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A systematic scoping review of environmental and socio-economic effects of COVID-19 on the global ocean-human system

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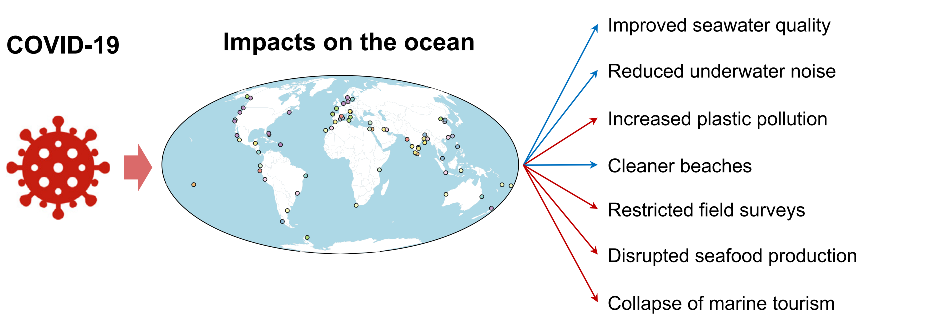
HIGHLIGHTS

- The first scoping review of impacts of COVID-19 on the ocean-human system.
- Improvement of seawater quality and underwater noise pollution with concurrent increase in medical plastic waste.
- The COVID-19 pandemic offers an opportunity for transformation towards sustainable ocean development.

GRAPHICAL ABSTRACT



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ABSTRACT

The global outbreak of the coronavirus disease 2019 (COVID-19) has strongly affected human lives. The restrictions taken to slow down the spread of the virus impact socio-economic activities and the environment. A comprehensive review of these COVID-19 impacts on the ocean-human system is lacking. The current study fills this gap by synthesizing the environmental and socio-economic effects of the COVID-19 pandemic on the global ocean by conducting a systemic scoping review of 92 published articles. From a geospatial perspective, the studies covered a total of 37 countries, mainly from Asia, Europe, and North America, with a particular focus on the Indian Ocean and the Mediterranean Sea. From an environmental perspective, both positive and negative effects on global oceans were summarized. Notably, improved coastal water quality and reduced underwater noise were reported. On the other hand, the increasing COVID-19-related medical waste such as personal protective equipment leads to severe pollution, which threatens the marine ecosystem and wildlife. From a socioeconomic perspective, the impacts of the pandemic were negative throughout with marine tourism and the fishery industry being severely disrupted. Coastal communities suffered from loss of income, unemployment, inequalities and health problems. The COVID-19 pandemic offers an opportunity for transformation of management and economic practices in order to save our ocean and boost progress towards Sustainable Development Goal 14 (SDG 14). Future research should include other sectors such as marine biodiversity, marine renewable energy, climate change, and blue economy development of Small Island Developing States. Effective policies and strategies across land and ocean around the world need to be developed and implemented to enhance resilience of the human-ocean system and to achieve post-pandemic global sustainable ocean development.

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1. Introduction

The 2019 coronavirus disease (COVID-19), caused by the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), has caused health crises and various associated global environmental and socioeconomic impacts (Cheval et al., 2020; Verma and Prakash, 2020). As of December 2021, two years after the first case was detected in Wuhan, over 280 million cases have been confirmed infected globally, resulting in over 5 million deaths (https://coronavirus.jhu.edu/map.html). A range of measures have been taken by governments around the world to control the rapid spread of COVID-19, including lockdown, travel restriction, workplace and school closure (Hale et al., 2021). COVID-19 has resulted in various economic challenges such as unemployment, economic loss and severe social disruption such as inequality, hunger, education across countries (Aristovnik et al., 2020; Bashir et al., 2020). Human mobility or activities have decreased around the world, which had directly or indirectly affected the environment (Khan et al., 2021; Rutz et al., 2020; Shakil et al., 2020).

Impacts of the COVID-19 pandemic have been reviewed in various studies covering the atmosphere, hydrosphere and anthroposphere (Table 1). For instance, the temporal lockdown periods prompted sharp declines of global greenhouse gases (GHG) emission (Kumar et al., 2022). Carbon emission has dropped about 8.8 % in the first half of 2020 relative to 2019, resulting from lockdown policies such as the industry closure and transport control in many countries (Liu et al., 2020; Nguyen et al., 2021). A remarkable decline of air pollutant emissions such as PM and NO_2 were observed at both national and regional level around the world, especially for huge emitters such as China, United States, and Europe (Hoang et al., 2021a; Le et al., 2020; Venter et al., 2020; Zhang et al., 2021a). However, the impacts of COVID-19 are evident in the marine environment as well, which have not been fully reviewed to date. The ocean provides food, jobs and livelihoods to about 40 % of the global population that live within 100 km of the coast, and plays a critical role in regulating climate by absorbing ~30 % of human-generated CO_2 emissions and more than 90 % of excess heat in our climate system (Cheng et al., 2017; Halpern et al., 2012). Insights regarding the influences of the pandemic on the ocean are important for understanding the interaction between human and ocean, and help us better prepare for the future challenges in the marine environment and economies (Murphy et al., 2021).

There is a need to identify the effects of the COVID-19 pandemic on the marine environment and the related industry. Ultimately, humanity will face pandemics in the future, and learning from the current COVD-19 pandemic can aid in developing strategies to cope with future pandemics. This must include the development of knowledge of the effects of a pandemic on air and land, which have both been studied comprehensively, and the global ocean. Therefore, this study, for the first time, reviews the impacts of the COVID-19 pandemic on the various aspects of the marine environment and socio-economy, including beaches, seawater, biodiversity, marine tourism, fishery and aquaculture. The research landscape and mature evidence were further described and identified, with various research clusters (e.g., coastal water quality, underwater soundscape, medical waste, seafood production, fishers' livelihoods, marine tourism) being categorized and each of them was analyzed in detail. This study provides valuable information for ocean and coastal management to achieve sustainable ocean development towards a post-COVID-19 and to develop robust strategies for a sustainable human-ocean system to cope with future pandemics.

2. Methods

This study performs a systemic scoping review regarding the impact of the COVID-19 pandemic on the global ocean. The review process follows the systemic approach of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Tricco et al., 2018), by considering relevant literatures that analyzed the effects of COVID-19 in the marine realm in both, the ecological and socioeconomic dimension. Details on source, search strings and exclusion criteria of published articles can be found in Supplementary Information.

3. Results

3.1. Research focus and geographic distributions

A total of 2665 research articles were retrieved based on the above search criteria. We manually screened all articles by title and abstract, which removed 2435 articles that did not meet the requirements (see Supplementary Text). After the assessment of the full texts and considering the research purpose of this systematic review, 92 studies (see Supplementary Table 1) were selected for the final analysis of the ecological and socioeconomic effects of the COVID-19 pandemic in the marine realm (Fig. 1).

The reviewed articles had an extensive geographical coverage (Fig. 2a), with stronger focus on Asia, Europe, and North America, in total covering 37 countries. At the country level, most of the studies were implemented in countries severely disrupted by COVID-19, including India (10 studies), Spain (7 studies), the United States (6 studies) and Bangladesh (6 studies) (Fig. 2b). In India, most studies have focused on the COVID-19 lockdown-induced changes of coastal water quality. Various water quality parameters such as chlorophyll-a (Chl-a), total suspended matter (TSM), suspended particulate matter (SPM), particulate organic carbon (POC), turbidity, nutrient concentration, dissolved oxygen (DO) levels have been studied for comparison before and after the lockdown with advanced remote sensing techniques. In North America, studies were mostly focused on reduced underwater noise, seafood supply chain and marine conservation. Surprisingly, as the country with the worst initial outbreak, China had few

Table 1
Summary of comprehensive reviews and analyses on impacts of COVID-19 on the total environment.

Title	Spheres	Impacted factors	Source
Impact of COVD-19 on greenhouse gases emission: A critical review	Atmosphere	GHG emissions	(Kumar et al., 2022)
Record decline in global CO2 emissions promoted by COVID-19 pandemic and its implications on future climate change policies	Atmosphere	CO_2 emissions	(Nguyen et al., 2021)
A remarkable review of the effect of lockdowns during COVID-19 pandemic on global PM emissions	Atmosphere	PM emissions	(Le et al., 2020)
An analysis and review on the global NO_2 emission during lockdowns in COVID-19 period	Atmosphere	NO_2 emissions	(Hoang et al., 2021a)
COVID-19 and the environment: A critical review and research agenda	Atmosphere	Air, sound, climate	(Shakil et al., 2020)
Review on the contamination of wastewater by COVID-19 virus: Impact and treatment	Hydrosphere	Wastewater	(Lahrich et al., 2021)
A qualitative and quantitative synthesis of the impacts of COVID-19 on soundscapes: A systematic review and meta-analysis	Anthroposphere	Soundscapes	(Hasegawa and Lau, 2022)
Impacts of the COVID-19 pandemic on household food waste behaviour: A systematic review	Anthroposphere	Household food waste	(Iranmanesh et al., 2022)
The COVID-19 pandemic: Impacts on cities and major lessons for urban planning, design, and management	Anthroposphere	Cities	(Sharifi and Khavarian-Garmsir, 2020)
A systematic scoping review of environmental and socio-economic effects of COVID-19 on the global ocean-human system	Hydrosphere, Biosphere	Ocean	This study

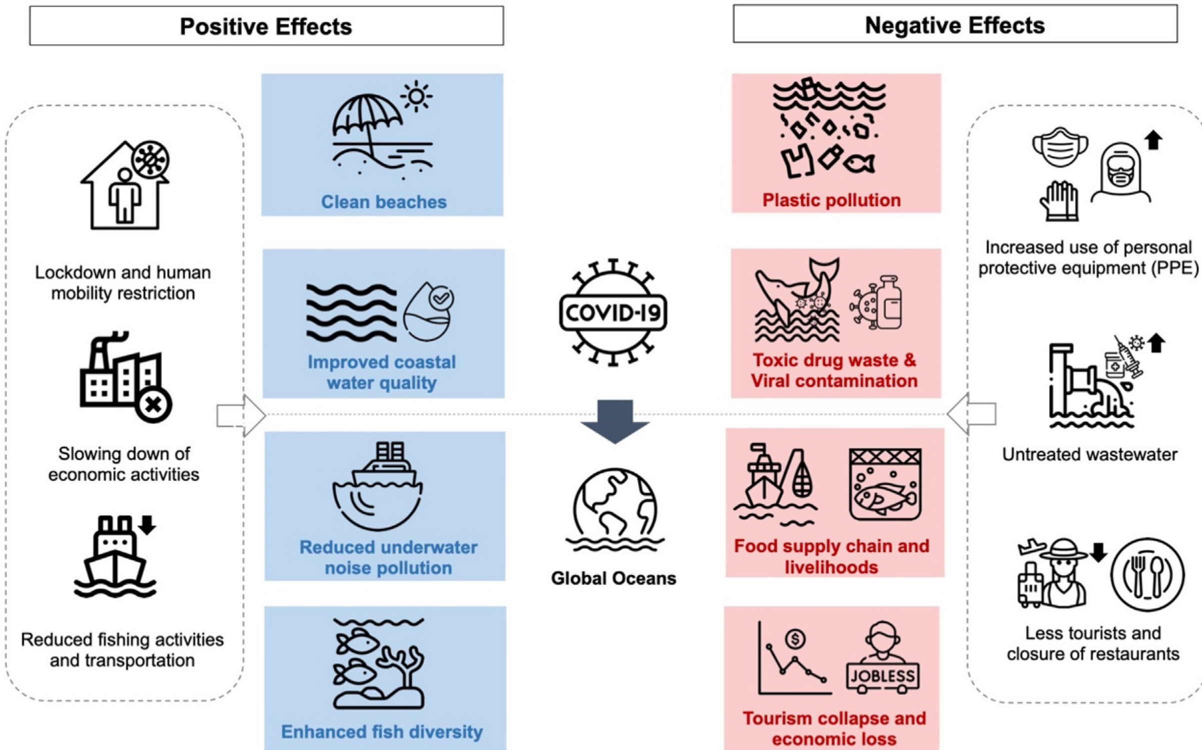

Fig. 1. Schematic diagram of positive and negative effects of the COVID-19 pandemic in the marine realm.

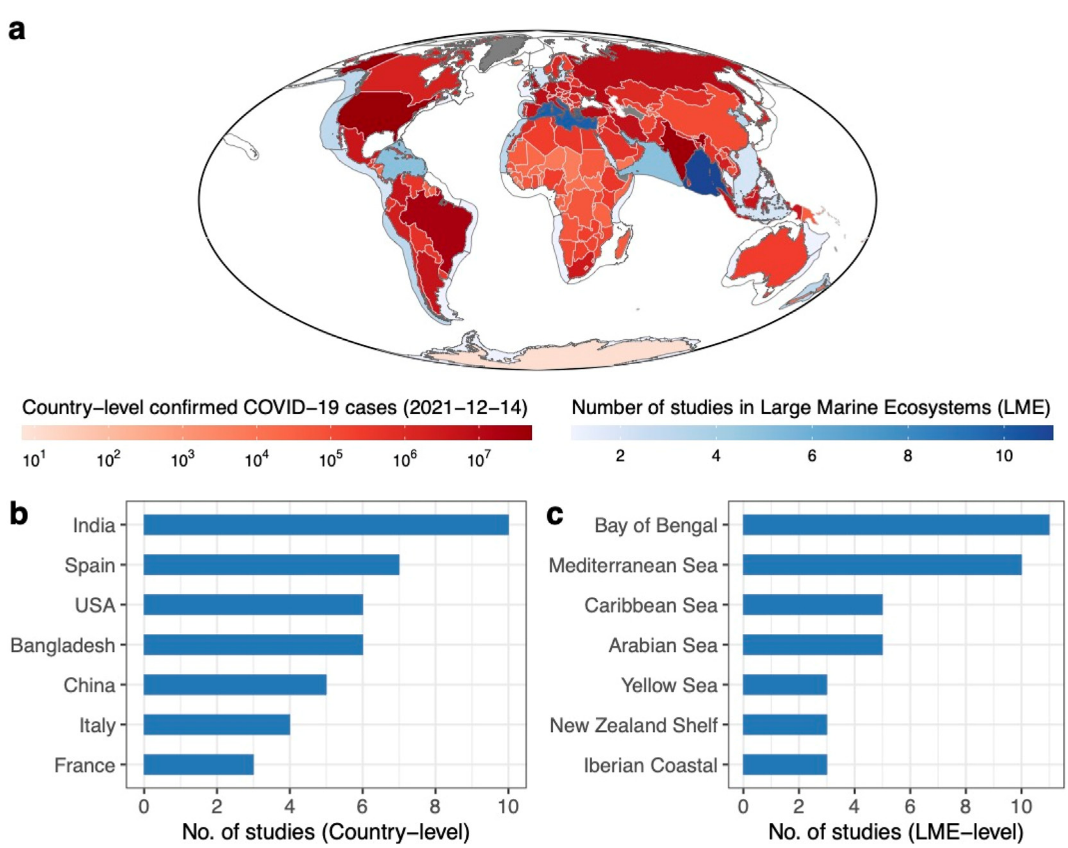

Fig. 2. (a) Spatial distribution of accumulated confirmed COVID-19 cases and reported studies in Large Marine Ecosystems (LME); (b) Number of studies in the top seven countries; (c) Number of studies in the top seven LME regions.

studies considering COVID-19s impacts on the ocean with only 5 studies meeting the criteria to be included in our review. It was also interesting to discover that studies in India, Europe and the United States mostly focused more on the positive marine environmental impacts resulting from reduced disturbances of human activity due to pandemic lockdown policies, while the 5 studies in China were concentrated exclusively on the negative impacts such as the waste pollution due to the increased use of face masks, food and biodiversity safety, and the tourism crisis.

For the different Large Marine Ecosystems (LME) regions, where coastal areas are heavily affected by human activities, most studies investigated the Bay of Bengal (11 studies), the Mediterranean Sea (10 studies), the Arabian Sea (5 studies) and the Caribbean Sea (5 studies) (Fig. 2a & c). Few studies have considered the Northern Arctic and Southern Antarctic regions.

3.2. Extent of COVD-19s impacts on the ocean

Both positive and negative impacts of COVID-19 on the global ocean were reported in the 92 studies that were considered (Fig. 3a). Overall, 33 % of studies ($n = 30$) were linked to the positive effects of the COVID-19 pandemic, while 58 % of studies ($n = 53$) focus on the negative effects. Ecological impacts were reported in 63 % of reviewed articles ($n = 58$), socio-economic impacts in 34 % of articles ($n = 31$) while only 3 studies covered both ecological and socio-economic aspects (Fig. 3c). For various ecological outcomes, we found that 26 % of the studies ($n = 15$) assessed the effects of the COVID-19 pandemic on the coastal water quality, the majority of which were reported in India and Italy. Reduced underwater noise ($n = 12$) were mostly reported in North America and Europe, while waste pollution ($n = 10$) was reported everywhere around the world. For the socio-economic aspects, all studies reported negative impacts, with 8 studies focusing on aquaculture, 10 on capture fishery, 11 on fishers' livelihoods and 5 on marine tourism industry.

3.3. Types of effects across different dimensions

3.3.1. Environmental dimensions

Marine pollution is a widespread problem around the world, adversely affecting environmental and human health. For instance, excess anthropogenic nutrient inputs from land to sea raised coastal eutrophication, which promotes algal blooms. Underwater noise caused by intensified shipping can negatively impact ocean animals and ecosystems. Before the pandemic, marine pollution problems such as eutrophication and noise pollution were already threats to ocean health in coastal waters including the East China Sea, Chesapeake Bay and Gulf of Mexico (Jiang et al., 2019; Malone and Newton, 2020). The worldwide confinement restriction during the COVID-19 pandemic led to the reduction of marine shipping, closure of industries and recreational beaches, which all alleviated human pressures such as nutrients, noise, odor and litter on the marine environment (Soto et al., 2021b). A range of benefits have been brought to the marine environment such as cleaner beaches, improved coastal water quality, increased fish density, and reduced underwater noise in many regions (Lotliker et al., 2021; Mishra et al., 2020). At a global scale, there was an observed drop of the water quality parameter Chl-a concentrations in the coastal regions, especially off the coast of Alaska, North Europe, South China and Southeast USA, associated with a 60 % reduction of particulate inorganic and organic carbon (PIC:POC). Meanwhile a decrease of 0.5 °C in mean sea surface temperature (SST) was observed over most of the coastal regions (Al Shehhi and Abdul Samad, 2021). It was suggested that maintaining human activities as sustainable as during the COVID-19 pandemic period could help preserve the oceans and mitigate climate change effects. In India, which experienced a peak of the COVID-19 pandemic in April 2020, strict lockdown measures have led to a strong decline of urban activities and varied associated improvements in coastal waters across the country. It was estimated from satellite images that the TSM and SPM concentration of coastal waters decreased up to 50 % and 37.5 % in the

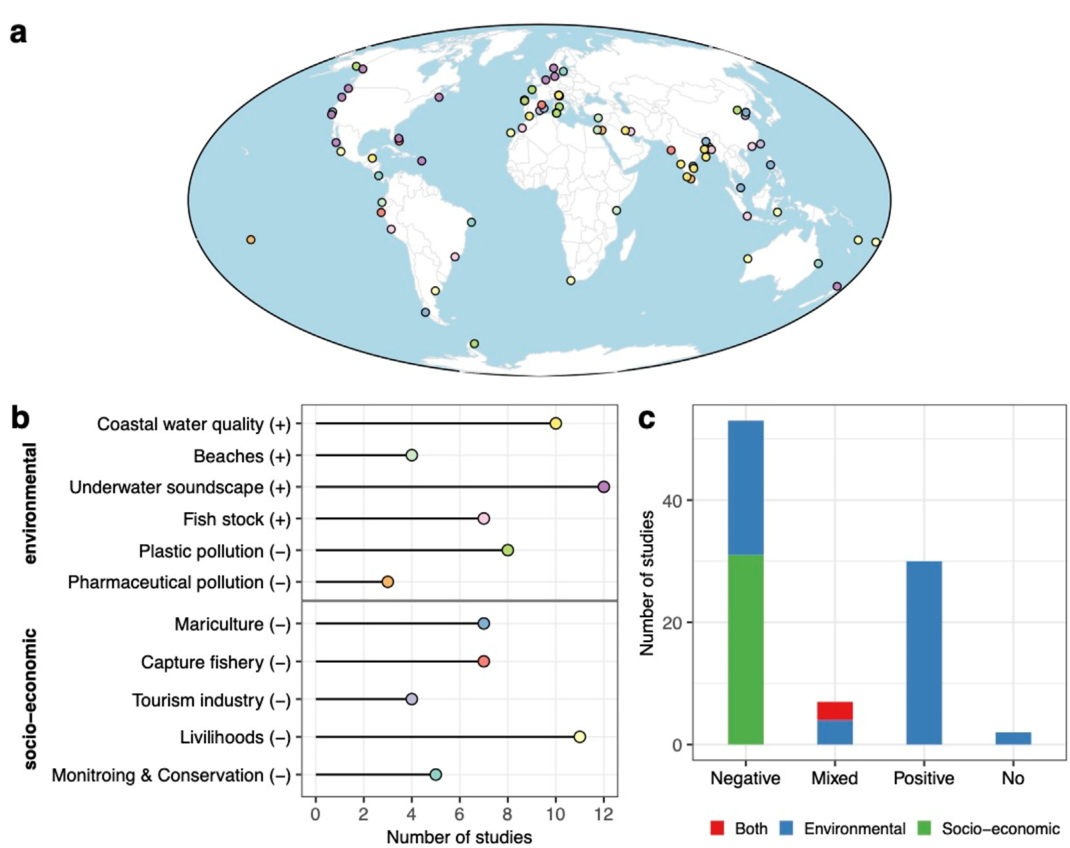

Fig. 3. (a) The spatial distribution of study sites of reviewed articles and (b) & (c) classification of negative (−) and positive (+) effects of the COVID-19 pandemic.

Hooghly estuary (Jayaram et al., 2021) and the Chennai coast (Vijay Prakash et al., 2021), respectively. In addition to the reduction of directed terrestrial pollutants, the global improvement in coastal water quality might also be related to the reduced deposition of atmospheric nitrogen due to COVID-19 related restrictions on industrial and transport emissions (Mumtaz et al., 2021). Besides, when comparing the pre- and post-lockdown data, as the marine tourism activities ceased during the lockdown, it was found that the reef fish density and harvested species increased by 25 %–215 % and harvested species by 215 % (Edward et al., 2021; Lecchini et al., 2021). Underwater noise reduction due to the reduced maritime transportation-related activities was observed in many important marine protected areas, such as Monterey Bay National Marine Sanctuary (Ryan et al., 2021a) and Glacier Bay National Park (Gabriele et al., 2021), which led to favorable underwater soundscapes for communications of marine organisms (De Clippele and Risch, 2021). Changes in human activities can have rapid and significant effects on the underwater soundscape, thus affecting marine life such as shrimps, bivalves, dolphins and whales. The pandemic, in terms of slowing down some marine activities, gave the opportunity for comparative studies - exploring effects of human activity on marine organisms and how marine organisms respond to changes (Rutz et al., 2020). For instance, there were significant increases in dolphin (hundreds of meters to several kilometers) and fish (tens of meters to hundreds of meters) communication ranges, maintaining their social cohesion over longer distances during the lockdown (Pine et al., 2021).

However, there are worrisome negative effects on the marine environment. Before the pandemic, plastic debris was already the most abundant type of litter in the ocean, with more than 8 million tons of plastic waste entering the ocean every year (Jambeck et al., 2015). It causes harm to marine life and has become a major global environmental concern. With the outbreak of COVID-19, the medical plastic waste increased steadily due to the COVID-19 related virus testing, single-use personal protective equipment, packaging of increased online shopping, to name a few. These pandemic-associated plastic wastes are discarded on beaches or transported over a long distance from land into the ocean via waterways, threatening marine life and ecosystem (Peng et al., 2021). Based on coastal population and face mask acceptance, it is estimated that approximately 289.63 and 61.02 billion face masks were used annually in Asia and Europe, respectively (Chowdhury et al., 2021). However, the increased use and disposal of PPE worldwide could potentially pose critical ecological risk to the marine environment. Globally more than 25,000 tons of pandemic-associated plastic have been discarded into the ocean (Peng et al., 2021). It was identified that most PPE items (more than 95 %) along the beaches was from discarded face masks (De-la-Torre et al., 2021; Haddad et al., 2021).

3.3.2. Socio-economic dimension

The marine tourism industry and the livelihoods of coastal communities were severely impacted by the pandemic. Under the global travel restrictions, the number of tourists visiting coastal and island destinations dropped sharply (Gounder and Cox, 2021; Wu, 2021). Furthermore, livelihoods of coastal communities, small-scale artisanal fishing and related workers were greatly affected.

For the marine tourism industry, the COVID-19 pandemic has dealt a severe blow, which is mainly due to the transportation restrictions and lockdowns. Marine tourism is highly socio-economically consequential because of its role in providing economic income and well-being for millions of people. Take the Penghu Islands for instance, one of the famous island tourism destinations located to the south of the Taiwan Strait, where the local tourism industry has taken a heavy toll. Before the outbreak of the COVID-19 pandemic, the Penghu Islands attracted more than one million tourists and created countless business opportunities with more than 30,000 jobs and 190 million US dollars of economic benefits (Wu, 2021). But the number of visitors to the Penghu Islands dropped to less than 10,000 each month due to the COVID-19 pandemic, which also resulted in a 4.8 % increase of unemployment. According to a vulnerability assessment in Spain by Duro and co-authors (Duro et al., 2021), the tourism industry of coastal provinces is more vulnerable to the COVID-19 pandemic than inland tourist destinations, with the Balearic and Canary Islands and the Mediterranean coast being the most vulnerable. It is estimated that a maximum 89 % drop in arrivals in the Balearic Islands was caused by the pandemic (Arbulú et al., 2021). Globally, the coastal and islands tourism industries were vulnerable to the crisis since the countermeasures to virus propagation affect most tourism related services. It was indicated that the economies of Small Island Developing States (SIDS) that are more dependent on tourism have suffered larger economic shocks (Gounder and Cox, 2021).

During the COVID-19 lockdown period, the fishers, fish laborers and other workers of fisheries value chains suffered negative impacts of lowered income and unemployment due to the transport restrictions, lower consumer demand, reduced fish price, and a lack of storage facilities of fish. Most fishers were not able to sell their fish and fish products, which forced them to borrow with high interest rates from the local money lender, especially in developing countries such as Bangladesh and Indonesia (Hoque et al., 2021; Islam et al., 2021; Sunny et al., 2021). For coastal communities of varying remoteness across Vanuatu, access to food was even cut off due to the restricted mobility, loss of cash income and growing indebtedness, which were all resulting from the COVID-19 pandemic (Steenbergen et al., 2020). People suffered from the loss of fishing opportunities, reduced economic income and unemployment. Notably, in Fiji, the main impact of COVID-19 was the reduction in sales of fish and loss of purchasing power, resulting in a fifth of Indo-Fiji Small-Scale Fisheries (SSFs) being unable to obtain sufficient food to meet families' daily needs. Social inequities and power relations surrounding access to fishery resources and government aid contributed to fishers' vulnerability to economic stress from COVID-19 (Mangubhai et al., 2021). For some small-scale artisanal fishers in coastal areas of Argentina, most of them were even compensating the decrease of their economic incomes by sailing illegally or selling ambulant food (as walking/street vendors) during the COVID-19 lockdown (Truchet et al., 2021). For SSFs in South Africa, limited access to adequate water emerged as a major issue early on in the pandemic, and the major impact was the impairment on their ability to market and sell fish due to the travel restrictions (Sowman et al., 2021). As a tropical nation, Indonesia's food security largely relies on the fishery sector. But the onset of the COVID-19 pandemic negatively affected its SSFs, with the number of active fishers and traders declining by more than 90 %, and low demand for fish and the price drop disrupting lives of fishing communities (Campbell et al., 2021). In Mexico, SSFs experienced a massive shut down with 89 % of the markets closed in April 2020. Furthermore, woman faced increased inequalities in accessing fishing resources or healthcare (Lopez-Ercilla et al., 2021).

For recreational fishers, according to an online survey of 5998 recreational fishers in 15 countries, 98 % of them had higher reductions in physical activity and fish consumption during COVID-19, as well as poorer sleep and fouler mood (Pita et al., 2021). In Western Australia, the impact of COVID-19 on boat-based recreational fishing has varied within the recreational sector, with the isolation policy negatively affecting fishers 60 years or older and the impacts of travel restriction being greater for metropolitan based fishers (Ryan et al., 2021b).

For capture fisheries, globally the fishing effort decreased by 5.2 % during the lockdown, particularly the trawling activities in China and Spain (He et al., 2021). In the Spanish Mediterranean and Galicia, the fish landings dropped by 49 % and 19 %, respectively, with negative economic impacts (Coll et al., 2021; Fernández-González et al., 2021; Villasante et al., 2021). On the north-western coast of India, the fishing boat parking area near the docks or on the shore had increased between 200 % to 800 % during the peak of lockdown. It is estimated that a quarter of the annual seafood production would be lost (Avtar et al., 2021). In Peru, there was an 80 % reduction in the number of fishing trips and an 83 % reduction in landings for small-scale hake fishery (Grillo-Núñez et al., 2021). As a top importer and exporter of seafood, the US fisheries were also affected by the pandemic. It was found that the fresh seafood catches declined by 40 % and the imports and exports decreased by 37 % and 43 % after the outbreak of COVID-19 (White et al., 2021).

For aquaculture, the COVID-19 pandemic could amplify economic losses and food insecurity by adding further vulnerability to aquaculture systems already challenged by multiple human stressors. In China, a farm-level survey across provinces indicated that shellfish farmers and sellers have experienced a sharp drop in profits largely due to the shrinking demand in the early stage of the pandemic (Zhang et al., 2021b). In India, it was estimated that the shrimp aquaculture sector had an economic loss of 1.5 billion USD and a reduction of 40 % in shrimp production and export (Kumaran et al., 2021). In Bangladesh, the COVID-19 pandemic also caused a squeeze on profit for the finfish and shrimp farmers, the cost of seafood production increased considerably, while the market demand reduced and the prices of shrimp decreased due to the outbreak of COVID-19, leading to severe negative impacts on financial capital and additional socio-economic burdens for people in rural areas (Hasan et al., 2021; Rahman et al., 2021). As the second largest worldwide producer and exporter of farmed salmon, Chile relies on export markets to generate income. The outbreak of the COVID-19 pandemic presented great risks to the salmon farming industry in Chile with limited access to farms and processing capacity, as well as reduced market demand (Soto et al., 2021a). But it should be noted that the impacts of the pandemic on aquaculture varied across countries and was not perceived as the main long-term disruption risk at a global scale. For instance, climate-related effects and anthropogenic stressors such as salinity increase, harmful algae, hypoxia and pollution were thought to be a source of economic loss greater than the pandemic in countries such as China and Egypt. Diseases and storms are the main damaging factors for aquaculture systems in countries such as Brazil, India and Chile (Sarà et al., 2022). To cope with amplified risks and to enhance resilience of aquaculture systems, a range of different mitigation measures should be employed. Direct financial aid, new market development and fostering resilient supply chains were identified to be efficient measures (Mangano et al., 2022).

4. Discussion

4.1. Long-term negative impacts of COVID-19 on coastal waters and sediment need further research

Despite the observation that the COVID-19 pandemic had selected positive effects on the marine environment, the negative impact associated with increasing medical waste is cause for concern. As recommend by WHO, personal protective equipment (PPE) such as face masks, gloves and protective suits has become the effective tool to slow down the spread of COVID-19. The public was encouraged to wear face masks to protect themselves. Apart from causing a long-lasting plastic pollution problem on beaches and in coastal sediment, the pandemic-associated plastic waste could cause great immediate harm to marine life. On the Juquely beach of Brazil, a dead Magellanic penguin was found with a face mask in its stomach, which is the first recorded instance of marine animal mortality by COVID-19 PPE (Neto et al., 2021). The disposable face masks could also be a source of nanoplastics and microplastics, which could accumulate in humans and marine organisms. Moreover, the downgraded particles could be adsorbed onto diatom surfaces and then be ingested by marine organisms of different trophic levels (Ma et al., 2021). With the increasing daily use of PPE around the world due to COVID-19, it is necessary to raise environmental awareness and strengthen the waste management, thus reducing the negative impact of PPE on the coastal environment and marine life.

Furthermore, the coastal waters and sediments are potentially exposed to SARS-CoV-2 viral contamination and drugs used to combat the COVID-19 pandemic as they are the ultimate destination for terrestrial untreated municipal sewage and medical waste. Risks for wildlife and ecosystems increase when these contaminated effluents discharge into the ocean. Studies from Italian coastal waters (Audino et al., 2021) and Alaska (Mathavarajah et al., 2021) showed that the potential SARS-CoV-2 contamination put vulnerable marine mammals, such as whales, dolphins and seals, at risk when swimming and feeding in specific risk areas. Even in the remote Antarctica (Barbosa et al., 2021), it is suggested that there is great risk of infection for cetaceans through human research and tourism activities. Yet it should also be noted that the presence of SARS-CoV-2 virus in seawater is unstable, with many factors such as temperature, salinity and light affecting its survival (Desdouits et al., 2021). As for pharmaceutical contaminants, with the number of people being infected still increasing worldwide, more treatment drugs, such as ivermectin (Essid et al., 2020), might be used in medical facilities for patient treatment. High quantities of pharmaceutical residues will be deposited into the sea through the sewage systems, thus contaminating the marine ecosystem and threatening marine species and human health. As coastal waters are the ultimate sinks for municipal waste and sewage, these pollutants, as well as potential pharmaceutical residue, is imposing immense disturbances on the blue carbon ecosystems, such as the fauna and flora in the mangrove forest, thus reducing the ocean's capacity as the largest active carbon sink on Earth for climate change mitigation. Combining the environmental benefits and costs, the ecological impacts of COVID-19 on the ocean remains complicated, unclear, and require further exploration. Moreover, there is a potential risk to human health due to the bioaccumulation of pharmaceutical pollutants in seafood. Currently, the sewage treatment techniques are crucial for reducing coastal water contamination, but efficient sewage treatment systems are in general only available for developed countries.

4.2. Challenges for marine monitoring and conservation

The COVID-19 pandemic has caused unprecedented cancellations of fisheries and ecosystem-assessment surveys, resulting in a global decrease of observations needed for management and conservation (Santora et al., 2021). For example, at the outbreak of COVID-19, the budget for ecosystem restoration actions in Brazil were cut and ecological monitoring activities were restricted and stopped. For Brazilian seagrasses conservation, the COVID-19 pandemic negatively affected conservation efforts by reducing scientific budget and restricting systematic field surveys, resulting in increased underestimation of affected seagrass areas and ecosystem losses due to oil spill (Magalhães et al., 2021). In Costa Rica, the COVID-19 lockdown led to serious economic difficulties for Pacuare Reserve's operations which depended on student groups and visitors for its funding (Quesada-Rodríguez et al., 2021). Furthermore, according to (Hentati-Sundberg et al., 2021), the absence of tourists caused by the lockdown could lead to an animal redistribution due to an increase in eagles' disturbance of breeding common murres in Sweden and hence causing 26 % lower murre productivity, which could heavily affect marine animals conservation works (Gilby et al., 2021). It should be noticed that the geospatial distribution of some reported studies, take underwater noise studies for example, could also attribute to the fact that there were local researchers who were in place and able to conduct monitoring and gain measurements during the pandemic. Such specific effects may also happen elsewhere around the world. In the future, innovative technology such as remote sensing or unmanned aerial vehicles could be employed in marine ecological monitoring and conservation, and increased investment from stakeholders could enhance coastal and ocean resilience.

4.3. Marine renewable energy for green recovery

The COVID-19 pandemic has been a major setback to the global energy sector, with adjusted production and reduced demand for natural gas, coal and oil (Hoang et al., 2021c). A market distortion was observed with the sharp temporal falls in global energy prices. Regarding the expansion of the ocean energy system, COVID-19 delays the majority of capacity additions. But generally ocean energy proves its resilience despite the pandemic, with a total 865 kW tidal and 700 kW wave energy devices installed around the world, especially in the UK, China and United States (Europe, 2021). Global cumulative installations for tidal and wave energy reached 60 MW as of the deployments completed by 2020. However, the pandemic has significantly slowed down new investments that may impede progress in the deployment of new renewable energy projects (Hoang et al., 2021b), which play important roles in sustainable energy strategies. For a sustainable post-pandemic future of the ocean, promoting marine renewable energy could contribute to aid blue economic recovery and tackle climate change.

Table 2
COVID-19 impacts on SDG 14 (conserve and sustainably use the oceans, seas and marine resources for sustainable development) targets.

Targets	Content	Positive	Negative	Implications
14.1	Reduce marine pollution	✓	✓	Improved water quality Growing plastic pollution
14.2	Protect and restore ecosystems	✓	✓	Decreased human pressure Enhanced fish stock Reduced scientific budget
14.3	Reduce ocean acidification			Unclear
14.4	Sustainable fishing	✓	✓	Increased illegal, unreported and unregulated fishing Uptake of new technologies for the monitoring of fishing activities
14.5	Conserve coastal and marine areas		✓	Less funding and disrupted conservation work
14.6	End subsidies contributing to overfishing		✓	Failing to meet 2020 deadline to reach an international agreement on eliminating harmful fishing subsidies
14.7	Increase the economic benefits from sustainable use of marine resources		✓	Significant economic loss for marine tourism and seafood industry
14.a	Increase scientific knowledge, research and technology for ocean health	✓		More automation and remote monitoring
14.b	Support small scale fishers	✓		Increased support for small scale fishers
14.c	Implement and enforce international sea law		✓	Disrupted international meetings and projects

4.4. Ocean science for sustainable development linking SDG 14 and COVID-19

Observed and potential impacts of the pandemic are challenging the progress towards the sustainable "Ocean Goal"-SDG 14 (Table 2). Currently, merely a few studies have linked SDG 14 (life below water) with COVID-19. As the marine environmental long-term problems caused by the COVID-19 pandemic emerge, governments and researchers should pay more attention to the waste management (production, processing and recycling) to reduce marine pollution (SDG 14.1) in the future, which would benefit both marine wildlife and human beings. The COVID-19 pandemic led to a global decline of carbon emission, with up to 5.6 % of reduction expected from economic sectors in 5 years (Shan et al., 2021). But as most countries gradually resumes economic activities, global and regional emissions will substantially increase. The ocean is one of the world's largest carbon sinks and particularly susceptible to the change of CO_2 levels. Therefore, the response of the global oceans to the pandemic-related emission decline is significant for global climate change and reduction of ocean acidification (SDG 14.3), but this has not yet been fully understood (Lovenduski et al., 2021). Research on increasing the resilience of marine fishery activities and reduction of illegal fishing will be central for sustainable development of both global fisheries (SDG 14.4) and the wellbeing of coastal communities.

In addition, current research mostly focuses on countries of large economies with more infected cases, resulting in a lack of publications focusing on the Small Island developing States (SIDS), which are largely dependent on marine tourism and the fishery industry to provide jobs, income, and food for millions of people. COVID-19 has exposed the economic vulnerability of SIDS, disrupting their food and tourism industries. As an important target of SDG 14, the increase of economic benefits to SIDS (SDG 14.7) requires further attention and adaptation management exploration in the post-COVID-19 era. In order to prepare for other possible epidemics and maintain sustainable ocean development in the future, it is critical to strengthen the resilience of ocean-human systems. For instance, developing countries whose marine fishery industry play an important role for economic development could potentially exclude fish production from a lockdown order and provide temporary income support for affected fishers. SIDS that rely on marine tourism could develop low-impact tourism products, digital tourism and work towards strengthening the relationship between tourist and coastal communities. Promoting circular economies will be key to reduce marine pollution. Recycling programs need to be implemented worldwide to end waste entering the ocean. Smart maritime transport and promoting decarbonized shipping for maritime industry are other steps to be taken to make this sector more sustainable. Moreover, governance and education in coastal regions should be emphasized to strengthen the capacity of effective crisis responses. Future research directions could focus on marine socio-economic resilience enhancement, land-ocean integrated management to reduce marine pollution and effective interventions to sustain ecosystem health and to further develop blue economy.

5. Conclusion

This study has presented the first systematic scoping review of the existing studies on the impacts of the COVID-19 pandemic on the marine environment and its socio-economic connection. Both positive and negative effects were summarized for the global ocean-human system across environmental and socio-economic dimensions. Improved water quality, enhanced fish stock and reduced underwater noise were observed in many sea areas such as Indian Ocean, North Pacific and Mediterranean Sea. However, the pandemic has also raised global concerns regarding increasing amounts of plastics wastes in the ocean. Furthermore, coastal community livelihoods and the marine economy of tourism and food industry were strongly affected. Currently there is a lack of studies on the impacts of COVID-19 on marine renewable energy, biodiversity and carbon emissions.

Future research should focus on ways to reduce human impacts on the marine ecosystem and marine socio-economic resilience. It is critical to strengthen the resilience of densely populated coastal urban areas in order to be able to cope with challenges of climate change and disasters. The pandemic has directly and indirectly affected various aspects of coastal human lives and resulted in long-term effects on the marine environment. Yet the COVID-19 pandemic offers an opportunity to work towards saving our ocean. Effective strategies and international cooperation are urgently needed to mitigate negative COVID-19 impacts and to achieve sustainable ocean development at both global and regional levels.

Abbreviations

COVID-19	The coronavirus disease 2019
SARS-CoV-2	The severe acute respiratory syndrome coronavirus-2
SDG 14	Sustainable Development Goal 14
GHG	Greenhouse gases
PRISMA	the Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Chl-a	Chlorophyll-a
TSM	Total suspended matter
SPM	Suspended particulate matter
POC	Particulate organic carbon
DO	Dissolved oxygen
PIC	Particulate inorganic carbon
SIDS	Small Island Developing States
SSFs	Small-Scale Fisheries
PPE	Personal protective equipment

CRediT authorship contribution statement

Z.X. and Q.J. designed the study. Q.J. collected and analyzed the data. Q.J. and Z.X. drafted the manuscript. Q.J., Z.X. and M.P. interpreted the results. M.P., M.H., G.Y. and S.Q. reviewed and edited the manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary information

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