rookeries will vanish [47].

3.2.3. Impacts on Benthic Habitats

Even as we take pride in the technological advancements of recent times, our knowledge of benthic habitats and benthic communities is limited. These habitats range from sand to hard substrates and may occur singly or in combination, providing the benthic communities with a substrate to grow on. While some unique benthic habitats have been identified, such as polymetallic sulfides and ferromanganese crusts, many others still elude our knowledge due to limited knowledge of the deep oceans.

These benthic communities and habitats play an important role in maintaining the biodiversity and integrity of the marine ecosystem and the various ecological services in the ocean. Some of them act as important recruitment and nursery sites for marine fauna, provide food resources for larger marine mammals, and act as a foundation for many marine food webs. They attenuate wave and current energy, thereby protecting shorelines and coastal infrastructure, and supporting organisms that filter the water column [48].

Today, most deep-seabed benthic habitats remain pristine and have not been exploited, while coastal ones have been seriously impacted by anthropogenic activities. Unfortunately, since the impact of anthropogenic threats does not occur in isolation, their impact is poorly understood and, hence, is a matter of serious concern and continual research [49].

3.2.4. Factors Impacting Marine Life in Ports

As observed in the preceding discussion, marine life, great and small, is impacted by the environmental deterioration being inflicted by humanity [50]. The main contributors to this deterioration are discussed herein for better clarity, to eventually develop an understanding of how these stimulants can be addressed to ensure a sustainable marine environment.

Water Quality

Unwanted substances contaminate water, resulting in a reduction in water quality. This disrupts marine life and activities around the port, and it causes diseases in marine life and humans alike [51]. Water quality in ports can be deteriorated by planned or accidental discharges of oil and chemicals into the sea as a result of fuel operations in ports [52], dry dock and repair activities [53], ship breaking [54], stormwater runoff [55], thermal water pollution [56], water stagnation and eutrophication (thereby increasing algae and cyanobacteria in the port region) [57], and dredging and excavation activities [58] that may suspend silt and pollutants in water, creating turbidity, to name but a few. To add to these pollutants, the recently enforced SOx limits have forced ships to use seawater-based scrubbers by converting 95% of the SOx in the exhaust to sulfurous acid (SO_3^{2-}) and sulfuric acid (SO_4^{2-}) and discharging them as wash water into the sea. When done in ports where ships are numerous, this leads to an increase in ocean acidification [59]. The resulting poor water quality has a serious impact on the marine life of ports.

A systematic review by Madon et al. [60] of the various studies undertaken on biodiversity losses due to environmental impacts on ports showed that anthropogenic impacts have been reported for biodiversity, communities, and invertebrates. While the study of biodiversity in ports lacks an effective methodology for monitoring (limited to 0.01% of the world's commercial ports) due to underwater turbidity conditions, such studies are on the rise. However, there is limited involvement of local authorities and public participation when addressing issues of biodiversity in ports. This thus necessitates involving citizens for increased awareness and acknowledging the interactions of humanity with biodiversity. Accordingly, the biological impacts due to deteriorating water quality in the port area are discussed herein.

(a) Due to nutrients: Nutrient accumulation as a result of discharge in ports causes eutrophication. This eutrophication depletes oxygen levels, causing the death of fishes and other species [61] due to higher chlorophyll-a concentrations [57]. The impact of chlorophyll-a concentration was found to be high in a 6 km radius from the ports, beyond which the impact reduced [62]. For a newly constructed port, the chlorophyll-a concentration was found to increase during the final two months before starting operations. However, this effect was too small to create an algal bloom that could cause the death of fishes [47].

Phytoplankton growth is yet another outcome of increased nutrients, such as those found in fertilizers, or the addition of pollutants during activities such as dredging or the loading and unloading of cargo [63,64]. When ballast water is released, the response of the phytoplankton community may be impacted due to the introduction of non-native species bringing about changes to the whole ecosystem and marine resources [65]. These uncertainties increase with tropical temperatures and port activities [66]. While zooplankton increases with phytoplankton to some extent [67] and provides food for fish, thereby encouraging marine life, increased growth of phytoplankton reduces the available oxygen levels in the water [68], thereby impacting the survival of marine life. Hence, with increased nutrients due to water pollutants, the chance of survival of marine life is reduced, thereby having an adverse biological impact on marine life in the port.

(b) Due to non-native species from ballast water: The exchange of ballast water by a ship occurs as a requirement for maintaining stability during the passage of the ship and the loading and unloading of cargo. When a ship moves from one port to another without adequate cargo and consumes fuel and water, it is forced to take in seawater as ballast to ensure its transverse stability. This ballast water carries species local to the region from which the ballast water was taken and is eventually transported to a foreign oceanic space, where the ballast water is discharged. This mechanism allows the migration of species from one oceanic space to another. The species introduced in this way are referred to as bioinvaders, exotic species, alien species, or non-indigenous species. Studies have shown that nearly 10 billion tons of ballast water is transported each year [69]. When these species are released, the temperature, salinity, resources available, existing competition for food, and the presence of predators determine whether these species will survive in the new conditions. If the non-indigenous species survive, they become invasive to the existing species, thereby creating an imbalance in the food chain.

Species such as *Dreissena polymorpha*, known as the zebra mussel, are native to the freshwater lakes of Russia and Ukraine. These mussels become invasive in other regions as they consume oxygen and food, thereby limiting the available resources for native species. This mussel was introduced to the Great Lakes in the 1980s through ballast water, and since then it has cost billions of USD for the cleaning and repairs of underwater infrastructure [70]. Another species from the Baltic Sea, the green crab, is known to be a predator to many species of worms, oysters, mollusks, and clams. This species, since being introduced to Eastern Canada through ballast water in the 1950s, has outperformed local crabs for food and disrupts eelgrass beds, thereby causing critical damage to the marine environment [71]. Similarly, the edible seaweed known as Asian kelp is native to cold regions but then moved to San Francisco via ballast water, becoming an environmental disaster that requires frequent cleaning [72]. Not only larger organisms, but also bacteria such as *Vibrio cholera*, can spread easily and quickly through ballast water, impacting marine and human life [73].

The presence of such invasive species may result in disastrous consequences for the local ecosystems of fish stocks [13]. Accordingly, several studies of foreign species from ballast water have been undertaken. Saburova et al. [74] reported the blooming of *Heterocapsa circularisquama* in the northwest Indian Ocean due to the discharge of ballast water from the western Pacific, resulting in a high mortality rate among bivalves. Queiroz et al. [75] reported the presence of invasive phytoplankton on the Maranhão coast in Brazil due to shipping, while Tempesti et al. [76] reported the presence of non-indigenous fouling communities in the western Mediterranean ports. They found that tourist ships carried more alien species compared to cargo ships. In addition to the non-native species, ballast water also transports heavy metals, isotopes of radium and thorium, trace metals (such as barium, manganese, phosphorous, molybdenum, uranium, and vanadium), toxins, and sediments [77–79].

Realizing the importance and the damage that such discharges cause to the port areas, the International Maritime Organization (IMO) discussed this issue in detail during the Ballast Water Management Convention of 2004. As an outcome, the ballast water now needs to be treated in ports before its release [79]. Additionally, the mid-ocean exchange (MOE) of ballast water needs to be undertaken [80]. While treating the ballast water is considered to be effective in addressing the invasive species, concerns regarding the release of chemicals as a result of disinfection byproducts have come to the fore. However, research in this regard is presently limited [81]. Similarly, a literature review of the efficacy of water-exchange techniques revealed that even though the majority of the water is removed due to this exchange, organisms continue to thrive in the available sediment to repopulate the exchanged water [82]. With water-exchange techniques not being entirely effective, the marine species ecosystem in port water continues to be challenged for space and food. These invasive species prey on native species and alter habitats, environmental conditions, the food web, and the overall ecosystem. This eventually displaces the native species, reduces native biodiversity, and may cause extinctions of species [83]; hence, it is considered to be a major area of concern for the sustenance of the maritime ecosystem of the port.

(c) Due to non-native species from biofouling: Yet another method by which invasive species may be introduced to ports is through biofouling on vessels. Biofouling is the colonization of marine species on a substrate when it comes into contact with water. Through prolonged contact with water, multiple colonization layers deposit on one another to eventually allow larger macro-fouling species to be deposited. If the structure is moving, the deposited layers are likely to be washed away. However, the problem becomes acute when the structure is stationary. The problem of biofouling is common to both stationary structures such as dykes, groins, jetties, and piers and moving structures such as ships, boats, and yachts. This biofouling causes corrosion of the adhering surface, and for moving structures it increases resistance, thereby increasing fuel consumption and blocking water intake, leading to engine damage due to overheating. However, the translocation of such invasive species through vessel biofouling has received little attention from researchers and policymakers [84].

Since biofouling can cause corrosion and has an economic impact on vessels (i.e., reduced speed and efficiency) [85] and marine structures (especially the structural integrity and performance of renewable marine structures) [86], studies have been limited to the development of protection systems for both the vessels and the marine structures. Accordingly, the European OCEANIC project [87] aims to provide a long-lasting "one-size-fit-all" protection system against both biofouling and corrosion for renewable marine structures [88]. Similarly, the International Maritime Organization (IMO)'s Marine Environment Protection Committee (MEPC) adopted Resolution MEPC 207(62) to minimize the transfer of invasive species from biofouling from ships through management [89], and from recreational boats through practical prevention and management [90]. This has encouraged the use of chemically active coatings (e.g., antifouling paints using toxic substances such as bis(tributyltin) oxide (TBTO) and tributyltin fluoride (TBTF)) [91], as well as nontoxic fouling release coatings that inhibit the growth of these organisms and allow for their easy removal without involving chemical reactions [92]. Unfortunately, the toxic substances released from these coatings accumulate in fishes, with direct or indirect effects on human beings [93].

To mitigate the negative impacts of biofouling, it is important to understand the organisms so that an appropriate response mechanism can be developed. Accordingly, monitoring programs through verified observations [94], metabarcoding [95], numerical methods [96], and sampling methods have been used to validate the species, but these have been limited to morphological identification for developing antifouling control methods [86], while the impact of such species on port biodiversity has not been an area of study. This is primarily because of the difficulty in identifying when a species can become invasive or the factors that make a species invasive. This notwithstanding, since the negative impacts of invasive species on biodiversity are numerous and will only intensify with climate change, increasing human pollution and habitat destruction, greater scholarship is needed for the effective management of invasive species, along with enhanced knowledge about their impacts, diversity, and uses.

(d) Due to pollutants, e.g., chemicals, oil, human waste, plastics: Water quality in ports can be impacted by several pollutants, such as oil and chemicals, human waste, plastics, etc., which may be discharged accidentally or intentionally by ships, industries, or anthropogenic activities in the port, both terrestrial and marine. These pollutants may originate from land-based sources, marine traffic, port infrastructure, or neighboring coastal areas. The resulting contaminants include chemicals, metals, plastics, and polycyclic aromatic hydrocarbons (PAHs), which accumulate in the sediments and persist in the environment for prolonged durations. While the natural process of degradation of these pollutants is by bacteria, the presence of high concentrations of these pollutants and multiple of them at the same time exerts a toxic effect on the bacteria present [97], making them nearly ineffective. Similarly, untreated human sewage delivers pathogenic bacteria and viruses that may not be killed when exposed to seawater. Increased concentrations of these microbes make local seafood (such as clams and mussels) unsafe for consumption, transmit waterborne viruses such as cholera, and make the contaminated waters unsafe for bathing [98].

Yet another major pollutant is plastics, on which several studies have been undertaken, resulting in a growing focus on minimizing their use [99]. Plastic, when irresponsibly disposed of in nature, can cause the stranding and death of marine animals [100] such as turtles through entanglement, smothering, and ingestion. Estimates indicate that by 2050 there will be more plastic than fish (by weight) in the oceans [101], which would certainly impact food security for many.

(e) Due to the impact of climate change: Climate change is likely to have a severe impact on biodiversity by altering habitats. Since climate determines the distribution of species, it is possible that all existing plants and animals may not be able to accept the resulting climate change, which may lead to the extinction of some species, leading to biodiversity losses. With some species becoming extinct, those dependent on the extinct ones may not be able to survive, leading to further species becoming extinct or modifying their behavior. While the exact impacts of climate change have not been studied to date, an increase in temperature due to climate change would impact planktons and alter disease behavior, while an increase in sea level would impact certain species of frogs and toads, and increased acidification would impact living corals.

Noise and Vibration

Anthropogenic noise in the ocean is increasing continually. This increase has been observed due to shipping traffic, high-powered sonar, underwater explosives, offshore surveys, drilling, pile driving, and the development of large offshore floating structures [102]. Noise propagation is controlled by physical factors (e.g., absorption, reflection, refraction), it is a function of depth and topography, is frequency-dependent, and can propagate hundreds of kilometer under the right conditions. Hence, it is an area of concern, especially for marine ecosystems near ports, where anthropogenic marine noise has been reported to be high.

Several studies [103,104] undertaken on the impacts of anthropogenic noise on marine ecosystems have shown that such noise can lead to the killing of zooplankton [105], cause cochlear damage [106,107], mask fish communication [108], change individual and social behavior [109], alter metabolism [110], and hamper growth and reproduction, including damage to eggs. This impact is especially amplified in closed spaces, such as ports, and is a matter of growing concern. However, the use of nonstandard measurements makes it difficult to compare the reported results. Similarly, the scarcity of studies with larval or juvenile individuals severely constrains the understanding of noise pollution. It is hence essential that preventive measures, both at the national and international levels, are instituted to avoid any irreversible damage to biodiversity and the marine ecosystem [111,112].

Construction of Maritime and Coastal Structures

The construction of coastal structures has several environmental impacts, both positive and negative, on the ecology [24]. The algal macroflora present 1–5 m below the water level provide biological nutrients, a shelter for epiphytic algae, and fauna for invertebrates and marine life. With the introduction of coastal structures, the hydrochemical parameter of the region changes due to increased structure roughness, decreased water transparency, and the presence of petroleum residues. These changes encourage the development of macrophyte-tolerant opportunistic species, thereby reducing the marine perennial plant species, as seen during a study along the Romanian coast [9]. Similarly, such structures lead to the accumulation of sediments, which decreases the wealth of benthic invertebrates considerably [113]. The very presence of these structures disrupts the natural movement of species, encouraging invasion by invasive species [114]. During the maintenance of these coastal structures, temporary disturbances have an impact on the sessile fauna, algae, and mobile fauna that have colonized the structure. This impact is usually negative but short-term.

Coastal structures also result in varying levels of beach nourishment. This beach nourishment impacts several ecosystem mechanisms. In addition, the resulting muddy water can decrease phytoplankton and benthic algal efficiency due to reduced light, prevent polychaetes and bivalves from feeding and breathing, and determine the pace of recovery of macrobenthic organisms [115].

One such ecological ecosystem that is impacted by these structures, especially when unplanned, is mangroves. Even though mangroves encourage the control of environmental pollution, they are under threat due to such structures and other anthropogenic activities, like urbanization, dumping of waste, and industrial effluents. Unplanned development of seaports, salt works, jetties, and other coastal structures has been found to impact the mangrove cover [116,117]. While studies have shown that there is no direct evidence to support the notion that harbor development affects the health of mangroves, the reduction in local groundwater salinity impacts their survival [118]. Carugati et al. [119] showed that disturbed mangroves display a loss of 20% in benthic biodiversity and a loss of 80% in the microbial-mediated decomposition rate of the benthic mass of trophic resources. In addition, due to anthropogenic activities, four phyla (Cladocera, Kynorincha, Priapulida, and Tanaidacea) were found to have become extinct. It is hence essential that these fragile ecosystems be protected for the numerous ecosystem services that they provide [120,121].

Despite the growing awareness of the influence that such structures have on flora and fauna, a comprehensive understanding is lacking of how these structures modify ecological connectivity in near- and offshore environments, and of when and where their effects on connectivity are the greatest [122].

4. Existing Policies and Legal Provisions to Address These Pollutants

Since the factors influencing ports are well known, it is natural to assume that the process of quantification of the diffusion and transportation of pollutants in the ports is well established. One such method, the US EPA's WASP4 model, helps analyze several pollutants in almost all water bodies [123]. When it comes to regulations, the maritime industry is an inherently reactive one that is slow to adopt disruptive and new technologies [124]. Accordingly, most of the regulations that exist in the maritime industry are a result of learning from an incident or a set of incidents. The International Convention for the Prevention of Pollution from Ships (MARPOL) [125], which aims to address tanker accidents and routine pollution through methods such as tank cleaning and the disposal of oily engine-room wastes, is an outcome of the Torrey Canyon disaster of 1967 [126]. As awareness of maritime pollution increased, long-term monitoring was utilized to refine the existing policies for ships [127] and port facilities through the development of various environmental performance indicators to measure environmental performance [128].

Similarly, various national, regional, and international regulations, guided by the IMO, aim to help achieve sustainability in the maritime industry. However, currently, the IMO guidelines are optional, and for a sustainable world they need to be made mandatory, along with strict enforcement. To encourage greater results, the efforts of those striving to achieve sustainability must be recognized, awarded, and encouraged. Similarly, those falling behind need to be educated and supported adequately with management solutions, finance for green technologies, and research and development. However, since whatever happens on the land has a direct impact on the oceans, this education needs to be holistic, addressing even those issues that are not directly connected to maritime shipping, such as plastic pollution [99], which need to be addressed to avoid the deterioration of our oceans. While several efforts, such as decarbonization by digitalization [129], the use of LNG as a decarbonizing fuel [130], the use of hydrogen as a decarbonizing fuel, and adopting the principles of a circular economy for the maritime industry [131], are considered to represent positive steps towards achieving the commitment of the IMO to achieving the targets of the Paris Agreement, there is a lot that needs to be done to achieve a net-zero emissions regime and towards the reception and treatment of ship-generated garbage. Similarly, issues regarding the reporting of ship collisions, ship damage due to piracy, and more need to be established and enforced.

To safeguard species and habitats, Europe has a program named Natura 2000, which is the largest coordinated network for species and habitat protection and involves many European coasts and estuaries. Such regions should aim to restrict the discharge of scrubber wash water [46]. In this regard, the use of technology is on the rise, with AI and ML being used extensively to address the growing menace of plastic in the maritime space [132].

5. Discussion

There is no doubt that anthropogenic activities of various kinds aimed solely towards economic gains have become a bane for the future generations of humanity. Since the land and the ocean are connected intrinsically to one another, the negative impacts of anthropogenic activities on land can be felt even in the oceans. To add to these activities, the construction of artificial coastlines through concrete structures such as ports, dykes, quays, etc., has created an imbalance in coastal ecosystems. Realizing that a delicate balance is required between economic growth and sustainability, the focus has shifted to ensuring that something, rather than nothing, is done to monitor and restore the ecological environment.

Accordingly, humanity has begun to focus on repairing natural habitats through both active (i.e., modifying physical characteristics and reintroducing species) and passive (i.e., reducing human pressure on the environment to allow for natural rejuvenation) restoration. Since new ocean activities such as marine renewables, deep seabed mining, and nautical tourism are being pursued for development, most of them are progressing only after undertaking an environmental impact analysis (EIA). While the completeness and correctness of EIA is a matter of debate in some of these projects, it can be considered to be a baby step in the right direction to ensure greater sustainability and stem the deterioration of the marine environment due to anthropogenic activities.

Similarly, new monitoring standards and tools have been devised and used extensively for addressing the environmental performance of ports. One of the best known is the European *EcoPorts* initiative, which allows the port managers to self-assess the environmental management of port performance [133]. Similarly, the Port Environmental Review System (PERS) is used to review and report significant environmental aspects of port processes [134], while the Green Marine Program offers ways and means to reduce the environmental footprints of maritime companies [135]. However, these approaches provide a qualitative rather than a quantitative assessment of port environmental issues, and they do not provide a comparison between the performances of ports. To provide such an inter-port comparison, Široka et al. [136] proposed the development of an IoT-leveraged, comprehensive, and standardized Port Environmental Index (PEI) as part of the European Union's Horizon 2020 project Port IoT for Environmental Leverage (PIXEL).

To reduce the impact of the damage being caused, efforts towards the rehabilitation of the ecological functions of the ports have also been experimented with. Hence, ecological engineering [137] and eco-design [138] have been used. These processes focus on modifying port structures such that fish nursery functions can be rejuvenated in ports, preferably to a level that is equivalent to that of the natural reference areas. In some cases, the densities of species in such eco-designed structures are 2.7 times higher than those observed in smooth structures [139], with non-native species being in the range of 28% to 61% lower than in conventional port structures [140], and their health being equivalent to that in adjacent natural areas.

While some success has been seen in these efforts, skeptics term these efforts greenwashing, since these operations are undertaken empirically, without clearly defined objectives, on an experimental basis, with monitoring undertaken only for a short period. Such efforts do not encourage the upward scalability of these projects to provide advantages at a larger scale. That said, it is important to acknowledge that the benefits provided by such rehabilitation processes are the need of the hour. While humanity cannot replicate nature, these processes can at least be used as mitigation measures for our misdoings [141].

6. The Way Ahead

With the increasing stress of a growing population on natural resources, the control of anthropogenic, environmental, and biological impacts on nature cannot be avoided. It is no wonder that the planet, including the oceans, has begun to experience these impacts. It would not be incorrect to say that humanity is still trying to understand these impacts and the factors that cause them. While the understanding of some of these impacts is increasing, those with biological significance are mostly still unknown, especially in the oceans. As studies advance, new species continue to be discovered in the oceans, requiring recalibration of the studies to understand the observed responses afresh.

With a range of unknowns, the need for sustainability has taken center stage, and it is considered to be a necessary building block for all human activities. This necessarily requires concerted efforts toward understanding and analyzing the forces that cause these impacts so that they can be kept to a minimum, if not completely stopped.

Several efforts in the maritime domain in the recent past have ensured that the industry has changed to be proactive, as opposed to its usual status of being reactive. It is in keeping with this thought that the adoption of Industry 4.0 norms has made inroads in the maritime industry. The use of artificial intelligence to monitor the oceans for pollutants, using digitalization to reduce carbon emissions from ships, 3D printing for ship repairs, the use of 5G for improved performance, the use of automation for unmanned vessels, the use of AUVs for deep-seabed surveys [142], and the introduction of a circular economy in the maritime industry are some such steps that would help achieve sustainability in the maritime sector and ensure retarding of the continued deterioration of the maritime environment.

While technology can help monitor and support humanity in achieving sustainability, the role of the man behind the machine cannot be overlooked. This essentially dictates the need for awareness and education of humanity to ensure that the resulting impacts due to anthropogenic efforts are kept to a minimum. It further demands that the standards of design, data collection, data analysis, and reporting be defined so that the obtained results across space and time can be compared and the unknowns and consequences can be understood better across all spectrums of the world.

It is important to mention that numerous times, when evaluating an area of concern, the full product cycle is avoided to skew the results. It is also important to mention that, in doing so, the burden of environmental deterioration is merely transferred to some other system or process, which needs to be avoided. The need of the hour is hence to evaluate options and solutions over their entire life cycle to ensure their effectiveness in creating a zero-emissions environment and achieve true sustainability. Since we as a species have no "Planet B" for ourselves, saving the present one through environmentally prudent actions is considered to be the only and the best option available for all, which cannot be avoided or undermined. For this, the support and involvement of all stakeholders is considered to be a definite necessity.

7. Conclusions

The present article has discussed the numerous environmental facets that impact and pollute ports, with a focus on those emanating from the ocean environment. There is no doubt that for a sustainable living and working environment with increased efficiency, sustainability is essential and, hence, must be achieved. However, in the same breath, it is important to say that this is easier said than done, and efforts are limited to certain nations and silos, thus pushing the final goal further away than it already is.

While no singular element can be pinpointed as a possible weak link, a coordinated effort by all stakeholders should include the policymakers, ship owners, ship operators, freighters, port authorities, port workers, and the common person, all playing an equal and important part in raising awareness, creating policies, and implementing them on the ground for the true realization of a green planet.

It is no wonder that ports across the world have begun to focus on "Green Ports Initiatives" by focusing on protecting communities, creating environmental awareness and compliance through education, promoting sustainability, and minimizing pollution using technology, with the Port of Long Beach in the United States being the first to develop specific policies on 31 January 2015. Over the years, ports such as Rotterdam, Hamburg, San Diego, Singapore, Gothenburg, Vancouver, and Hong Kong have adopted these policies, with India initiating its own Project Green Ports in January 2016 [143]. However, achieving and sustaining a green port is a continuous process that requires planning, organization, and dedicated efforts. Since noncompliance towards achieving sustainability is not an available option for our planet, the importance of ports becoming green must be emphasized in the overall interest of humanity. Towards this, understanding the factors that are responsible for environmental degradation and then taking active steps to control them, as discussed here, is considered to be the first and most important step.

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