

Review

Environmental and Public Health Impacts of Shipping Emissions Following the IMO 2020 Sulfur Cap: A Systematic Literature Review

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Abstract

Maritime transport emits a range of atmospheric pollutants, including sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), and volatile organic compounds (VOCs), which contribute to air pollution and are associated with adverse environmental and public health impacts. To mitigate these impacts, the International Maritime Organization (IMO), London, UK introduced the global sulfur cap (IMO 2020), which entered into force on 1 January 2020, limiting the sulfur content of marine fuels to 0.50% m/m. This study systematically reviews the environmental and public health impacts of shipping emissions following the implementation of IMO 2020. A systematic literature review was conducted in accordance with PRISMA 2020 guidelines using Scopus, Web of Science, PubMed, and supplementary sources. Following a structured screening process, 67 studies published between 2020 and 2025 were included and analyzed through descriptive, bibliometric, and thematic synthesis approaches. The reviewed studies consistently reported substantial reductions in sulfur dioxide (SO₂) emissions, sulfate aerosols, and shipping-related particulate matter following IMO 2020. These reductions were associated with improved air quality in major maritime and port regions and reduced population exposure to harmful pollutants. However, the reviewed evidence also identified ongoing challenges, including emissions of ultrafine particles and volatile organic compounds, secondary pollutant formation, contamination associated with scrubber washwater discharge, and reduced sulfate aerosols contributing to positive radiative forcing. Overall, the reviewed evidence suggests that sulfur-related air pollution generally declined following the entry into force of IMO 2020, although these observations should be interpreted alongside other concurrent developments that influenced global shipping activities during the study period. This review synthesizes current evidence on the environmental and public health impacts of IMO 2020, identifies emerging knowledge gaps, and provides an evidence base to support future shipping emission policies and research.

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1. Introduction

Maritime transport is fundamental to the global economy, carrying more than 80% of the world's traded goods by volume and supporting international trade and global supply chains [1]. As maritime transport continues to expand, the sector is undergoing rapid transformation driven by technological advancement, digitalization, geopolitical developments, and increasing demands for sustainability and climate resilience [1].

However, maritime transport is also a major source of atmospheric pollutants, including sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), and black carbon (BC), emitted during the combustion of marine fuels, particularly the high-sulfur heavy fuel oil that was widely used before recent sulfur regulations [2–4]. Continued growth in shipping activity is projected to increase emissions and their contribution to coastal and urban air pollution despite improvements from cleaner technologies, technological advancements, and stricter environmental regulations [5–7]. Among these pollutants, sulfur oxides are of particular concern because of their environmental and public health impacts [2–4].

Sulfur oxides (SO_x), particularly sulfur dioxide (SO₂), are among the most important pollutants emitted from the combustion of sulfur-containing marine fuels. Atmospheric oxidation of SO₂ produces sulfate aerosols, which contribute to PM_{2.5} formation, influence atmospheric chemistry and radiative forcing, and contribute to acid deposition [8–10]. Exposure to SO₂ and PM_{2.5} has been associated with adverse respiratory and cardiovascular health outcomes [11]. Consequently, reducing SO_x emissions is expected to improve air quality and public health, although reductions in sulfate aerosols may also diminish their cooling effect and introduce climate trade-offs [7,10].

In addition to atmospheric pollution, shipping also affects marine ecosystems through multiple pollution pathways [2,12]. Among these, scrubber washwater discharge has attracted particular attention following IMO 2020 because it releases acidic effluents containing heavy metals and organic contaminants into marine environments [12,13]. Shipping activities also contribute to nutrient enrichment and acidification through the atmospheric deposition of NO_x and SO_x, highlighting the need to evaluate both atmospheric and marine environmental impacts [2,8,9].

From a public health perspective, emissions from marine diesel engines are an important source of ambient PM_{2.5} and other air pollutants associated with respiratory and cardiovascular diseases and premature mortality [14–16]. Shipping emissions also include greenhouse gases (GHGs) and short-lived climate pollutants, such as black carbon (BC), which contribute to climate forcing and global climate change [2,17].

Before 2020, the absence of stringent global sulfur limits contributed substantially to ship-related air pollution [18]. To address this issue, the International Maritime Organization (IMO) adopted the Global Sulfur Cap under MARPOL Annex VI, which entered into force on 1 January 2020. The regulation limits the sulfur content of marine fuels to 0.50% m/m globally while maintaining the 0.10% m/m standard within designated Emission Control Areas (ECAs) [19]. Compliance can be achieved through low-sulfur or alternative fuels, or by installing exhaust gas cleaning systems (scrubbers) [18]. The regulation was expected to substantially reduce SO_x and particulate emissions, improve air quality, and reduce pollution-related health burdens [7]. At the same time, concerns have emerged regarding scrubber washwater discharge because of its potential impacts on marine environments, while reductions in sulfate aerosols may also diminish aerosol cooling and introduce climate trade-offs [7,13,20]. Although IMO has introduced additional air pollution control measures, such as Nitrogen Emission Control Areas (NECAs) [19], this review focuses specifically on the environmental and public health impacts of the IMO 2020 global sulfur cap.

Although modelling studies have projected substantial reductions in SO₂, PM_{2.5}, and associated health burdens following IMO 2020 [7], recent observational studies have increasingly evaluated these impacts under real-world conditions in different geographical settings [21,22]. Collectively, the available evidence demonstrates important environmental improvements following implementation of IMO 2020. However, the overall environmental effectiveness of IMO 2020 has not yet been comprehensively synthesized.

Beyond these environmental concerns, important knowledge gaps also remain regarding public health outcomes following implementation of IMO 2020. While modelling studies have projected reductions in pollution-related mortality and morbidity [7], relatively few epidemiological studies have evaluated whether these benefits have been realized under real-world conditions [23]. Moreover, the relatively short post-implementation period and concurrent external influences, including the legacy of the COVID-19 pandemic and geopolitical disruptions affecting global shipping, complicate attribution of observed health outcomes solely to IMO 2020 [18,24].

Compliance strategies under IMO 2020 have also introduced important environmental trade-offs, particularly regarding scrubber washwater discharge [25,26]. Although several studies have characterized its chemical composition and associated contaminants [27,28], uncertainties remain regarding its long-term ecological impacts on marine ecosystems [29]. Similarly, the transition to very-low-sulfur fuel oils (VLSFOs) has raised concerns regarding fuel quality, engine performance, and broader environmental implications [30]. In addition, different IMO 2020 compliance strategies may influence emissions of pollutants such as black carbon (BC), particulate matter (PM), and NO_x [25,26]. These findings highlight the need to evaluate both the intended and unintended consequences of IMO 2020 from an integrated environmental perspective.

Existing reviews have primarily focused on specific aspects of shipping emissions or IMO 2020, such as atmospheric pollution and air quality [18], health impacts [18,23], and mitigation strategies and IMO policies [31]. However, a comprehensive systematic synthesis integrating environmental impacts, public health outcomes, marine ecological consequences, and unintended environmental trade-offs based on post-implementation evidence remains lacking.

To address this gap, the present systematic review synthesizes evidence from post-2020 studies across atmospheric science, environmental chemistry, marine ecology, and public health to provide a comprehensive assessment of the environmental, public health, and unintended consequences associated with the IMO 2020 global sulfur cap. Accordingly, this study aims to systematically evaluate the real-world environmental and public health implications of IMO 2020 while identifying key knowledge gaps to support future research and evidence-based policy development. Our three research questions are as follows:

RQ1: What environmental impacts associated with IMO 2020 have been reported across atmospheric and marine environments?

RQ2: What public health impacts associated with shipping emissions have been reported following the implementation of IMO 2020?

RQ3: What implementation challenges and unintended environmental trade-offs have emerged following the implementation of IMO 2020?

The remainder of this paper is organized as follows. Section 2 presents the materials and methods, including the systematic literature review framework, search strategy, eligibility criteria, screening procedures, and data extraction process adopted in this study. Section 3 presents the results of the review, including descriptive analysis, bibliometric analysis, and thematic synthesis of studies published between 2020 and 2025. Section 4 discusses the environmental, health, and policy implications of the findings, as well as key research gaps and future research directions. Section 5 concludes the study by summariz-

ing the major findings and their implications for sustainable maritime regulation and environmental governance.

2. Materials and Methods

2.1. Systematic Literature Review

This study adopts a Systematic Literature Review (SLR) as the primary research methodology, complemented by concept description and content analysis. Over the past two decades, systematic reviews have advanced as a rigorous approach to synthesizing research evidence [32]. In contrast to traditional narrative reviews, which are often descriptive and may lack methodological rigor [33,34], an SLR follows a structured, transparent, and replicable process designed to minimize bias and enhance reliability [35–37]. An SLR is expected to be transparent, explicit, comprehensive, auditable, and reproducible [38–41]. It involves well-defined procedures for defining the research topic, systematically searching and selecting relevant literature, and evaluating the quality of included studies using predefined criteria and standardized appraisal methods [38–41].

Several methodological frameworks have been proposed for conducting systematic literature reviews. Among them, the frameworks proposed by Tranfield et al. [36] and Jesson et al. [34] are widely adopted. Tranfield et al. [36] adapted systematic review principles and procedures from medical research to the management and social sciences, while Jesson et al. [34] proposed a step-by-step framework (see Table 1) suitable for management and social research. Given the interdisciplinary nature of this review, the framework of Jesson et al. [34] was adopted because it provides a clear and sequential process for conducting systematic reviews across multiple research domains. To ensure transparent and reproducible reporting, the review was conducted and reported in accordance with the PRISMA 2020 guidelines, including the use of a PRISMA flow diagram and a structured summary of the extracted data [42]. While the Jesson framework guided the review process [34], PRISMA 2020 was used to enhance the transparency and reproducibility of reporting rather than to determine the analytical procedures [42]. This systematic literature review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review protocol was registered with the Open Science Framework (OSF) and is publicly available at 10.17605/OSF.IO/EKYTQ.

Table 1. Systematic Literature Review Steps Adapted from Jesson et al. (2011) [34].

Steps	Objective	Key Activities
Step 1	Research Planning	Define the research purpose, formulate research questions, and outline the research procedure.
Step 2	Literature Search	Identify relevant studies using multiple databases, record retrieval details (dates, keywords, languages), and track the number of articles found.
Step 3	Literature Evaluation	Assess the quality of retrieved studies to determine inclusion/exclusion and ensure data reliability and validity.
Step 4	Data Extraction	Use structured forms (e.g., basic info sheet, connotation sheet) in Excel or other software to minimize errors and biases.
Step 5	Data Integration and Analysis	Examine relationships within the extracted data and apply descriptive, thematic, and content analysis methods to address the research questions.
Step 6	Report Writing	Prepare and report the review findings, including the methodology, analysis, discussion, and conclusions.

2.2. Search Strategy

A systematic and comprehensive search was conducted to identify all relevant studies on the environmental and health impacts of shipping emissions following the IMO 2020 sulfur cap. Multiple databases were used, including Scopus and Web of Science, serving as the primary databases due to their broad multidisciplinary coverage and strong indexing of high-quality, peer-reviewed journals in environmental, maritime, and public health research. PubMed was additionally included to capture studies focusing on health-related impacts, particularly those examining PM_{2.5} exposure and public health outcomes.

The search strategy was structured around four key conceptual blocks: (i) maritime transport, (ii) emissions and pollutants, (iii) environmental and health impacts, and (iv) sulfur-related regulatory measures under the IMO 2020 framework, connected using Boolean operators (AND, OR) to refine the search scope (see Table 2). Searches were conducted using title, abstract, and keyword fields. Peer-reviewed journal articles served as the primary sources, while conference proceedings were selectively included when they provided substantial and relevant empirical contributions.

Grey literature from reputable organizations [e.g., IMO, World Health Organization (WHO), European Environment Agency (EEA), Environmental Protection Agency (EPA)] including technical reports and port authority assessments, was selectively included when directly relevant to the research questions and when they reported original empirical findings with sufficient methodological transparency and detail [43]. Google Scholar was used only as a supplementary search tool to support both forward and backward snowballing by examining reference lists and citation records of relevant studies, following the methodological guidance proposed by Wohlin [44].

Table 2. Search strings.

Concept	Synonyms	Rationale
Shipping	"ship" OR "vessel" OR "maritime shipping" OR "ocean? going vessel"	Captures all terms related to vessels and maritime transport activities responsible for emissions.
Emissions	"emission" OR "air pollution" OR "water pollution" OR "SO _x " OR "NO _x " OR "particulate matter" OR "PM _{2.5} " OR "PM ₁₀ " OR "black carbon" OR "PAH" OR "pollutant"	Includes all major air and water pollutants associated with shipping, covering both targeted (SO _x , PM _{2.5}) and secondary/unintended emissions (black carbon, PAHs, NO _x).
Environmental and Health Impacts	"environmental impact" OR "air quality" OR "water quality" OR "marine environment" OR "ecosystem" OR "health" OR "mortality" OR "morbidity" OR "exposure" OR "risk"	Captures studies reporting environmental outcomes (air, water, ecosystem) and human health effects (mortality, morbidity, exposure).
IMO 2020 Regulation	"IMO 2020" OR "global sulfur cap" OR "sulfur cap" OR "sulphur cap" OR "fuel sulfur limit" OR "0.5% sulfur" OR "low sulfur fuel" OR "VLSFO" OR "scrubber" OR "fuel sulfur regulation"	Ensures retrieval of studies specifically related to the IMO 2020 sulfur cap, fuel transitions, and emission control technologies.
Search string	("ship" OR "vessel" OR "maritime shipping" OR "ocean? going vessel") AND ("emission" OR "air pollution" OR "water pollution" OR "SO _x " OR "NO _x " OR "particulate matter" OR "PM _{2.5} " OR "PM ₁₀ " OR "black carbon" OR "PAH" OR "pollutant") AND ("environmental impact" OR "air quality" OR "water quality" OR "marine environment" OR "ecosystem" OR "health" OR "mortality" OR "morbidity" OR "exposure" OR "risk") AND ("IMO 2020" OR "global sulfur cap" OR "sulfur cap" OR "sulphur cap" OR "fuel sulfur limit" OR "0.5% sulfur" OR "low sulfur fuel" OR "VLSFO" OR "scrubber" OR "fuel sulfur regulation")	

2.3. Eligibility and Selection Criteria

The literature search was restricted to publications written in English and published from 2020 onwards to ensure relevance to the post-IMO 2020 regulatory context. Eligible studies primarily comprised peer-reviewed journal articles, which served as the main sources of empirical and conceptual evidence. Conference proceedings were selectively included when they offered relevant empirical or analytical contributions based on qualitative, quantitative, or mixed-methods research designs.

Studies were excluded if they were unavailable in full text, written in languages other than English, or not directly related to the research objectives. The restriction to English-language publications was applied to improve consistency and feasibility in the review process and is supported by evidence suggesting that language-restricted meta-analyses do not substantially differ from multilingual analyses in overall conclusions [45]. Furthermore, English remains the dominant language of global academic knowledge dissemination [46,47]. The detailed inclusion and exclusion criteria are summarized in Table 3.

Table 3. Inclusion and Exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Published from 2020 onwards (post-IMO 2020 regulatory context)	Published before 2020
English-language publications	Non-English publications
Peer-reviewed journal articles	Conference papers without explicit peer-review information
Conference proceedings with clear peer-reviewed processes (selectively included)	Studies not related to shipping emissions, IMO 2020, or sulfur-related regulatory frameworks
Studies addressing shipping emissions and their environmental and/or health impacts in relation to IMO 2020 or sulfur-related regulations	Studies without accessible full-text versions

2.4. Screening and Data Management Process

This systematic literature review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was employed to ensure a transparent and reproducible process for literature identification, screening, eligibility assessment, and study inclusion. This review was not prospectively registered in any systematic review database.

The initial database search yielded a total of 1977 records, including 1756 from Scopus, 160 from Web of Science, and 61 from PubMed. All retrieved records were exported into EndNote (version 2025) reference management software for organization and duplicate removal. Duplicate records were removed using EndNote, and non-English publications were excluded prior to screening, resulting in 1732 unique records eligible for title and abstract screening.

Title and abstract screening were conducted to assess the relevance of the identified records to the review objectives. Articles that did not address the environmental and/or health impacts of maritime shipping emissions under the IMO 2020 sulfur regulation were excluded at this stage, leading to the removal of 1208 records. Consequently, 524 reports were sought for retrieval.

Among these, 23 reports were not retrieved, leaving 501 studies for full-text eligibility assessment. Following full-text eligibility assessment, 434 studies were excluded due to insufficient relevance to IMO 2020 sulfur regulation, absence of environmental and/or health impact assessment, a purely technical or engineering focus, or other reasons identified during screening. These included, for example, studies that mentioned the IMO 2020

sulfur cap only as background information without evaluating its environmental or public health impacts, studies focusing primarily on policy, economic, or regulatory compliance aspects, and studies evaluating multiple emission sources without distinguishing the specific contribution of shipping emissions.

Ultimately, 67 studies met all predefined inclusion criteria and were included in the final systematic review. The complete screening and study selection process is illustrated in the PRISMA 2020 flow diagram (Figure 1) [42].

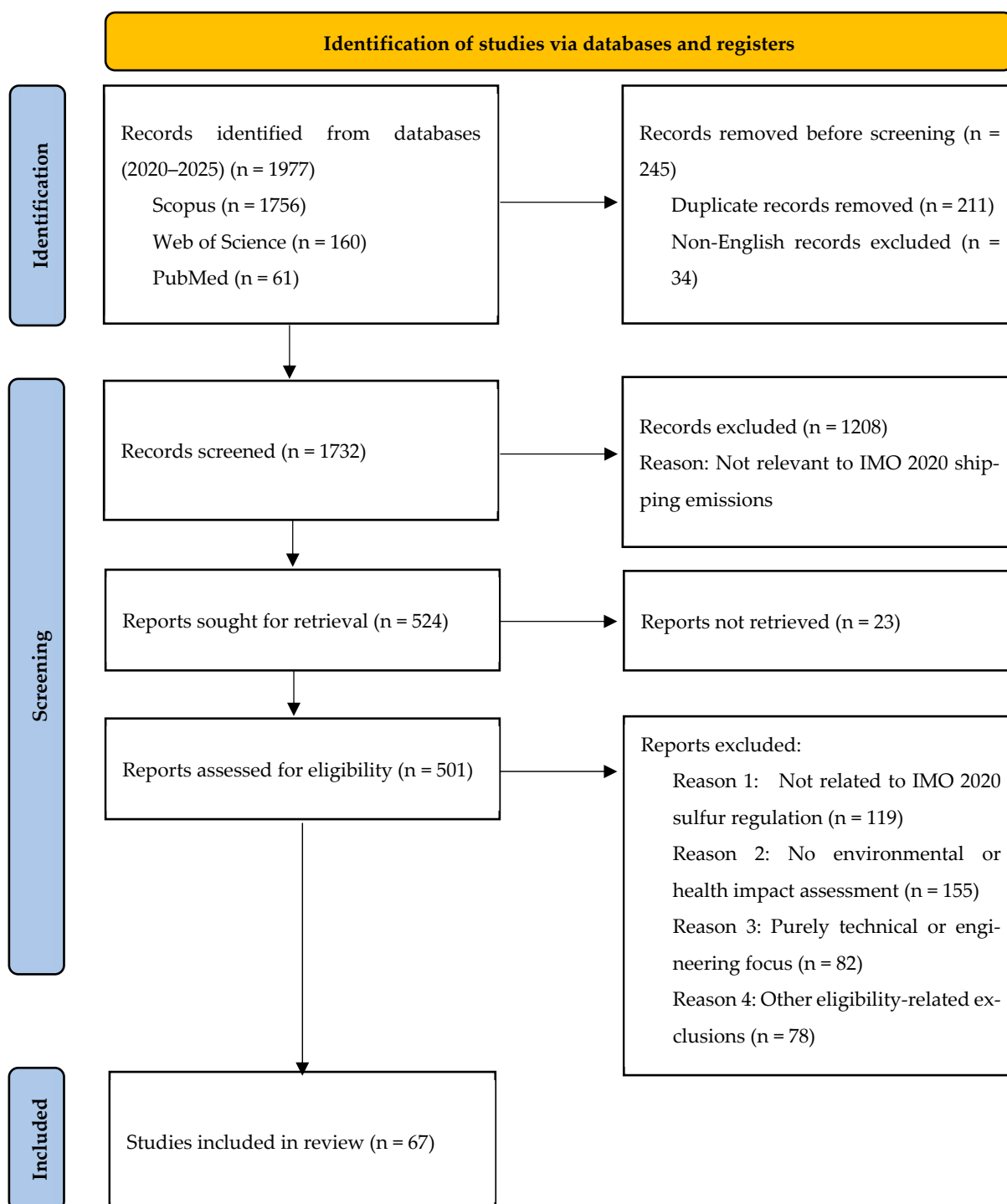


Figure 1. PRISMA 2020 flow diagram of the literature search and study selection process.

2.5. Data Extraction

Data were systematically extracted from each included study using a standardized data extraction framework developed in accordance with the review objectives and research questions. The extracted variables (Table 4) were selected to capture the key methodological and thematic characteristics relevant to the evidence synthesis. These variables included the author and publication year, study location, study design, pollutants investigated, impact category (environmental, health, climate, or marine ecological), and the IMO-related policy focus. The extracted information was used to facilitate cross-study comparison and thematic synthesis. Detailed characteristics of the included studies are provided in Supplementary Table S1.

Table 4. Extracted Characteristics of the Included Studies Used for Evidence Synthesis.

No.	Author & Year	Study Location	Method	Pollutants	Impact Type	IMO Focus
1	Jin et al. (2025) [48]	Bay of Bengal (Shipping lane versus reference region)	Satellite observation analysis; regression kriging; Random Forest counterfactual estimation	SO ₂ ; sulfate aerosols	Climate	IMO 2020 sulfur cap
2	Lee et al. (2025) [49]	Panama Canal (anchorage & port area)	Atmospheric modeling: AIS-based bottom-up emission inventory (Tier 3); GRAMM/GRAL dispersion modeling	CO ₂ ; NO _x ; SO ₂ ; PM ₁₀ ; PM _{2.5}	Environmental & Health	Post-IMO 2020 shipping context
3	Chang et al. (2025) [50]	Southeast coast of China (WCTS region)	Emission inventory modeling; ship-call-based bottom-up inventory; IVOC-specific emission-factor construction; Monte Carlo uncertainty analysis	IVOC; secondary organic aerosol (SOA)	Environmental & Health	IMO 2020 and DECA sulfur regulations
4	Nunes et al. (2025) [51]	Iberian Peninsula (Portugal & Spain)	Integrated modeling: AIS-based emission inventory (STEAM); atmospheric chemistry transport modeling (EMEP/MSC-W); health impact assessment (WHO-HRAPIE); economic valuation (VSL/VOLY)	NO _x ; SO _x ; PM _{2.5} ; PM ₁₀ ; O ₃	Environmental, Health & Economic	IMO 2020, SSE and future ECA scenarios
5	Yu et al. (2025) [52]	China (coastal & inland waters)	Integrated CTM modeling: AIS-based emission inventory; WRF/CMAQ; chemical speciation; zero-out method	PM _{2.5} and components (SO ₄ ²⁻ , NO ₃ ⁻ , NH ₄ ⁺ , V, Ni)	Environmental	IMO 2020 and DECA sulfur regulations
6	Shukla et al. (2025) [53]	Controlled laboratory experiment (Europe)	Laboratory experiment: PEAR reactor; TD-GCMS; REMPI-TOF-MS; HR-TOF-AMS; SOA modeling	VOCs, IVOCs, SOA	Environmental	IMO fuel-switching policy
7	Kang et al. (2025) [54]	Coastal & port shipping routes	Mathematical modeling: diffusion and pH simulation modeling	Sulfur compounds; seawater pH	Marine Ecological	IMO sulfur regulation and scrubbers
8	Fragkou et al. (2025) [55]	Mediterranean coastal region (30 cities)	Ensemble modeling: EMEP/STEAM; SILAM; CMAQ	NO ₂ ; SO ₂ ; PM _{2.5} ; O ₃	Environmental & Health	SECA/NECA and scrubbers vs. alternative fuels
9	Xiao et al. (2025) [56]	China (onboard ships)	Onboard field measurement: GC-MS analysis	I/SVOCs; SOA precursors	Environmental	Low-sulfur fuel policy
10	Benas et al. (2025) [57]	Southeastern Atlantic shipping corridor	Satellite observation analysis: CLAS-3 geostationary satellite dataset (20-year record)	Shipping-related aerosols	Climate	IMO 2020 sulfur cap
11	Le Berre et al. (2025) [58]	Marseille port, Mediterranean (France)	Empirical field measurement: plume-based emission-factor estimation; AIS-meteorology integration; high-resolution chemical characterization	NO _x ; SO ₂ ; CO; CH ₄ ; NMVOCs; PM ₁ ; black carbon (BC); sulfate; trace metals (V, Ni, Fe)	Environmental & Health	IMO 2020 sulfur cap and EU port sulfur regulation
12	Kolovoyianis et al. (2025) [59]	Saronikos Gulf, Eastern Mediterranean (Greece)	Integrated modeling framework: STEAM (shipping emissions and discharges); SILAM (atmospheric transport and deposition); Delft3D (marine fate and water-quality simulation); scenario analysis (2018 vs. 2050)	Heavy metals (Cd, Pb, Ni, Cu, Zn); PAHs (BaP, Flu); nitrogen compounds	Marine Ecological	IMO 2020 sulfur cap and scrubber (EGCS) regulation scenarios
13	Dong et al. (2025) [21]	Shanghai, China	Atmospheric modeling: AIS-based high-resolution emission inventory; WRF-CMAQ air-quality modeling; BenMAP-CE health assessment; metal risk assessment (Ni, V)	PM _{2.5} ; SO ₂ ; NO _x ; Ni; V	Environmental & Health	IMO 2020 sulfur cap and China DECA policy
14	Zapata-Restrepo &	Controlled laboratory experiment (UK/EU marine context)	Ecotoxicological bioassays: fertilization and larval-development assays	PAHs; heavy metals (V, Ni, Cu, Zn, Pb); nitrates	Marine Ecological	Scrubber (EGCS) compliance strategy

Williams (2025) [60]						
15	Jeong et al. (2025) [61]	Controlled laboratory experiment (in vitro human lung-cell exposure)	Experimental toxicology assays: cytotoxicity; genotoxicity; mutagenicity; ROS generation; inflammatory-response analysis; PM chemical characterization	CO ₂ ; SO ₂ ; NO _x ; PM _{2.5} ; PAHs; trace metals	Environmental & Health	IMO 2020 fuel-switching policy
16	Stathatou et al. (2025) [62]	Mediterranean Sea (commercial vessel onboard measurements)	Empirical onboard measurement; well-to-wake life-cycle assessment (WtW LCA); comparative scenario analysis (fuel switching vs. scrubber compliance)	CO ₂ ; SO ₂ ; NO _x ; PM _{2.5} ; PAHs; trace metals	Environmental, Health & Climate	IMO 2020 sulfur cap and scrubber compliance strategies
17	Anders et al. (2025) [63]	Controlled laboratory engine experiments	Experimental combustion analysis: single-particle mass spectrometry (LDI and REMPI); principal component analysis (PCA) of particle composition	Ultrafine PM (60–200 nm); PAHs; trace metals; sulfate particles	Environmental & Health	Scrubber (EGCS) compliance strategy
18	Paul et al. (2025) [64]	Controlled laboratory atmospheric-aging experiment	Experimental atmospheric simulation: oxidation flow reactor (PEAR); high-resolution aerosol measurement (HR-ToF-AMS; SMPS); secondary aerosol formation analysis	SOA; SO ₄ ²⁻ ; BC; PM	Environmental	IMO 2020 fuel-switching policy
19	Dai et al. (2025) [65]	Shanghai, China (port & coastal waters under Shanghai MSA jurisdiction)	Integrated emission modeling: AIS-based high-resolution emission inventory; bottom-up emission estimation; LEAP and ARIMA scenario analysis	CO ₂ ; CO; hydrocarbons (HC); NO _x ; PM _{2.5} ; PM ₁₀ ; SO ₂	Environmental & Climate	IMO decarbonization and sulfur-emission control policies
20	Calgaro et al. (2025) [66]	Northern Adriatic Sea (Italy–Slovenia–Croatia coastal basin)	Integrated modeling framework: AIS-based emission inventory (STEAM); atmospheric transport and deposition modeling; marine load estimation; scenario analysis	Metals (Cu, Zn, Ni); PAHs; nutrients (N, P); CO ₂ ; SO ₂ ; NO _x ; PM _{2.5}	Marine Ecological	IMO 2020 sulfur cap and scrubber (EGCS) scenarios
21	Zhang et al. (2025) [67]	Global stratocumulus cloud regions (NE Pacific, SE Pacific, SE Atlantic)	Satellite observation analysis: machine-learning counterfactual modeling of aerosol–cloud interactions	SO ₂ ; sulfate aerosols	Climate	IMO 2020 sulfur cap
22	Aghito et al. (2025) [68]	European seas (Baltic, North, Mediterranean, and Black Seas)	Integrated modeling framework: STEAM emission and discharge estimation; SILAM atmospheric transport and deposition modeling; ChemicalDrift marine transport modeling; scenario projection (2018 vs. 2050)	PAHs; heavy metals (Cu, Zn, Cd, Pb)	Marine Ecological	IMO 2020 sulfur cap and scrubber use scenarios
23	Bauer et al. (2024) [69]	Controlled laboratory marine-engine combustion experiments (Germany)	Experimental marine-engine combustion analysis: MW-TOCA; single-particle mass spectrometry (SPMS); optical and radiative-forcing analysis	Carbonaceous particles (OC; EC; BC; BrC); PM _{2.5} ; PAHs	Environmental, Health & Climate	IMO 2020 sulfur cap and SECA low-sulfur/distillate fuel transition
24	Xing et al. (2024) [70]	Shenzhen, China (ship-influenced coastal urban environment)	Ambient PM _{2.5} field sampling; high-resolution mass spectrometry (HRMS); oxidative-potential assays (OPDTT and OPOH); source-apportionment and correlation analysis	PM _{2.5} ; water-soluble organic compounds (WSOC); CHON; CHOS; metals; ROS-active compounds	Environmental & Health	Post-IMO 2020 low-sulfur shipping context
25	Achten et al. (2024) [71]	North Sea and Baltic Sea (onboard scrubber-discharge sampling)	Empirical onboard sampling; GC-MS and GC-APLI-MS chemical characterization; non-target analysis; emission-factor estimation; comparative analysis of open- and closed-loop scrubber discharge	PAHs; PACs; alkylated PAHs; heterocyclic aromatic compounds (PASH, PANH, PAOH); soot-associated high-molecular-weight PAHs	Marine Ecological	Scrubber (EGCS) compliance strategy
26	Zhang et al. (2024) [72]	China coastal and inland waters (Yangtze River and ocean-going cargo ships)	Onboard real-world emission testing; VOC sampling and GC/MS analysis; emission-factor estimation; ozone-formation potential (OFP) and SOA-formation potential (SOAFP) assessment	VOCs (alkanes, alkenes, aromatics, OVOCs, halohydrocarbons); benzene; toluene; ethylbenzene; naphthalene; acetone; acrolein	Environmental	IMO 2020 global sulfur cap and low-sulfur fuel policy
27	Jordan & Henry (2024) [73]	Global major shipping corridors	Earth-system climate modeling (UKESM1); atmosphere-only and coupled atmosphere–ocean simulations; aerosol–cloud interaction and radiative-forcing analysis	SO ₂ ; SO ₄ ²⁻ ; aerosol optical depth (AOD); cloud drop-	Climate	IMO 2020 global sulfur cap

				let number concen- tration		
28	Ek-mekçioglu et al. (2025) [22]	Istanbul Bosphorus Strait, Türkiye	Bottom-up emission inventory estimation (EPA-based); AIS ship-activity analysis; AERMOD dispersion modeling; spatial SO ₂ concentration mapping	SO ₂ ; NO _x ; PM ₁₀ ; CO	Environmental & Health	IMO 2020 global sulfur cap
29	Bendl et al. (2024) [74]	Controlled laboratory marine-engine experiments (Germany)	Controlled marine-engine combustion experiments; comparative fuel testing; wet-scrubber evaluation; FTIR and GC/FID analysis; VOC and carbonyl analysis; ozone-formation potential (OFP) assessment	NO _x ; CO; hydrocarbons (HC); VOCs; benzene; formaldehyde; acetaldehyde; SO _x ; ozone precursors	Environmental & Health	IMO sulfur regulations and scrubber-compliance strategies
30	Grigoriadis et al. (2024) [75]	Onboard measurements during a Rotterdam–Gebze commercial voyage	Real-world onboard emission measurements; upstream/downstream scrubber comparison; PN/PSD analysis using SMPS; gaseous-emission monitoring	SO ₂ ; NO _x ; CO; THC; particulate matter (PM); particle number (PN); particle size distribution (PSD); ultrafine particles; sulfuric-acid particles	Environmental & Health	IMO 2020 sulfur cap and scrubber-compliance strategies
31	Kuittinen et al. (2024) [76]	Baltic and North Sea ECA (modern cruise ship onboard measurements)	Real-world onboard emission characterization; upstream/downstream scrubber sampling; SMPS/Nano-SMPS particle analysis; SP-AMS chemical-composition analysis; PAH and metal filter analysis	SO ₂ ; NO _x ; CO; CO ₂ ; PM; ultrafine particles (UFP); particle number (PN); BC; PAHs; trace metals (V, Ni, Fe, Ca, Na); sulfate; organics	Environmental & Health	IMO 2020 sulfur cap and ECA compliance technologies
32	Yuan et al. (2024) [77]	Global oceans (North Atlantic, North Pacific, South China Sea, and other major shipping regions)	Satellite-observation analysis; chemical-transport modeling (NASA GEOS-GOCART); deep-learning cloud-droplet estimation; radiative-forcing and energy-balance climate modeling	SO ₂ ; sulfate aerosols; aerosol optical depth (AOD); cloud-droplet number concentration (Nd); aerosol–cloud interactions	Climate	IMO 2020 global sulfur cap
33	Lunde Hermansson et al. (2024) [78]	Global shipping fleet with Baltic Sea case study	STEAM-based ship-traffic simulation; economic break-even modeling; marine ecotoxicity assessment; willingness-to-pay (WTP) damage-cost estimation	SO _x ; PM; metals; PAHs; acidic scrubber washwater; nitrates; sulfuric-acid residues	Marine Ecological & Economic	IMO 2020 sulfur regulations and scrubber compliance under MARPOL Annex VI
34	Bufato Moreira et al. (2024) [79]	Paranaguá Port, Brazil (major Latin American grain port)	PM _{2.5} monitoring campaign; XRF elemental analysis; enrichment-factor analysis; tracer-based PM _{2.5} source apportionment; health-risk assessment	PM _{2.5} ; sulfur (S); vanadium (V); nickel (Ni); BC; heavy metals	Environmental & Health	IMO 2020 global sulfur cap
35	Du et al. (2024) [80]	Qingdao, coastal megacity in Northern China	PM ₁ chemical and trace-metal analysis; enrichment-factor (EF) analysis; backward-trajectory and PSCF analysis; K-means clustering; elemental-ratio analysis (V/Ni, V/Zn, V/Pb)	PM ₁ ; vanadium (V); nickel (Ni); zinc (Zn); lead (Pb); SO ₂ ; PM _{2.5} ; PM ₁₀	Environmental	DECA policies and IMO 2020 sulfur regulations
36	Genitsaris et al. (2024) [81]	Eastern Mediterranean Sea (Plagia Chalkidiki and Port of Thessaloniki, Greece)	Mesocosm experiments; metabarcoding sequencing (16S and 18S rRNA); metagenomic and microbial-community analysis; Bray–Curtis similarity analysis; ANOSIM and SIMPER analysis	Scrubber-effluent contaminants including PAHs; alkyl-PAHs; metals; SO _x -related pollutants; NO _x -related pollutants; naphthalene; phenanthrene; fluorene	Marine Ecological	IMO 2020 sulfur regulations and open-loop scrubber compliance
37	Jönander et al. (2023) [82]	Gullmar Fjord, Swedish west coast	Seasonal mesocosm toxicity experiments; zooplankton exposure assays; trophic-interaction experiments; NMDS ordination; ANOSIM and SIMPER analysis; toxic-unit (TU) modeling	SO _x -related scrubber contaminants; PAHs; metals; particulate-derived pollutants; vanadium; copper; nickel; zinc;	Marine Ecological	IMO 2020 sulfur cap and scrubber-compliance measures

				benzo[ghi]perylene (BghiP)		
38	Feng et al. (2023) [83]	Southern China (Pearl River Delta and coastal waters)	WRF-GC atmospheric modeling; AIS-based emission inventory; satellite (TROPOMI) analysis; ground-monitoring validation	NO _x ; SO ₂ ; PM _{2.5} ; O ₃ ; NMVOCs	Environmental	IMO 2020 sulfur cap and COVID-19 emission shock
39	Schneider et al. (2023) [84]	Controlled laboratory marine-diesel engine experiments (Germany)	FT-ICR MS ultrahigh-resolution analysis; controlled marine-engine combustion experiments; comparative fuel and scrubber-condition testing	HULIS (humic-like substances); CHO; CHNO; CHOS compounds; organic PM fractions	Environmental & Health	IMO sulfur regulations and scrubber use
40	Karl et al. (2023) [85]	Marseille port area, France	Coupled CTM modeling (CMAQ and EPI-SODE-CityChem); field measurements (SMPS, AMS, PTR-MS)	UFP (particle number); SOA; VOCs; NO ₂ ; SO ₂ ; PM _{2.5}	Environmental & Health	IMO global sulfur cap
41	Yeh et al. (2023) [86]	Kaohsiung Port, Taiwan	Field measurements (USEPA TO-15A); GC-MS ship-exhaust analysis of 16 vessels	Naphthalene (Nap); VOCs; PAHs	Environmental & Health	IMO global sulfur cap
42	Zhai et al. (2023) [87]	Greater Bay Area (GBA), China (Shenzhen and regional coastal shipping network)	Field measurements (HR-SPAMS, 15 months); trajectory analysis (HYSPLIT, PSCF); high-resolution chemical transport modeling (WRF/CMAQ, 1 km); AIS-based emission-inventory analysis	PM _{2.5} ; NO _x ; SO ₂ ; V; Ni; O ₃	Environmental	IMO 2020 global sulfur cap
43	Ji et al. (2023) [13]	China (scrubber wash-water context)	Controlled laboratory ecotoxicology experiments; chemical analysis (GC-MS, ICP-MS); bioassays across trophic levels	PAHs; heavy metals (Ni, Cr, Zn, Cu, Pb, V); sulfite (SO ₃ ²⁻); PM	Environmental	IMO sulfur regulation compliance via scrubbers (EGCS)
44	Genitsaris et al. (2023) [88]	Eastern Mediterranean Sea (Thermaikos Gulf, Greece; polluted vs. unpolluted coastal sites)	Mesocosm experiments (6-day exposure); microscopy; 16S rRNA metabarcoding; chemical analysis	PAHs (naphthalene, phenanthrene, fluorene); alkyl-PAHs; heavy metals (V); NO _x -derived nutrients	Marine Ecological	IMO 2020 sulfur cap and open-loop scrubber discharge
45	Van Roy et al. (2023) [89]	Southern North Sea (Belgian coastal and inland monitoring stations)	Empirical monitoring; airborne sniffer measurements (2015–2022); statistical analysis; inland air-quality assessment	SO ₂ ; NO _x	Environmental & Health	MARPOL Annex VI regulations; SECA; IMO 2020 sulfur cap; NECA; scrubber compliance
46	Lunde Hermansson et al. (2023) [90]	4 ports (Copenhagen, Gdynia, OECD EU, OECD Baltic)	STEAM- and MAMPEC-based modeling; cumulative environmental risk assessment	Heavy metals (Cu, Zn, V, Ni); PAHs (16 priority compounds)	Marine Ecological	MARPOL Annex VI scrubber regulations and IMO MEPC scrubber guidelines
47	Fuentes García et al. (2022) [91]	Veracruz Port, Mexico	Bottom-up emission inventory; CALPUFF dispersion modeling; meteorological analysis	SO ₂ ; sulfate aerosols; PM	Environmental & Health	MARPOL Annex VI and IMO 2020 sulfur cap
48	Zhang & Aikawa (2023) [92]	Kitakyushu, Japan	Long-term field observation (2017–2021); chemical analysis; HYSPLIT trajectory modeling; health-risk assessment	PM _{2.5} ; SO ₄ ²⁻ ; NH ₄ ⁺ ; NO ₃ ⁻ ; heavy metals (As, V, Ni, Sb, Cd)	Environmental & Health	IMO 2020 sulfur cap
49	Kim et al. (2022) [93]	Busan, South Korea	Air-quality modeling (WRF-SMOKE-CMAQ); emission-inventory analysis; pre/post-IMO scenario assessment	PM _{2.5} ; SO ₂ ; NO ₂ ; sulfate aerosols	Environmental & Policy evaluation	IMO 2020 sulfur cap
50	Shen et al. (2022) [94]	Trans-Pacific route (Asia–Central America, open ocean)	Empirical onboard experiment; comparative fuel analysis (HFOWD vs. VLSFO); statistical testing	CO ₂ ; SO _x ; PM	Environmental & Climate	IMO 2020 sulfur cap and VLSFO fuel switching
51	Haugen et al. (2022) [95]	Port of Rafina, Greece	Field measurements using UAV and ground sensors; Gaussian plume modeling; ISRN particle-dynamics modeling	PM; particle number (PN); lung-deposited surface area (LDSA); BC; SO _x -related particles	Environmental & Health	IMO low-sulfur fuel regulations and PM transformation processes
52	Di Natale et al. (2022) [96]	Channel of Procida, Italy	Field measurements; bottom-up emission modeling; HYSPLIT dispersion modeling	PM _{2.5} ; PM ₁ ; PM _{0.5} ; particle number (PN); ultrafine particles	Environmental & Health	EU sulfur regulations and IMO fuel-policy scenarios
53	Ytreberg et al. (2022) [20]	Baltic Sea	Emission inventory compilation; comparative analysis using the STEAM model; HELCOM-based monitoring assessment	Heavy metals (Cu, Zn, V, Ni, Pb); PAHs (16 priority compounds)	Marine Ecological & Policy Evaluation	Scrubber regulations, antifouling emissions, and MARPOL Annex VI

54	Tauchi et al. (2022) [97]	Seto Inland Sea, Japan	Field observations (coastal and onboard); time-series analysis; chemical composition analysis	SO ₂ ; NO _x ; PM _{2.5} ; sulfate (SO ₄ ²⁻); heavy metals (V, Ni)	Environmental & Policy Evaluation	IMO 2020 global sulfur cap
55	Song et al. (2022) [98]	Busan Port and 5 major ports, South Korea	Observational study; regression discontinuity design (RDD); chemical composition analysis	SO ₂ ; NO ₂ ; PM _{2.5} ; NH ₄ ⁺ ; SO ₄ ²⁻ ; NO ₃ ⁻ ; BC	Environmental & Health	IMO 2020 sulfur cap
56	Du et al. (2022) [99]	Onboard ships and laboratory experiments (global shipping operations)	Field sampling; GC–MS chemical analysis; laboratory mimic experiments	PAHs (EPA 16 and alkylated PAHs)	Marine Ecological & Toxicological	IMO 2020 sulfur cap and scrubber adoption
57	Zhou et al. (2022) [100]	Guangzhou, China (urban site near Huangpu Port, DECA region)	Real-time single-particle analysis using SPAMS; cluster analysis (ART-2a); regression analysis	SO ₂ ; sulfate; organic carbon (OC); elemental carbon (EC); NO _x ; heavy metals (V, Ni)	Environmental & Health	China DECA low-sulfur fuel policy aligned with IMO 2020
58	Karjalainen et al. (2022) [101]	Baltic Sea SECA region (onboard RoPax vessel operations)	Real-world onboard measurements; oxidation-flow-reactor experiments; SP-AMS and SMPS aerosol analysis; emission-factor assessment	SO ₂ ; NO _x ; PM; sulfate; black carbon (BC); organic carbon (OC); PAHs; heavy metals	Environmental & Health	SECA sulfur regulations and IMO 2020 global sulfur cap
59	Grönholm et al. (2021) [102]	Baltic Sea (Utö Island, Finland; remote marine station near shipping lanes)	Long-term field measurements (2015–2021); plume analysis; AIS ship-tracking; regression analysis	CH ₄ ; CO ₂ ; NO _x	Environmental & Climate	IMO 2020 sulfur cap and LNG-fuel transition
60	Gren et al. (2021) [103]	Baltic Sea (multi-basin system)	Economic modeling; abatement-cost analysis; shadow pricing; optimization modeling	NO _x ; nitrogen deposition	Marine Ecological & Economic	Ox emission-control policies in the post-IMO regulatory context
61	Nguyen et al. (2021) [104]	Port of Kaohsiung, Taiwan (urban port and surrounding city)	Emission estimation; AERMOD dispersion modeling; scenario analysis	NO _x ; SO ₂ ; PM ₁₀ ; PM _{2.5}	Environmental & Health	IMO 2020 sulfur cap and shore-power implementation
62	Lunde Hermansson et al. (2021) [28]	Global shipping context (vessels using HFO, MGO, and scrubber systems)	Literature-based emission-factor (EF) compilation; comparative scenario analysis (Pre-IMO, Open-loop, Closed-loop, MGO scenarios)	PAHs (16 EPA priority compounds); heavy metals (V, Ni, Pb, Cd)	Environmental & Marine Ecological	IMO 2020 sulfur cap; scrubber system; fuel switching strategies
63	Thor et al. (2021) [105]	North Sea shipping routes and laboratory exposure experiments (Swedish west coast)	Laboratory ecotoxicity experiments; chemical characterization of scrubber effluents; mortality and metabolic-response assessment	Heavy metals (Hg, Ni, V, Cr, Cu, Zn); PAHs; alkylated PAHs; hydrocarbons; sulfur compounds	Marine Ecological & Toxicological	IMO 2020 sulfur regulations and scrubbers
64	Zhao et al. (2021) [106]	East Asia coastal regions (China, Korean Peninsula, Japan, East China Sea)	Emission inventory development; CMAQ atmospheric modeling; AIS-based ship emission estimation; seasonal spatial analysis	Heavy metals (V, Ni) in PM _{2.5}	Environmental & Health	IMO low-sulfur fuel policy and heavy fuel oil emissions from ocean-going vessels
65	Kuittinen et al. (2021) [107]	Global shipping routes, Baltic Sea, Southeast Asia, and coastal/open-ocean regions	Laboratory engine experiments; onboard ship measurements; aircraft plume observations; STEAM global-emission modeling	Particle number (PN); ultrafine particles (UFPs); particulate emissions from HFO, IFO, MGO, MDO, LNG, and BIO30 fuels	Environmental & Health	Air-pollution regulations, climate forcing, and ultrafine-particle exposure from shipping emissions
66	Bilsback et al. (2020) [108]	Global shipping routes with strong impacts in Europe, North America, China, India, Arctic, and coastal regions	Global chemical-transport modeling using GEOS-Chem-TOMAS; aerosol microphysics simulation; health-impact and radiative-forcing assessment	SO _x ; NO _x ; black carbon (BC); organic aerosol (OA); PM _{2.5} ; sulfate (SO ₄ ²⁻); nitrate (NO ₃ ⁻); ammonium (NH ₄ ⁺)	Environmental, Health & Climate	IMO 2020 global sulfur cap and additional BC/OA/NO _x control scenarios
67	Nunes et al. (2020) [109]	Iberian Peninsula (Portugal, Spain, Strait of Gibraltar, Mediterranean Sea, Atlantic coast)	STEAM3 bottom-up shipping emission inventory; EMEP/MSC-W chemical transport modeling	NO _x ; SO _x ; PM _{2.5} ; PM ₁₀ ; O ₃ ; sulfate; elemental carbon (EC); organic carbon (OC); CO ₂	Environmental & Health	Sulfur-control policies and future Mediterranean ECA implementation

2.6. Bibliometric and Analytical Tools

To complement the systematic literature review, a bibliometric analysis was conducted using VOSviewer (Nees Jan van Eck and Ludo Waltman, Leiden, The Netherlands; version 1.6.20) to explore the structure of the research field and identify key thematic patterns within the selected studies. VOSviewer is a widely used tool for constructing and visualizing bibliometric networks, particularly in keyword co-occurrence analysis [110]. VOSviewer was selected because of its ability to construct and visualize bibliometric networks efficiently and its widespread application in systematic literature reviews [111].

The analysis was performed on the final dataset of 67 studies obtained through the PRISMA screening process. Author keywords were extracted and used as the primary unit of analysis. A keyword co-occurrence network was generated using the full counting method, which considers the total frequency of keyword occurrences across all studies [111]. A minimum threshold of three occurrences per keyword was applied to ensure that only the most relevant and frequently used terms were included in the analysis.

The resulting keyword network was interpreted to identify major research themes and relationships among keywords. Accordingly, bibliometric analysis served as a complementary analytical technique to characterize the intellectual structure of the literature and inform the subsequent thematic synthesis addressing the predefined research questions, rather than replacing the qualitative synthesis. Because bibliometric analysis identifies publication patterns and thematic relationships rather than evaluating the methodological quality of individual studies, it was used as a complementary analytical approach alongside thematic synthesis.

In addition to bibliometric mapping, descriptive and thematic analyses were conducted using the data extracted from the 67 included studies. Descriptive statistics were used to summarize the general characteristics of the included studies, including publication year, study location, methodological approach, and pollutant categories, thereby providing an overview of publication patterns. Subsequently, thematic synthesis was applied to classify findings according to the three predefined research questions [112]. This approach enables evidence from heterogeneous studies to be integrated into conceptually coherent themes [112].

3. Results

3.1. Descriptive Analysis

This section provides an overview of the characteristics of the 67 studies included in the review. Descriptive analysis was conducted to examine publication trends, geographical distribution, methodological approaches, and pollutant categories. These descriptive findings provide contextual information on the evolution and research focus of the post-IMO 2020 literature before presenting the thematic synthesis addressing the research questions.

3.1.1. Publication Trends over Time

Figure 2 illustrates a steady increase in publications following the implementation of IMO 2020, rising from only two studies in 2020 to twenty-three studies in 2025. Rather than reflecting immediate interest alone, this upward trend indicates the gradual accumulation of post-implementation evidence, enabling researchers to move beyond prospective modelling toward empirical evaluations of environmental and public health outcomes. The sustained growth in publication output suggests that assessing the real-world impacts of IMO 2020 has become an increasingly important area of interdisciplinary research.

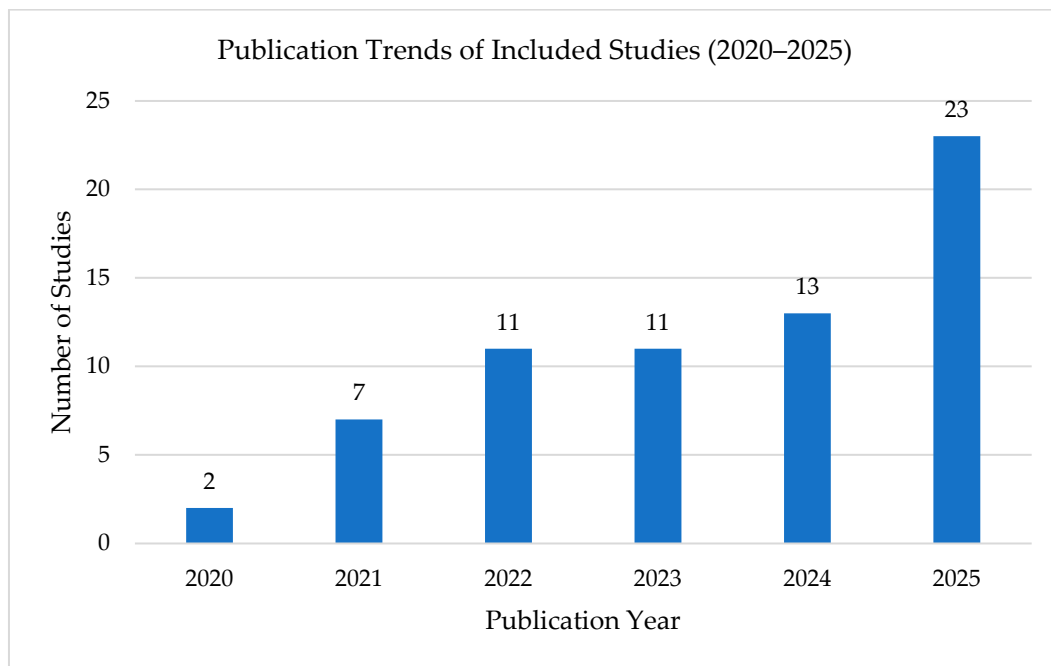


Figure 2. Annual publication trends of the 67 studies included in the review (2020–2025).

3.1.2. Methodological Distribution

Figure 3 summarizes the methodological distribution of the included studies. Simulation-based approaches accounted for the largest proportion of the literature, followed by empirical and observational investigations, whereas satellite and remote-sensing studies were comparatively less common. The predominance of simulation studies reflects the need to estimate emission reductions, pollutant dispersion, and population exposure during the early years following IMO 2020, when long-term monitoring data remained limited. Nevertheless, the increasing number of observational studies suggests a gradual transition toward validating model projections with real-world measurements.

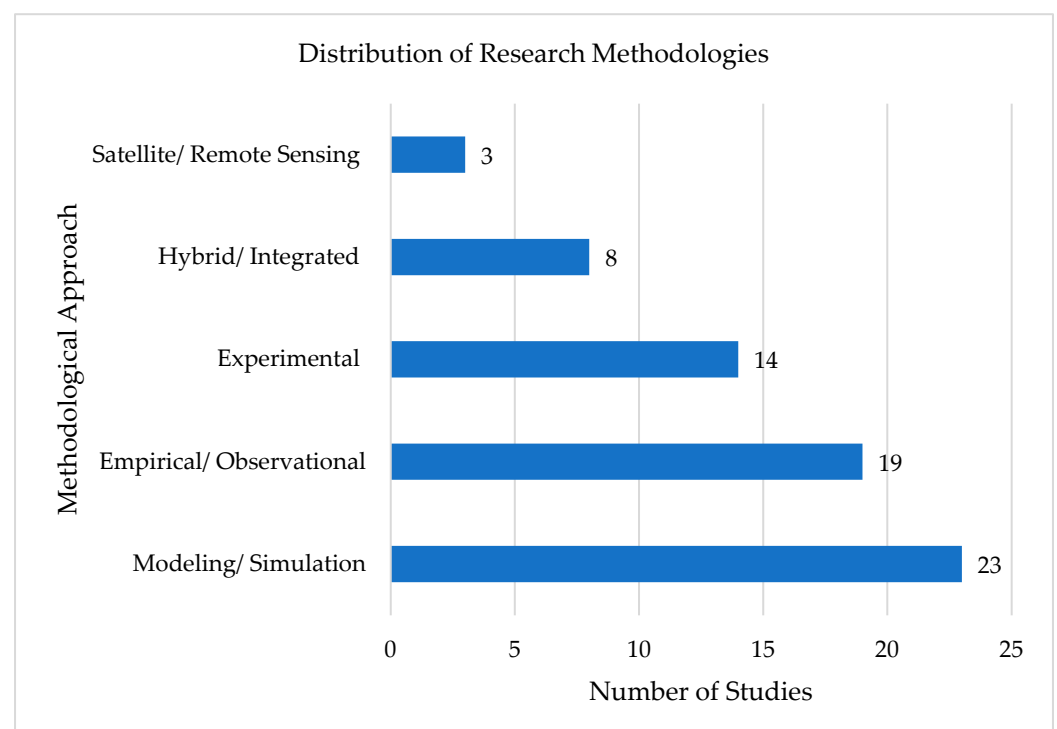


Figure 3. Methodological distribution of the reviewed studies.

3.1.3. Geographic Distribution

Figure 4 illustrates the geographic distribution of the location-specific studies included in this review. China accounted for the largest number of studies, followed by several European countries, whereas comparatively fewer studies were conducted in other regions. This distribution suggests that post-IMO 2020 research has primarily focused on major maritime regions where shipping activities and air-quality concerns have attracted substantial scientific attention. In addition, several studies adopted global or multi-regional perspectives and were therefore not assigned to individual countries in the geographic visualization.

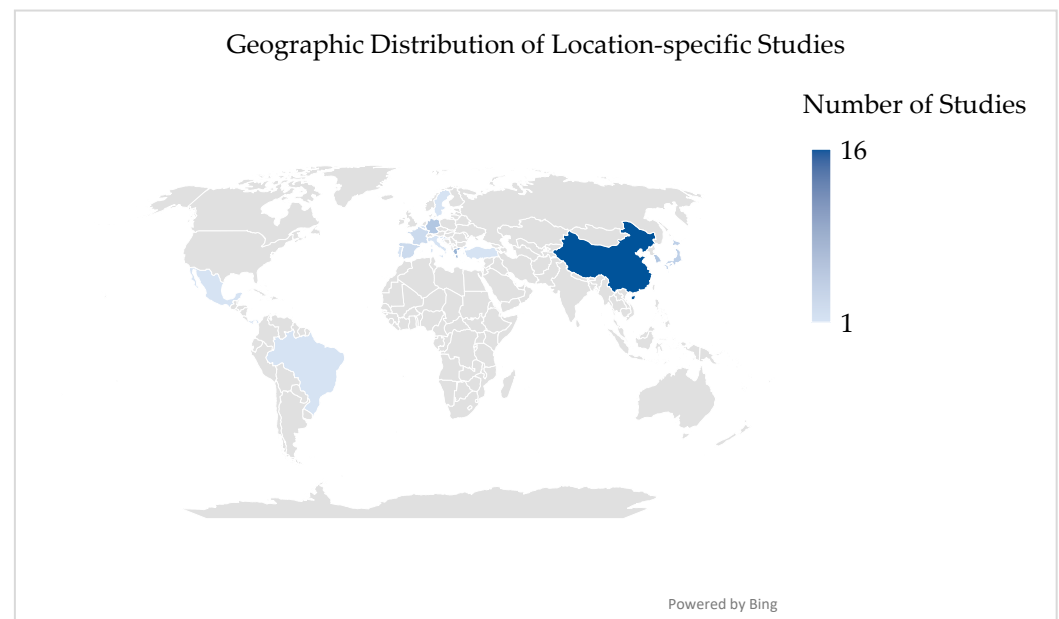


Figure 4. Geographic distribution of location-specific studies included in the review. Darker shading indicates a higher number of studies conducted within a country. (Microsoft Excel for Microsoft 365, Version 2506 (Microsoft Corporation, Redmond, Washington, USA)).

Global and multi-regional studies are not represented on the map.

3.1.4. Pollutant Distribution

Figure 5 presents the frequency of pollutant categories examined across the reviewed studies. Particulate matter and black carbon were the most frequently investigated pollutants ($n = 42$), followed by sulfur-related pollutants ($n = 39$) and nitrogen oxides ($n = 27$). This distribution is consistent with the central objectives of IMO 2020, which primarily target sulfur emissions and their implications for air quality. Heavy metals, PAHs, marine pollutants, VOCs, greenhouse gases, and ozone-related pollutants received comparatively less attention, although these pollutants remain important for understanding broader environmental, ecological, and climate-related consequences of shipping activities. Because many studies examined multiple pollutant categories simultaneously, the cumulative frequencies exceed the total number of studies included in the review.

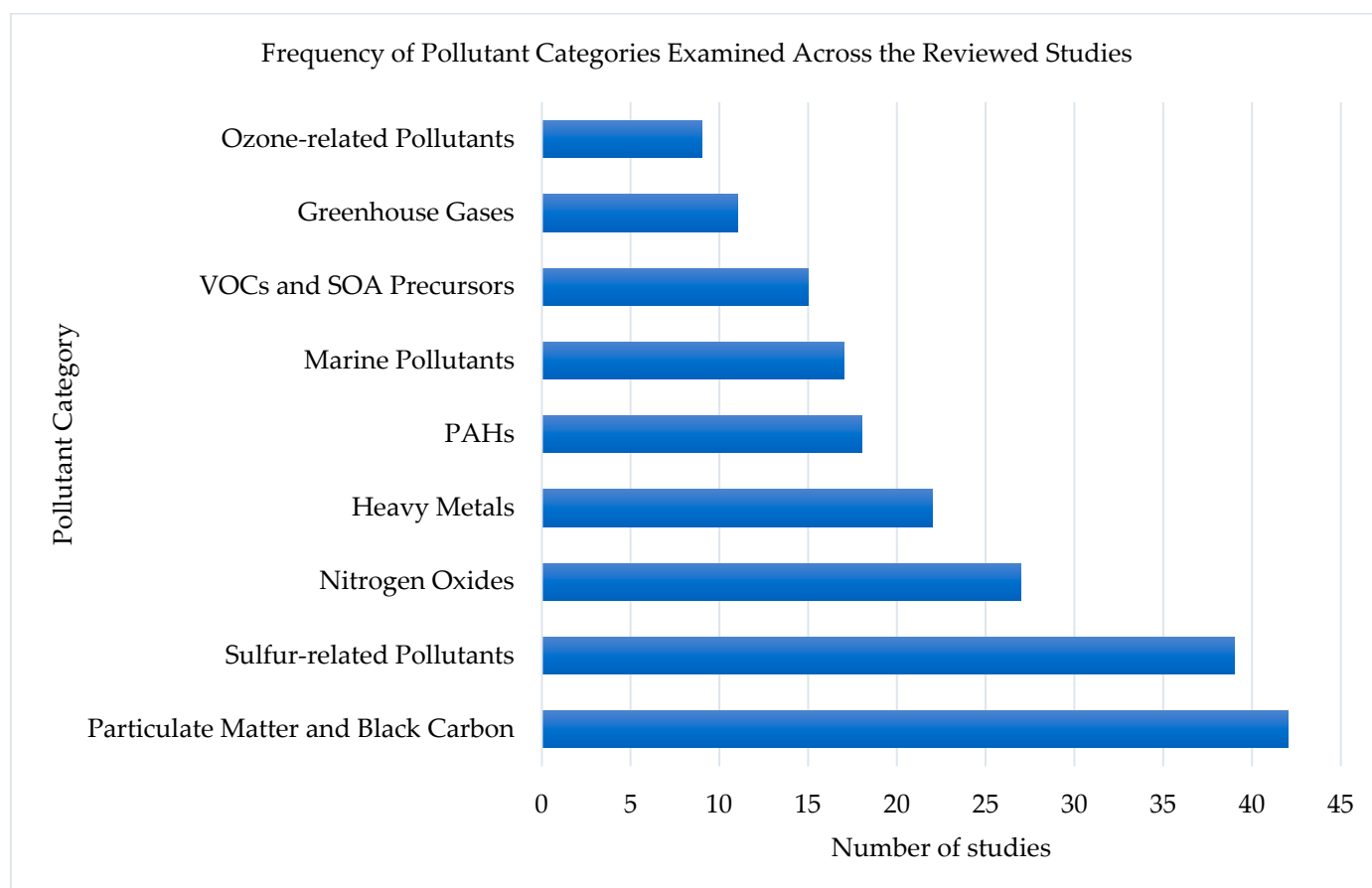
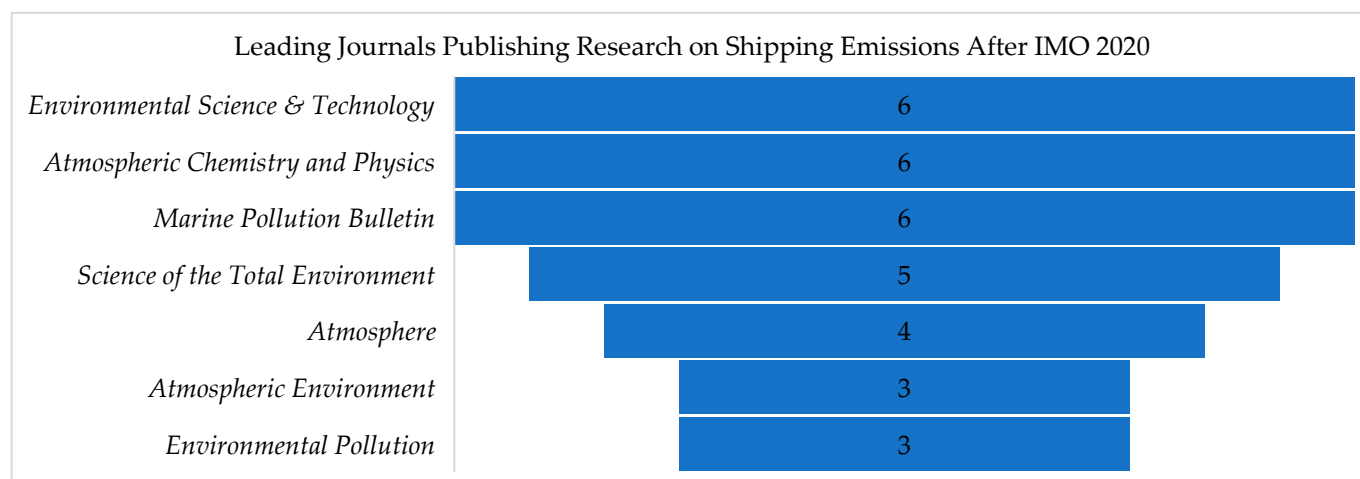


Figure 5. Frequency of pollutant categories examined across the reviewed studies. Individual studies may be represented in multiple categories because several pollutants were often investigated simultaneously.

3.1.5. Journal Distribution

Figure 6 presents the leading journals represented in the reviewed literature. *Environmental Science & Technology*, *Atmospheric Chemistry and Physics*, and *Marine Pollution Bulletin* were among the most frequent publication venues, followed by *Science of the Total Environment*, *Atmosphere*, *Atmospheric Environment*, and *Environmental Pollution*. The concentration of publications in well-established journals specializing in environmental science, atmospheric chemistry, and marine pollution indicates that the evidence synthesized in this review is primarily derived from reputable peer-reviewed sources and highlights the interdisciplinary nature of post-IMO 2020 research.



vironmental monitoring and large-scale modelling. The fourth cluster (yellow) represents studies examining pollutant emissions from shipping activities, particularly particulate matter, PM_{2.5}, gaseous emissions, and related atmospheric pollutants.

Overall, the bibliometric findings indicate that the existing literature is primarily concentrated on environmental and technical aspects of shipping emissions, particularly air pollution processes, emission inventories, and fuel-related characteristics, and pollution control technologies, whereas health-oriented terms are not among the most frequently occurring keywords. These findings provide a data-driven foundation for the thematic analysis presented in the subsequent section. The prominence of emission-related, fuel-related, and air-quality-related clusters suggests that research following IMO 2020 has primarily focused on environmental assessment and regulatory compliance. Comparatively less attention has been directed toward human health outcomes and broader socioeconomic implications.

3.3. Thematic Synthesis

3.3.1. Environmental Impacts of Shipping Emissions Under IMO 2020

(1) Air-Quality Improvements

The reviewed literature consistently demonstrates that the IMO 2020 sulfur regulation substantially reduced sulfur-related air pollution and improved regional air quality in many maritime regions. Across both empirical and modeling studies, significant reductions in sulfur dioxide (SO₂), sulfate aerosols, and particulate matter (PM) were widely reported following the transition from high-sulfur heavy fuel oil (HFO) to low-sulfur fuel alternatives [21,22,79,91,93,97]. Representative findings include a 37.3% reduction in ship-related primary PM_{2.5} emissions in Shanghai [21], PM_{2.5} concentration improvements of up to 19% near Busan Port [93], an average decrease in ship-related PM_{2.5} contributions from 35.8% to 4.9% at Paranaguá Port [79], and an 88% reduction in SO₂ emissions at the Port of Veracruz [91] following the adoption of low-sulfur marine fuels. Similar reductions in sulfate aerosols and shipping-related PM contributions were consistently reported across the Seto Inland Sea [97], the Bosphorus Strait [22], and other coastal and port environments [21,79,93], confirming the effectiveness of the sulfur cap in improving regional air quality.

Beyond reductions in SO₂ and PM_{2.5}, several studies also documented substantial decreases in shipping-related trace metals, particularly nickel (Ni) and vanadium (V), reflecting reduced emissions associated with residual fuel combustion. In Shanghai, emissions of Ni and V decreased by 46.7% and 91.6%, respectively, following implementation of low-sulfur fuel policies [21], while field observations in the Seto Inland Sea and Paranaguá Port similarly reported notable reductions in ship-related trace metals together with lower SO₂ and PM_{2.5} concentrations [79,97]. Nevertheless, vanadium-containing particles continued to be identified as important tracers of ship emissions in Shenzhen, indicating that shipping activities remain an important contributor to coastal air pollution despite substantial sulfur reductions [87].

These improvements were further supported by regional atmospheric modeling and satellite observations. Regional modeling studies based on AIS-derived ship emission inventories consistently demonstrated substantial reductions in ship-related SO₂ and PM_{2.5} concentrations, including secondary aerosol contributions, across coastal urban areas and major shipping corridors following the implementation of IMO 2020 [52,83]. Satellite observations likewise revealed widespread declines in sulfate aerosol burdens and shipping-induced cloud signatures after the sulfur cap [67,73,77]. At the global scale, mean cloud droplet number concentrations decreased by approximately 0.5 cm⁻³, with regional reductions reaching 3 cm⁻³ along major shipping routes, providing independent evidence of the atmospheric effects of reduced sulfur emissions [77].

(2) Climate-Related Consequences

Beyond changes in atmospheric composition, the reviewed evidence also identified important climate-related consequences associated with sulfur regulation. Satellite observations and climate-modeling studies consistently showed that reductions in sulfate aerosols weakened aerosol–cloud interactions and diminished the cooling effect historically associated with shipping emissions [67,73,77]. Consequently, IMO 2020 was estimated to produce positive radiative forcing of up to $+0.20 \pm 0.11 \text{ W m}^{-2}$, partially offsetting the climatic cooling previously provided by shipping-derived sulfate aerosols [77] and contributing to short-term warming trends [73].

Recent observational evidence further suggested that the environmental influence of IMO 2020 extends beyond air quality and radiative forcing. Over the Bay of Bengal, SO_2 emissions decreased by approximately 66%, accompanied by an 11% reduction in lightning frequency associated with weakened deep convective cloud development, indicating that sulfur regulations can influence broader atmospheric processes through changes in aerosol–cloud interactions [48].

Overall, the reviewed literature demonstrates that IMO 2020 has substantially reduced sulfur-related air pollution and improved regional air quality across major maritime regions. Consistent reductions in SO_2 , sulfate aerosols, particulate matter, and shipping-related trace metals were reported across both empirical observations and atmospheric modeling studies. The reviewed evidence also indicates that these environmental benefits were accompanied by broader atmospheric consequences, including reduced aerosol–cloud interactions and diminished sulfate-driven cooling, highlighting the complex interactions between air-quality improvement and the climate system.

3.3.2. Health Impacts of Shipping Emissions Under IMO 2020

(1) Health Benefits Associated with Reduced Sulfur Emissions

A growing body of literature has examined the health implications associated with shipping emissions under the IMO 2020 sulfur regulation, particularly in relation to human exposure to particulate matter, toxic trace metals, ultrafine particles, and secondary pollutants [21,79,85,108]. The reviewed studies suggest that the sulfur cap contributed to important public health benefits through reductions in sulfur-related air pollution and ship-related $\text{PM}_{2.5}$ concentrations. However, several studies also indicate that residual health risks associated with ultrafine particles, toxic metals, and redox-active aerosol components may persist despite sulfur reductions [21,61,70,85].

Air-quality and health risk assessment studies consistently indicated that reductions in SO_2 and $\text{PM}_{2.5}$ concentrations following the implementation of IMO 2020 were associated with lower pollution-related health risks in coastal and port regions [21,51]. Representative evidence includes a reduction in long-term premature mortality associated with ship-related $\text{PM}_{2.5}$ exposure in Shanghai, where estimated deaths declined from 630 to 481 cases, together with decreases in short-term mortality from 43 to 29 cases between 2017 and 2021 [21]. Similar improvements were reflected in reduced hazard quotient and hazard index values following declines in vanadium, nickel, and sulfur concentrations near Paranaguá Port [79]. Long-term monitoring studies in Japan [97] and South Korea [98] likewise reported sustained reductions in SO_2 concentrations and shipping-related pollution indicators, providing consistent environmental evidence that supports the health risk reductions reported in other coastal regions.

(2) Population Exposure in Coastal Regions

The reviewed literature consistently showed that shipping-emission impacts remain particularly pronounced in densely populated coastal regions exposed to intensive maritime activities. Modeling analyses conducted for the Iberian Peninsula, the Panama Canal region, and Mediterranean coastal cities demonstrated that shipping emissions continue

to contribute substantially to urban PM_{2.5} and NO₂ concentrations and associated population exposure in coastal urban areas [49,55,109]. Additional evidence suggested that shipping emissions may contribute to elevated PM_{2.5} concentrations not only in coastal areas but also in inland regions affected by atmospheric transport [51]. Pollutant dispersion and population exposure were further shown to depend strongly on meteorological conditions, including sea–land breeze circulation and regional atmospheric transport processes [49,87].

(3) Toxicity of Residual Shipping Emissions

Despite reductions in PM mass concentrations, several toxicological and chemical characterization studies reported that low-sulfur fuels and scrubber systems do not fully eliminate the toxicity of shipping emissions. Experimental studies demonstrated that particle toxicity is strongly influenced by chemical composition rather than PM mass alone [61,70]. Ship-related particles containing polycyclic aromatic hydrocarbons (PAHs), metal-containing particles, and oxidized organic compounds were associated with oxidative stress, reactive oxygen species (ROS) formation, genotoxicity, mutagenicity, and inflammatory responses [61,84]. Experimental evidence further demonstrated that the transition to low-sulfur fuels may alter the composition of gaseous emissions, in some cases increasing VOCs and hazardous compounds such as benzene and naphthalene, which contribute to ozone formation and secondary aerosol toxicity [72,74,86].

(4) Emerging Concerns Regarding Ultrafine Particles

Ultrafine particles (UFPs) emerged as a recurring concern across the reviewed literature. Onboard measurements and port-based studies showed that scrubber-equipped ships and certain low-sulfur fuel operations remain important sources of ultrafine particles and secondary nanoparticles [75,76,85]. Onboard measurements and port-based observations showed that scrubber-equipped ships and certain low-sulfur fuel operations remain important sources of ultrafine particles and secondary nanoparticles [75,76,85]. In Marseille, local shipping contributed approximately 27–51% of total particle number concentrations and 6–9% of secondary organic aerosol concentrations, illustrating the continued importance of UFP emissions despite substantial sulfur reductions [85]. Owing to their small size, these particles can penetrate deeply into the respiratory system and potentially reach the bloodstream and other organs, including the nervous system [76,85]. The reviewed evidence indicates that sulfur-focused regulations substantially reduce SO₂ emissions while leaving ultrafine particles, VOCs, and other health-relevant pollutants comparatively less controlled [74,85].

Taken together, the reviewed evidence indicates that IMO 2020 has generated important public health benefits through reductions in sulfur-related air pollutants and PM exposure. Nevertheless, significant health concerns remain because ultrafine particles, toxic organic compounds, and secondary atmospheric pollutants are not fully addressed by sulfur-focused regulations. These findings suggest that although IMO 2020 substantially reduces exposure to conventional air pollutants, broader health protection will require integrated emission-control strategies targeting multiple pollutants beyond sulfur alone.

3.3.3. Implementation Challenges and Unintended Trade-Offs

Although IMO 2020 has been widely recognized for reducing sulfur emissions and improving air quality, the reviewed literature also identified several unintended environmental consequences associated with sulfur-compliance strategies, particularly the use of exhaust gas cleaning systems (scrubbers) and low-sulfur fuel switching. A major theme emerging from the literature is that compliance measures may shift pollution pathways rather than fully eliminate environmental risks.

(1) Marine Environmental Impacts of Scrubber Washwater

The reviewed literature consistently showed that one of the most important unintended consequences of IMO 2020 is the transfer of pollution from the atmosphere to marine environments through scrubber discharge water. Scrubber effluents contain elevated concentrations of heavy metals, polycyclic aromatic hydrocarbons (PAHs), acidic compounds, and combustion-derived residues that can accumulate in marine ecosystems [20,59,66,71]. In the Baltic Sea, open-loop scrubbers were estimated to contribute approximately 8.5% of total anthracene inputs [20], while integrated modeling studies projected that, under high scrubber-use scenarios, areas where scrubber effluent concentrations exceed the lowest observed effect concentration (LOEC) could expand from the Baltic and North Sea coastal regions to much broader areas across European seas by 2050 [59,68].

Beyond contaminant release, ecotoxicological and mesocosm studies consistently reported adverse biological effects associated with scrubber washwater exposure. Laboratory experiments demonstrated significant reductions in survival, reproduction, and developmental success of marine organisms even at relatively low concentrations [13,60,82]. Representative findings include toxic effects on marine zooplankton communities at washwater concentrations of only 1.5% (*v/v*) [82], a 96-h EC₅₀ of 2.48% for *Dunaliella salina*, and a lowest observed effect concentration (LOEC) of 1.25% for *Mysidopsis bahia* [13]. Chronic toxicity assays further identified adverse effects on fertilization success and larval development at concentrations below 1% (EC₁₀ < 1%) in marine invertebrates [60]. Zooplankton, algae, phytoplankton, and microbial communities were consistently identified as particularly sensitive to contaminant mixtures containing PAHs and heavy metals, with evidence of altered microbial community composition, trophic interactions, and biodiversity following scrubber exposure [81,82,88]. Together, these findings demonstrate that scrubber compliance strategies may reduce atmospheric emissions while simultaneously introducing new risks to marine ecosystems.

(2) Secondary Pollutants and Atmospheric Trade-offs

Another recurring unintended consequence identified across the reviewed studies was the formation of secondary atmospheric pollutants following the transition to sulfur-compliant fuels. Although IMO 2020 substantially reduced SO₂ emissions and sulfate aerosols, several studies reported that low-sulfur fuels may increase emissions of volatile organic compounds (VOCs), intermediate-volatility organic compounds (IVOCs), and secondary organic aerosol (SOA) precursors [50,53,56]. Representative field measurements showed that switching from heavy fuel oil to low-sulfur diesel increased VOC emission factors by approximately 48%, accompanied by enhanced ozone formation potential and SOA formation [72]. Consistent with these findings, regional atmospheric modeling projected a 3.8–4.9% increase in surface ozone concentrations in Southern China despite reductions in primary pollutants, reflecting the nonlinear nature of atmospheric chemistry under low-sulfur fuel conditions [83]. Experimental combustion studies further demonstrated that altered fuel composition and combustion chemistry can sustain or enhance ozone formation potential and secondary aerosol production despite reductions in sulfur-related pollutants [53,56,64,74]. In addition, sulfur-compliant fuels were associated with elevated emissions of aromatic hydrocarbons, including benzene and naphthalene, with naphthalene accounting for approximately 77–97% of total VOC emissions in ship exhaust [72,86].

(3) Climate-Related Trade-offs

Several studies also identified unintended climate-related consequences associated with sulfur emission reductions. Climate-modeling and satellite-observation studies increasingly suggested that IMO 2020 reduced sulfate aerosol concentrations and weakened aerosol–cloud interactions over major shipping corridors [48,67,73,77]. Consequently, positive radiative forcing was estimated to range from $+0.074 \pm 0.005$ to $+0.20 \pm 0.11$ W m^{−2}, across different observationally constrained and modeling-based estimates [67,77]. This

positive radiative forcing was further projected to increase global mean surface temperature by 0.046 ± 0.010 °C during 2020–2029, equivalent to approximately 2–3 years of additional global warming [73]. These findings indicate that sulfur-focused regulations improve air quality while simultaneously reducing the climatic cooling previously provided by anthropogenic sulfate aerosols through weakened aerosol–cloud interactions, including a diminished Twomey effect [73,77].

(4) Operational and Economic Challenges

Operational and economic trade-offs were also discussed in several studies. Experimental ship-based studies indicated that low-sulfur fuels may increase fuel consumption and CO₂ emissions under certain engine and operational conditions [94]. Other studies suggested that scrubbers, while economically beneficial for shipowners, generate substantial environmental externalities and long-term ecological costs [78]. Although fewer studies addressed operational aspects than environmental impacts, the available evidence suggests that compliance strategies may introduce trade-offs between operational efficiency, economic benefits, and broader environmental sustainability.

Overall, the reviewed literature demonstrates that IMO 2020 compliance measures generate complex environmental, climatic, and operational trade-offs extending beyond sulfur reduction alone. While the regulation has substantially improved air quality, persistent concerns remain regarding marine contamination, ecosystem toxicity, secondary atmospheric pollution, and climate feedback mechanisms. These findings underscore the need for integrated multi-pollutant and cross-media approaches to maritime emission management in order to maximize the environmental benefits of future shipping regulations.

4. Discussion

4.1. Overall Implications of IMO 2020

The reviewed evidence indicates that IMO 2020 was consistently associated with substantial reductions in sulfur-related emissions, including sulfur dioxide (SO₂), sulfate aerosols, and particulate matter (PM) concentrations in coastal and port regions. However, because most included studies were observational or modeling-based, these improvements cannot always be attributed solely to IMO 2020, as broader changes in shipping operations, fuel markets, and the ongoing energy transition may also have influenced emission trends. Nevertheless, the consistency of findings across different methodologies and geographic regions supports a meaningful association between IMO 2020 and improved shipping-related air quality [21,79,93,97].

Beyond improvements in air quality, the reviewed evidence suggests that these changes may also contribute to reduced human exposure to shipping-related pollutants, particularly in densely populated coastal and port areas where emissions are concentrated [49,109]. Although the magnitude of these benefits varies across regions and may also reflect concurrent developments in the maritime sector, the findings collectively indicate potential public health gains associated with reduced exposure to sulfur-related pollutants [21,51].

Despite these substantial improvements, emerging evidence indicates that important air-quality and health concerns remain unresolved. Several studies reported that reductions in sulfur emissions were not consistently accompanied by comparable reductions in ultrafine particles, volatile organic compounds (VOCs), and secondary organic aerosols (SOA) [72,85]. In some cases, fuel switching to low-sulfur fuels was associated with increased emissions of certain VOCs and photochemically reactive compounds, potentially contributing to ozone formation and secondary aerosol production [72,83]. Collectively, these findings suggest that future maritime emission policies should adopt broader multi-pollutant and cross-media management strategies that simultaneously address air qual-

ity, marine ecosystems, and climate effects rather than focusing predominantly on sulfur reduction alone.

4.2. Trade-Offs and Policy Challenges

One of the most important findings emerging from this review is the existence of significant environmental trade-offs associated with sulfur-compliance technologies, particularly exhaust gas cleaning systems (scrubbers). Although scrubbers effectively reduce atmospheric SO₂ emissions and allow continued use of high-sulfur heavy fuel oil, many studies reported that these systems transfer pollutants from the atmosphere to marine environments through discharge water rather than eliminating them entirely [13,66,71]. This redistribution of contaminants highlights a key limitation of sulfur-focused regulation and raises concerns regarding cumulative ecological impacts in receiving waters. Several ecotoxicological studies reported that scrubber washwater can impair reproduction, alter microbial communities, reduce biodiversity, and disrupt trophic interactions even at low exposure concentrations [82,88]. These findings raise important policy concerns because current IMO discharge guidelines mainly focus on regulating individual pollutants, while cumulative toxicity and combined ecological effects remain insufficiently addressed.

The reviewed literature also highlights important climate-related trade-offs associated with sulfur reduction policies. Sulfate aerosols emitted from ships historically contributed to atmospheric cooling through aerosol–cloud interactions. Consequently, several climate-modeling and satellite-observation studies reported that IMO 2020 may unintentionally contribute to short-term warming by reducing sulfate-driven cooling effects [67,73,77]. Although reducing sulfur emissions clearly improves air quality and public health, these findings demonstrate the complexity of balancing air pollution mitigation with broader climate mitigation goals.

Another major challenge identified across the literature concerns the persistence of health-relevant pollutants despite sulfur reductions. Several studies reported that low-sulfur fuels and scrubber systems do not fully eliminate ultrafine particles, black carbon, toxic organic compounds, or secondary aerosols [61,74,85]. In several cases, particle toxicity appeared to depend more strongly on chemical composition than on particulate mass alone [61]. These pollutants remain important because of their strong associations with oxidative stress, respiratory and cardiovascular diseases, and secondary aerosol formation. Future maritime regulation should therefore adopt a more holistic approach that considers interactions across environmental and health systems.

4.3. Research Gaps and Future Directions

Despite the growing body of evidence supporting the effectiveness of IMO 2020, several important knowledge gaps remain that limit understanding of its long-term environmental, health, and policy implications.

First, although many studies evaluated changes in air pollutant concentrations and modeled health impacts, relatively few directly investigated observed long-term human health outcomes associated with IMO 2020. Most health-related studies relied on exposure proxies, toxicological indicators, or modeled mortality estimates rather than longitudinal epidemiological evidence [21,51]. Future research should therefore prioritize long-term population-based studies examining chronic exposure to shipping-related pollutants in coastal communities.

Second, much of the current literature remains geographically concentrated in East Asia, Europe, and major port cities. Comparatively limited evidence is available for developing countries, smaller coastal communities, and understudied coastal regions. This geographical imbalance limits understanding of how IMO 2020 may affect areas with dif-

ferent shipping intensities, regulatory capacities, socioeconomic conditions, and environmental characteristics. Broader geographical coverage is therefore needed to improve the global representativeness of future research.

Third, the literature demonstrates a need for more integrated interdisciplinary approaches. Most studies examined atmospheric pollution, marine pollution, climate effects, or health impacts within relatively separate disciplinary frameworks. However, the findings of this review suggest that shipping emissions generate interconnected cross-media impacts involving air quality, marine ecosystems, climate processes, and human health through complex interacting pathways. Future research would therefore benefit from integrated frameworks combining atmospheric chemistry, marine ecology, toxicology, climate science, and public health methodologies.

Finally, additional research is needed regarding the long-term environmental and ecological consequences of scrubber technologies and alternative marine fuels. Although several studies identified ecological risks associated with scrubber discharge, substantial uncertainties remain regarding cumulative pollutant accumulation, long-term ecosystem recovery, and environmentally realistic exposure conditions. Further investigation into cleaner fuel alternatives, emission-control technologies, and integrated regulatory strategies will therefore be important for supporting sustainable maritime decarbonization and pollution mitigation.

4.4. Limitations of the Review

Several limitations should also be acknowledged in this review. First, the review included only English-language publications, which may have excluded relevant studies published in other languages. Second, the reviewed studies employed highly heterogeneous methodologies, including atmospheric modeling, laboratory experiments, field measurements, toxicological assessments, and scenario analyses, which complicated direct comparison across findings. Third, many studies focused on short-term environmental and health responses and region-specific case studies, limiting the broader generalizability of the findings. Finally, because IMO 2020 is still relatively recent, evidence regarding long-term environmental and health impacts remains limited.

5. Conclusions

This systematic review synthesized evidence from 67 studies examining the environmental and health implications of shipping emissions under the IMO 2020 standards. Through the integration of bibliometric and thematic analyses, the review provides a comprehensive synthesis of emerging evidence and provides a comprehensive synthesis of current evidence to inform future maritime emission governance.

Overall, the reviewed evidence indicates that IMO 2020 has been associated with substantial improvements in shipping-related air quality across many maritime regions. However, the findings also demonstrate that the environmental and public health implications of shipping emissions extend beyond sulfur control alone, highlighting important trade-offs involving atmospheric chemistry, marine ecosystems, and climate processes.

Taken together, these findings suggest that IMO 2020 represents an important milestone in international maritime emission regulation, while also underscoring the need for more integrated approaches to maritime environmental management. Future policies should therefore complement sulfur reduction with broader multi-pollutant and cross-media strategies that consider the interconnected impacts of shipping on air quality, marine ecosystems, climate, and human health. Continued interdisciplinary research will be essential to strengthen the evidence base for adaptive and sustainable maritime environmental governance.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/atmos17080715/s1>, Table S1: Extracted Characteristics of the Included Studies Used for Evidence Synthesis

Author Contributions: Conceptualization, T.Z. and L.T.N.; methodology, T.Z. and L.T.N.; validation, Y.L., Y.M. and M.C.; formal analysis, T.Z. and L.T.N.; investigation, T.Z. and L.T.N.; data curation, Y.L., Y.M. and L.T.N.; writing—original draft preparation, T.Z. and L.T.N.; writing—review and editing, L.T.N. and M.C.; visualization, T.Z. and L.T.N.; supervision, M.C.; project administration, M.C.; funding acquisition, T.Z. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

IMO	International Maritime Organization
SLR	Systematic Literature Review
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AIS	Automatic Identification System
AOD	Aerosol Optical Depth
BC	Black Carbon
CH ₄	Methane
CO ₂	Carbon Dioxide
ECA	Emission Control Area
EGCS	Exhaust Gas Cleaning System
GHGs	Greenhouse Gases
HFO	Heavy Fuel Oil
IVOCs	Intermediate-Volatility Organic Compounds
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
NECA	Nitrogen Emission Control Area
NMVOCs	Non-Methane Volatile Organic Compounds
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxides
O ₃	Ozone
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PM ₁	Particulate Matter with Aerodynamic Diameter ≤ 1 µm
PM _{2.5}	Particulate Matter with Aerodynamic Diameter ≤ 2.5 µm
PM ₁₀	Particulate Matter with Aerodynamic Diameter ≤ 10 µm
SO ₂	Sulfur Dioxide
SOA	Secondary Organic Aerosol
SO _x	Sulfur Oxides
ROS	Reactive Oxygen Species
SCR	Selective Catalytic Reduction
UFPs	Ultrafine Particles
VLSFO	Very-Low-Sulfur Fuel Oil

VOCs	Volatile Organic Compounds
WHO	World Health Organization
Ni	Nickel
V	Vanadium
Pb	Lead
Zn	Zinc
Cu	Copper
PMF	Positive Matrix Factorization
XRF	X-Ray Fluorescence

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