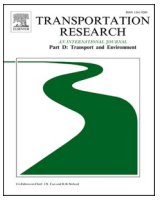
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Port environmental health Risks: Insights from the Tarragona Port-Industrial complex and planning implications

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ABSTRACT

Ports handle approximately 80% of world trade and concentrate vessels, cargo operations, and logistics that generate substantial pollution affecting nearby populations. Following a structured literature search and a narrative synthesis organized around a source-to-exposure-to-impact conceptual framework, this review evaluates the health risks associated with residential proximity to ports. Evidence consistently links port-related emissions to cardiovascular and respiratory mortality, asthma, lung cancer, adverse pregnancy outcomes, and neurodevelopmental effects. The Tarragona Port is used as an illustrative example of a complex port-industrial setting in which port and co-located petrochemical emissions jointly contribute to a quantified local burden of preventable deaths and disability-adjusted life years, although the fraction attributable to port activities alone cannot be readily isolated from that of the adjacent petrochemical complex and other urban sources. These findings support targeted interventions, including mandatory Health Impact Assessments, health-based buffer zones, optimized freight routing, and real-time air quality monitoring integrated into port operations.

1. Introduction

1.1. The global Port-City Nexus and public health Imperative

Ports are indispensable catalysts of the global economy, facilitating approximately 80% of world trade by volume (United Nations Trade & Development, 2025). Their strategic coastal locations have historically promoted metropolitan growth, creating significant confluence of population and heavy industry. Around 40% of the world's population lived within 100 km of a coast (Small and Nicholls, 2003), with substantial proportions residing in urban agglomerations surrounding major harbors. This spatial juxtaposition creates a critical public health paradox: ports generate immense economic value and employment, while simultaneously functioning as concentrated pollution hotspots degrading local environmental quality (Sorte et al., 2020).

The environmental footprint of port operations is multifaceted, impacting air, water, and soil, with airborne emissions representing the most pervasive and well-documented exposure pathway (Santos, 2025; Viana et al., 2014). Maritime vessels, particularly those burning heavy fuel oil, emit substantial quantities of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide, volatile organic compounds (VOCs), as well as other toxic contaminants including polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Agrawal et al., 2008; Eyring et al., 2010). These pollutants are emitted from ship stacks while ships are

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docked, maneuvering, and in transit, with the highest concentrations typically occurring in downwind coastal areas (Viana et al., 2014). Beyond maritime emissions, port-related air pollution encompasses diesel exhaust from cargo-handling equipment, heavy-duty trucks servicing terminals, fugitive dust from bulk material handling (coal, ores, grain), and emissions from co-located industrial facilities such as refineries and power plants (Cooper and Gustafsson, 2004; Lack et al., 2011).

1.2. Evolution of the scientific and regulatory Landscape

In the 20th century, health impacts of port activities were largely overlooked or subsumed within the assessment of general urban air pollution. Corbett et al. (2007) reported the first global estimate of mortality attributable to ship emissions. Subsequent research has progressively evolved from global-scale modeling to high-resolution, local-scale assessments capturing steep exposure gradients experienced by communities within the first few kilometers of port boundaries (Liu et al., 2016; Winther et al., 2014).

Concurrently, major regulatory milestones have been adopted. The implementation of Sulfur Emission Control Areas (SECAs) in North America and Europe, followed by the landmark 2020 global cap of 0.5% sulfur in marine fuels (IMO, 2020), represent large-scale natural experiments stimulating robust research evaluating air quality and health improvements at community levels.

1.3. Objectives

This literature review is focused on seven primary objectives: (1) to systematically catalog emission sources and chemical complexity of port pollution, (2) to review and critique exposure assessment methodologies, (3) to synthesize epidemiological, toxicological, and health risk assessment evidence by disease category, (4) to provide an integrative illustrative synthesis for the Tarragona port-industrial complex (Catalonia, NE Spain), examining source-to-exposure-to-impact pathways, (5) to evaluate mitigation strategies through a public health lens, and (6) to identify critical knowledge gaps and propose a research agenda. A seventh objective, directly responsive to the imperatives of transportation science, is to translate the consolidated health and exposure evidence into concrete, actionable recommendations for port planning, design, and environmental management, informing the design, operation, and governance of transport infrastructure in a manner that explicitly protects population health.

Fig. 1 shows the integrated pathway framework which conceptualizes the complex relationships between port activities, environmental contamination, and human health.

To operationalize this objective within a transportation systems perspective, Fig. 2 presents a conceptual framework linking port activities and freight logistics to emissions, community exposure, health outcomes, and the corresponding planning and management interventions.

Recently, various dimensions of the relationship between port activities and public health have been examined. Mueller et al. (2023) carried out a global scoping review on health impact assessments related to air pollution originating from shipping and port operations. Their analysis included several studies, mostly conducted in Europe, and mainly focused on mortality effects and the evaluation of emission control measures such as sulfur content limits and nitrogen oxide (NO_x) reductions. In turn, Ducruet et al. (2024) investigated data from close to 5,000 ports across 35 OECD countries, identifying statistical relationships between port activity levels, ambient air quality indicators, and health outcomes within three distinct categories of port regions. Although both studies made significant advances for the understanding in the field, each addressed only specific aspects of the port–health linkage.

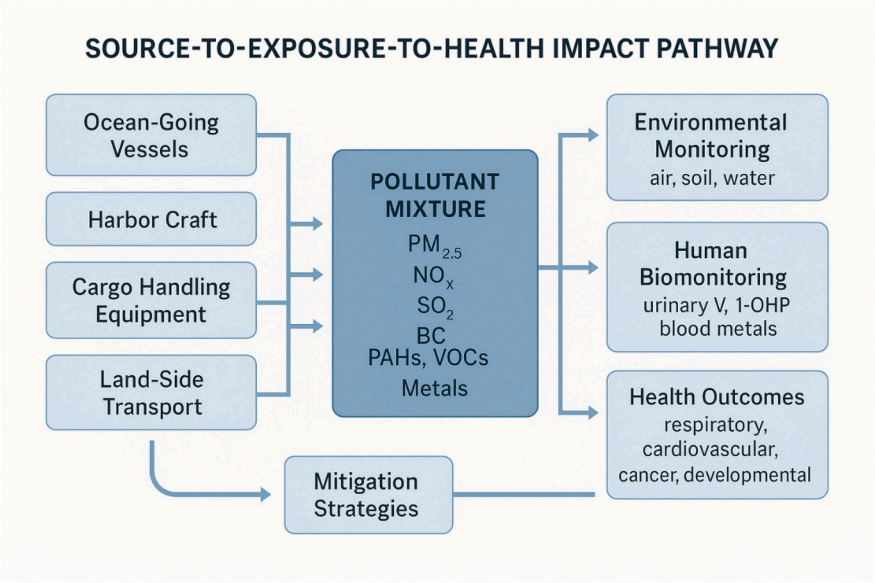


Fig. 1. Integrated source–to–exposure–to–health impact framework for port-related environmental pollution.

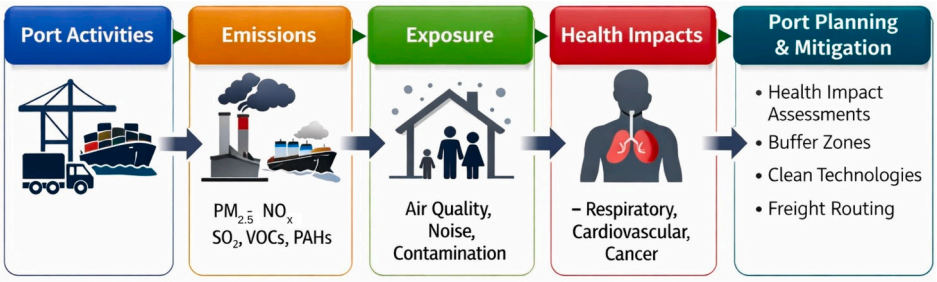


Fig. 2. Conceptual framework linking port-related transport activities to environmental emissions, population exposure, health impacts, and planning/management interventions.

The present review seeks to broaden and integrate those perspectives in three distinctive ways that, to our knowledge, have not previously been combined within one analytical framework. First, it employs a comprehensive source–to–exposure–to–impact approach that connects emission characterization with exposure assessment, epidemiological evidence across multiple outcomes, and evaluation of mitigation strategies in a single coherent structure. Second, it includes research published after 2022, encompassing new empirical findings on post–IMO 2020 fuel transitions, the environmental implications of exhaust–gas cleaning systems, and the evolving chemical composition of emissions from very–low–sulfur fuel oils, evidence that is not available in previous reviews (Ducruet et al., 2024; Mueller et al., 2023, 2024). Third, it provides a detailed, multi–decadal case study of Tarragona Port and its neighboring petrochemical hub, which uniquely integrates local data on emission sources, human biomonitoring, quantified health burdens, environmental equity considerations, and community perceptions. Collectively, these aspects aim to translate global evidence into actionable insights for regional and municipal port governance.

2. Methods: Literature search strategy and synthesis approach

2.1. Information sources and search strategy

For a systematic search of the scientific literature the databases PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar (January 2000–January 2026) were used. The core search string comprised four conceptual blocks: (1) Setting: (“port*” OR “harbor*” OR “harbour*” OR “maritime” OR “shipping” OR “dock*”) AND (“city” OR “urban” OR “coastal” OR “community”); (2) Exposure/Pollutant: (“air pollution” OR “particulate matter” OR “PM2.5″ OR ”PM10″ OR “ultrafine particle*” OR “black carbon” OR “NOx” OR “SO2″ OR ”polycyclic aromatic hydrocarbon*“ OR ”PAH“ OR ”heavy metal*“ OR ”volatile organic compound*“ OR ”VOC“ OR ”noise“); (3) Health Outcome: (”public health“ OR ”health risk*“ OR ”mortality“ OR ”morbidity“ OR ”cardiovascular disease“ OR ”respiratory disease“ OR ”asthma“ OR ”COPD“ OR ”lung cancer“ OR ”epidemiology“); (4) Study Type: (”review“ OR ”meta-analysis“ OR ”systematic review“ NOT ”greenhouse gas*“ NOT ”climate change“). Specific targeted searches for Tarragona included: ”Tarragona“ AND (”harbor“ OR ”port“) AND (”air quality“ OR ”pollution“ OR ”health“). To support the seventh objective, translating health evidence into port planning and policy recommendations, a fifth conceptual block was added to the search: (5) Planning/Policy: (”port planning“ OR ”port design“ OR ”port masterplan*“ OR ”green port“ OR ”onshore power supply“ OR ”cold ironing“ OR ”buffer zone*“ OR ”land use“ OR ”freight corridor*“ OR ”drayage“ OR ”health impact assessment“ OR ”environmental impact assessment“ OR ”port governance“ OR ”port sustainability“) AND (”port*“ OR ”harbor*“ OR ”harbor*“). Additional targeted searches were conducted in the Transport Research International Documentation (TRID) database and Google Scholar for grey literature on port environmental management plans, national and regional port planning guidance documents, and Health Impact Assessment frameworks applied to transport infrastructure.

2.2. Eligibility criteria

Original research, comprehensive reviews, systematic reviews, and *meta*-analyses in peer-reviewed journals were included, as well as studies focusing on pollution attributable to port/harbor activities; measurements in port-adjacent residential areas, exposure modeling, biomonitoring, epidemiological analysis, or quantitative health risk assessment. By contrast, studies exclusively focused on greenhouse gas emissions/climate change without direct health co-benefits linkages were excluded, as well as open-ocean shipping without near-port community exposure assessment, technical reports on port engineering/logistics/economics without primary environmental or health data, and non-peer-reviewed literature, commentaries, editorials, and conference abstracts without full data. For the port planning and policy synthesis, the eligibility criteria were extended to include: peer-reviewed studies and authoritative policy documents evaluating port planning instruments, environmental management systems, Health Impact Assessment methodologies applied to transport or port infrastructure, buffer zone and land-use separation standards, freight corridor routing assessments, and Green Port certification and governance frameworks. Technical reports from recognized international bodies (IMO, ESPO, PIANC, WHO, US EPA, European Commission) were also considered when directly relevant to health-protective port planning.

Data were extracted using standardized templates capturing: authors, year, location, design, pollutants/exposures, assessment

methods, health endpoints, key findings, and limitations. Given significant heterogeneity in study designs, locations, exposures, and outcomes, a formal *meta*-analysis was not feasible. A narrative synthesis approach was adopted, organizing evidence thematically, and assessing strength qualitatively based on volume, consistency, methodological quality, and biological plausibility.

Publications identified through database searches were screened in two stages. First, titles and abstracts were evaluated against eligibility criteria to exclude clearly irrelevant studies (e.g., those focused solely on climate outcomes, open-ocean shipping without community exposure, or purely technical/economic analyses). Full texts of potentially relevant articles were then assessed, with additional studies identified through backward and forward citation tracking. This work constitutes a narrative, not systematic, review. Accordingly, the search process was iterative and not designed to produce exhaustive record counts or a PRISMA flow diagram. Consequently, precise numbers of retrieved, screened, and excluded records were not systematically documented. The final body of evidence corresponds to the studies cited in Sections 3–5 and included in the list of references, representing those considered most relevant and methodologically informative.

Given the heterogeneity of study designs, no formal risk-of-bias tool was applied. Instead, methodological quality was evaluated qualitatively based on study design, exposure assessment rigor, confounder control (notably smoking, socioeconomic status, and co-exposures), sample size and statistical precision, and the validity of source-apportionment methods where applicable. Greater weight was assigned to findings replicated across settings and consistent with established biological mechanisms. Evidence strength ratings reflect the overall convergence of these factors rather than a quantitative scoring system.

2.3. Translation of health evidence into port planning recommendations

Translating health and exposure evidence into planning and policy recommendations have followed a structured evidence-to-action mapping process. For each planning domain identified (master planning and environmental impact assessment, buffer zones and land-use separation, freight corridor management, green port infrastructure design, and real-time monitoring) four steps were applied: (a) relevant health and exposure evidence was assembled from the narrative synthesis, (b) the mechanistic pathway linking each planning decision to the reported health burden was articulated, (c) existing planning instruments, regulatory frameworks, and case examples were identified from the planning/policy literature, and (d) recommendations were formulated at the level of specificity appropriate for port planning authorities or transport regulators, with explicit linkage to the supporting evidence. This approach is consistent with the established Health Impact Assessment methodology (Nieuwenhuijsen et al., 2017a) and evidence-to-policy translation frameworks in urban transport health research (Mueller et al., 2017; Iungman et al., 2021).

3. Results and discussion

3.1. Sources and chemical Signatures of Port-Related emissions

3.1.1. Ocean-Going Vessels: Dominant contributors and evolving profiles

Combustion of marine fuels in main and auxiliary engines has been the primary source of SO_2 and major source of NO_x and primary PM in coastal areas (Nguyen et al., 2021; Yu et al., 2025). The chemical signature of traditional heavy fuel oil (HFO) exhaust is characterized by high sulfate content and two trace metals (i.e., vanadium (V) and nickel (Ni)), serving as robust tracers for ship emissions (Pandolfi et al., 2011; Viana et al., 2008).

The IMO 2020 global sulfur cap has meant major fuel transitions to very low sulfur fuel oils and marine gas oil. While dramatically reducing ambient SO_2, recent research indicates altered physicochemical properties of ship-derived PM, potentially increasing relative contributions of organic carbon and black carbon with uncertain health implications (Chu Van et al., 2019; Shi et al., 2025). Exhaust gas cleaning systems (“scrubbers”), particularly open-loop systems, are controversial due to pollution transfer from air to water (Hassellöv et al., 2013; Stathatou et al., 2025).

Table 1
Primary Emission Sources in Port Areas and Their Characteristic Pollutant Profiles.

Source Category	Sub-Sources	Primary Pollutants	Characteristic Chemical Tracers/ Signatures
Ocean-Going Vessels	Main and auxiliary engines, boilers	SO_2, NO_x, $PM_{2.5}$ (SO_4, Black Carbon, OC), CO_2, CO, Hydrocarbon	V, Ni; High sulfate; Specific organic markers
Harbor Craft	Tugs, ferries, pilot boats, fishing vessels	NO_x, PM, CO	Often higher PM/NO_x per kWh than large vessels; Localized impact
Cargo Handling	Bulk material transfer (coal, ore, grain)	Fugitive PM_{10}, $PM_{2.5}$ (dust)	Si, Al, Fe, Mn, As (cargo-specific); Crystalline silica; Adsorbed PAHs
Diesel-powered cargo handling equipment		NO_x, $PM_{2.5}$ (Black Carbon, DPM), CO, Hydrocarbon	Black carbon; Diesel exhaust markers
Tanker loading/ballasting		VOCs (e.g., benzene, toluene, xylene)	Specific hydrocarbon ratios (e.g., BTEX)
Land-Side Transport	Heavy-duty diesel trucks (HDDT)	NO_x (dominant), $PM_{2.5}$, Black Carbon, CO	Major source of near-road NO_x in port communities
Locomotives		NO_x, PM, CO, Hydrocarbon	Line-source emissions along rail corridors
Co-located Industry	Refineries, power plants, chemical plants	SO_2, NO_x, PM, VOCs, Hazardous Air Pollutants (HAPs: benzene, 1,3-butadiene, etc.)	Industry-specific chemical profiles (e.g., specific VOCs, metals)

3.1.2. Harbor Craft and In-Port vessels

Tugboats, pilot boats, ferries, and commercial fishing vessels often use older diesel engines with weaker emission controls, adding a large share of the pollution released in ports. Because they frequently speed up, slow down, and stay stopped near the coast, these vessels can release more NO_x and PM per unit of activity than many other ships (Jayaram et al., 2011; Jonson et al., 2015).

3.1.3. Cargo handling Operations: Fugitive dust and diesel combustion

Handling of dry bulk materials in ports is a major source of fugitive PM_{10}, while $PM_{2·5}$ in port areas is frequently enriched in toxic metals such as chromium-VI (Cr-VI), manganese (Mn), zinc (Zn) and arsenic (As), conferring non–negligible carcinogenic and non-–carcinogenic risks (Pongpiachan et al., 2025). The extensive fleet of diesel-powered cargo handling equipment emits significant quantities of NO_x and diesel particulate matter (DPM), a known human carcinogen (IARC, 2014).

3.1.4. Land-Side Heavy-Duty Vehicle traffic and logistics

Drayage trucks (heavy-duty diesel vehicles) moving containers to and from port terminals constitute critical mobile source lines. These vehicles are major emitters of NO_x and primary $PM_{2·5}$ (including black carbon) along designated freight corridors, creating "pollution highways" traversing adjacent residential neighborhoods (Hatzopoulou et al., 2011; Ramirez-Ibarra and Saphores, 2023). Table 1 summarizes the primary emission sources in port areas, their characteristic pollutant profiles, and typical emission factors. Comparative emission inventory data from major international ports demonstrate the substantial variation in pollutant loadings attributable to differences in cargo throughput, fleet composition, fuel types, and regulatory frameworks (Table 2).

3.1.5. Noise and marine discharges as additional port stressors

Beyond airborne pollutants, port activities also generate substantial environmental noise and marine discharges. These two additional stressors are addressed in Section 3.4 due to their human-health and ecological implications. Noise arises from ship engines and auxiliary systems, cargo-handling operations, drayage trucks, rail traffic, and foghorns, and can extend into nearby residential areas. Contamination of water and sediments results from fuel-related spills, ballast-water releases, antifouling paint leachates (notably tributyltin and copper), and the accumulation of metals, PAHs, and persistent organic pollutants in port sediments (de Castro et al., 2017; Turner, 2010). Consideration of these stressors alongside atmospheric emissions is essential to the multi-media, multi-pathway framework adopted in this review.

3.2. Co-located industrial complexes

Many major ports are integrated with heavy industries: petroleum refineries, petrochemical plants, power stations, and metal processing facilities. These point sources emit complex suites of criteria pollutants (SO_2, NO_x, PM) and hazardous air pollutants including benzene, 1,3-butadiene, formaldehyde, and other VOCs (Ducruet et al., 2024; Tsai et al., 2024). Although separating the health impacts that are specifically due to port activities from those caused by nearby industries is methodologically challenging, it is essential for accurate risk attribution.

Separating port and industrial contributions relies mainly on receptor-based source-apportionment of chemically specified particulate matter. Techniques such as Positive Matrix Factorization and Chemical Mass Balance identify source profiles using characteristic tracers (e.g., vanadium and nickel for fuel–oil combustion; crustal elements for coal handling; BTEX for petrochemical activity), often combined with wind analysis, dispersion modelling, and multi-site data. Nonetheless, collinearity among co-located sources under similar meteorological conditions limits precise attribution, making results model- and site-dependent. From a health perspective, populations in port-industrial areas are exposed to complex pollutant mixtures. However, most studies assess pollutants individually, potentially underestimating combined effects. Accordingly, this review considers such environments as integrated systems (e.g., Tarragona) rather than attempting to isolate port-specific impacts and acknowledges these attribution constraints as a limitation.

Table 2
Comparative Emission Inventory Data from Major International Ports (2017–2023).

Port/Region	Year	OGV NO_x (tons)	OGV $PM_{2·5}$ (tons)	Harbor Craft NO_x (tons)	Cargo Handling NO_x (tons)	Drayage Trucks NO_x (tons)	Total NO_x (tons)	Key Notes
Port of Oakland, USA	2020	1,461.9	17.3	156.0	195.9	89.3	2,158.5	Cruise lay berths included; COVID-19 reduced cruise operations
Port of Houston, USA	2023	1,372	54.7	NR	NR	198.9	2,404.9	32% cargo increase vs. 2019; truck VMT + 32%
Port of Los Angeles/Long Beach, USA	2017	2,344.6	45.9	161.7	173.0	79.9	2,786.6	Pre-IMO 2020 baseline; CHE electrification since
Baltic Sea SECA Region	2020	NR	NR	NR	NR	NR	NR	0.1% sulfur limit; 50–70% SO_2 reduction

Note: NR = Not Reported in comparable format. OGV = Ocean-Going Vessels. Data compiled from Port of Oakland (2020), Port of Houston (2023), and Puget Sound Maritime Air Forum (2016) emission inventories.

3.3. Assessing exposure in Port-Adjacent Communities: Methodologies and challenges

3.3.1. Environmental monitoring strategies

Regulatory air quality networks are often too sparse to capture sharp concentration gradients near ports. Dedicated research-grade stations deployed strategically at 0.5–3 km from port boundaries measure criteria pollutants plus advanced metrics: particle number concentration of ultrafine particles (UFP), black carbon, and speciated PM for source apportionment (Barregård et al., 2019; Huber et al., 2025). Van-based mobile laboratories with high-time-resolution instruments are able to map spatial variability and to identify hotspots (Viana et al., 2014). Miniaturized wearable sensors for UFP and black carbon enable personal exposure assessment, capturing individual activity patterns and microenvironments (de Nazelle et al., 2017). Low-cost sensor networks offer denser spatial monitoring, though data quality assurance remains challenging (Castell et al., 2017). Ground-based techniques including Differential Optical Absorption Spectroscopy (DOAS) and MAX-DOAS map NO_2 and SO_2 plumes from individual ships and terminals (Berg et al., 2012). In turn, satellite observations (e.g., TROPOMI) provide synoptic views of NO_2 columns over major shipping lanes and port regions (Georgoulias et al., 2020).

3.3.2. Modeling exposure for epidemiological and risk assessment studies

Computer models are used to see how pollution from ports spreads and changes in the air. These models combine detailed data on ship emissions with weather and air-flow information to estimate how much ports add to city and regional air pollution and to test potentially different policy- or traffic-scenarios (Aksoyoglu et al., 2016; Brandt et al., 2013). Gaussian plume models (AERMOD) or Computational Fluid Dynamics (CFD) models simulate pollutant dispersion in complex building and terrain environments, essential for understanding street-level concentrations and exposure inequities (Fernández-Pacheco et al., 2023). On the other hand, developed from dedicated short-term monitoring campaigns, LUR models use geographic predictor variables (traffic, land use, population density, distance to port) to predict intra-urban spatial variation of NO_2, $PM_{2.5}$, and UFP. These are powerful tools for assigning exposure estimates to participant residences in large cohort studies (Eeftens et al., 2016; Wang et al., 2014).

3.3.3. Biomarkers of exposure and internal dose

While ambient monitoring estimates external exposure, biomonitoring provides direct evidence of internal dose integrating all exposure routes and individual pharmacokinetics. Thus, elevated urinary and blood V and Ni in port workers and residents in the neighborhood serve as biomarkers of fuel oil combustion exposure (Spada et al., 2018), while urinary 1-hydroxypyrene (1-OHP) reflects recent exposure to pyrene, a common PAH in combustion emissions like shipping (Buratti et al., 2000; Mari et al., 2009). Moreover, detection and quantification of black carbon particles in induced sputum or bronchoalveolar lavage fluid provide direct, lung-deposited evidence of inhalation of combustion-derived particulate matter (Bai et al., 2015).

Table 3
Synthesis of Health Outcomes Associated with Port-Related Pollution and Strength of Evidence.

Health Outcome Category	Specific Endpoints	Key Pollutants Implicated	Strength of Epidemiological Evidence	References
Mortality	All-cause, cardiopulmonary, lung cancer	$PM_{2.5}$ (especially secondary aerosols), NO_2, SO_2	Strong / Consistent	Corbett et al. (2007); Sofiev et al. (2018); Nunes et al. (2021); Ducruet et al. (2024); Lin et al. (2018); Brunekreef et al. (2009)
Cardiovascular Disease	Ischemic heart disease, heart failure, stroke, hypertension	$PM_{2.5}$, UFP, Black Carbon, NO_2	Strong	Brook et al. (2010); Barregård et al. (2019); Shah et al. (2015); Miller et al. (2012); Newman et al. (2020); Sagaro et al. (2023)
Respiratory Disease – Asthma	Incidence, exacerbation	$PM_{2.5}$, DEP, NO_2	Strong	Guarnieri and Balmes (2014); Kim et al. (2004); Singh and Sharma (2025); Brunekreef et al. (2009)
Respiratory Disease, COPD	Incidence, exacerbation, mortality	$PM_{2.5}$, PM_{10}, NO_2	Moderate to Strong	Schikowski et al. (2005); Gauderman et al. (2004); Brunekreef et al. (2009)
Lung Cancer	Incidence, mortality	$PM_{2.5}$-bound PAHs (BaP), DEP, As, Cr (VI)	Strong	IARC (2014, 2016); (Kærlev et al., 2005; 2014); US EPA (2025)
Adverse Birth Outcomes	Preterm birth, low birth weight, SGA	$PM_{2.5}$, PAHs, NO_2	Moderate to Strong (Growing)	Stieb et al. (2012); Shah and Balkhair (2011); Bové et al. (2019)
Neurodevelopmental Effects (Children)	Cognitive deficits, ADHD, autistic traits	UFP, PAHs, $PM_{2.5}$	Moderate (Growing)	Calderón-Garcidueñas et al. (2016); Perera et al. (2009); Vrijheid et al. (2016)
Noise-Related Health Effects	Cardiovascular disease, sleep disturbance, mental health	Noise (Lnight, Lden)	Moderate	Babisch (2011); Münzel et al. (2014); Basner et al. (2014); WHO (2011); Murphy and King (2014)
Environmental Justice / Vulnerable Populations	Socioeconomic disparities, disproportionate exposure	Multiple pollutants	Moderate (Growing)	Pastor et al. (2002); Miraftab (2004); Morello-Frosch et al. (2000); Hajat et al. (2015); O'Neill et al. (2007); Newman et al. (2020); Wu and Batterman (2006)

3.3.4. Major challenges in exposure assessment

Separating port contributions from background urban traffic, residential heating, and other industrial sources remains difficult, although advanced receptor modeling techniques (Positive Matrix Factorization, Chemical Mass Balance) with detailed chemical speciation have improved source resolution (Belis et al., 2013; Pandolfi et al., 2011). Ingestion of soil and household dust contaminated by atmospheric deposition of metals and PAHs, and dermal contact, are important secondary pathways, especially for children exhibiting hand-to-mouth behavior (Granero and Domingo, 2002; Moya and Phillips, 2014). Populations are exposed to dynamic, complex mixtures of pollutants (PM, gases, noise) with potential synergistic or antagonistic health effects. Risk assessments often treat pollutants in isolation, potentially underestimating or misattributing risk (Anenberg et al., 2017; Dominici et al., 2006).

3.4. Health Impacts: A critical synthesis of the evidence

Table 3 shows a summary of health outcomes associated with port-related pollution, categorized by strength of epidemiological evidence and biological plausibility. Mortality and cardiovascular effects are classified as strong due to consistent, biologically plausible associations observed across modelling, epidemiological, and mechanistic studies. In contrast, neurodevelopmental and reproductive outcomes are considered moderate and emerging, as much of the evidence is based on general traffic-related exposures rather than port-specific settings.

Three main limitations should be noted. First, many studies rely on proxy exposure metrics, leading to potential misclassification. Second, the co-location of ports with other emission sources limits attribution to port activities alone. Third, findings are not fully consistent, particularly regarding the relative toxicity of shipping-related $PM_{2.5}$ and the health implications of recent changes in fuel composition. These constraints are reflected in the more cautious evaluation of less developed evidence areas.

3.4.1. All-Cause and Cause-Specific mortality

Corbett et al. (2007) estimated thousands of annual cardiopulmonary and lung cancer deaths globally from shipping PM, although subsequent modeling studies have refined these values. Thus, Sofiev et al. (2018) estimated that cleaner shipping fuels could prevent approximately 137,000 premature deaths globally annually by 2020–2025. In turn, Nunes et al. (2021) attributed over 600 premature deaths per year in the Iberian Peninsula to shipping emissions. A recent global analysis by Ducruet et al. (2024) of 832 ports found robust associations between port activity intensity and elevated local $PM_{2.5}$ and NO_2 levels, key drivers of increased all-cause and cardiovascular mortality.

Cohort and time-series studies in specific port cities (i.e., Rotterdam, Los Angeles, Hong Kong, Ancona, and Guangzhou) have found associations between proxies for port pollution (distance to port, modeled ship emission contributions) and increased daily or long-term mortality rates (Lin et al., 2018; Nieuwenhuijsen et al., 2017b). In Ancona, Italy, long-term exposure to $PM_{2.5}$ and NO_2 near the harbor, was found to be higher and associated with increased natural, cardiovascular, respiratory and lung cancer mortality. The study estimates several dozen premature deaths per year attributable to these pollutants (Mei et al., 2023). In Guangzhou, China, each interquartile range increase in lag-1 shipping emission-derived $PM_{2.5}$ was associated with 4.60% (95% CI: 0.14%, 9.26%) increase in overall cardiovascular mortality and 13.35% (95% CI: 5.54%, 21.75%) increase in cerebrovascular mortality (Lin et al., 2018).

3.4.2. Cardiovascular diseases

Inhaled port-sourced PM, especially UFP and black carbon, can translocate into systemic circulation, inducing systemic oxidative stress and inflammation. This leads to endothelial dysfunction, atherosclerotic plaque destabilization, increased blood pressure, autonomic nervous system imbalance, and pro-thrombotic states (Brook et al., 2010; Miller et al., 2012). Studies in or near major port cities have shown increased hospital admissions and emergency department visits for ischemic heart disease, heart failure, and stroke associated with short-term $PM_{2.5}$ and NO_2 increases (Atkinson et al., 2001; Shah et al., 2015). Baltic Sea region research suggested shipping-derived $PM_{2.5}$ may carry higher myocardial infarction risk per unit mass than urban background $PM_{2.5}$, pointing to a more toxic composition (Barregård et al., 2019). Furthermore, occupational studies on seafarers indicate elevated cardiovascular disease risk (Sagaro et al., 2023).

A spatial health impact assessment in Catalonia revealed that while the Port of Barcelona contributes a small fraction of total city-wide pollutants, it significantly impacts local public health, particularly in southeastern neighborhoods. Specifically, port-sourced emissions accounted for roughly 8% of NO_2-related premature deaths and 1% of PM_{10} fatalities in 2017 (Mueller et al., 2024). These findings highlight the need for targeted urban policies that address specific industrial sources to mitigate localized morbidity and mortality burdens (Mueller et al., 2024). Neighborhoods closest to the port experienced highest mortality burdens, with spatial gradients decreasing toward areas further inland.

3.4.3. Respiratory diseases

Strong evidence has demonstrated that traffic-related air pollution, including port drayage trucks and equipment, contributes to pediatric asthma development and triggers exacerbations in children and adults (Brunekreef et al., 2009; Guarnieri and Balmes, 2014). Port community studies show higher asthma prevalence and medication use (Kim et al., 2004). Diesel exhaust particles are potent immune adjuvants enhancing allergic sensitization and airway inflammation (Singh and Sharma, 2025). Long-term $PM_{2.5}$, PM_{10}, and NO_2 exposure contributes to Chronic Obstructive Pulmonary Disease (COPD) development and progression. Studies carried out in Rotterdam (The Netherlands) and Los Angeles (US) showed accelerated lung function decline and higher COPD mortality in communities downwind of port complexes (Brunekreef et al., 2009; Gauderman et al., 2004; Schikowski et al., 2005). In Ancona, respiratory mortality was 37.9% higher (SMR: 1.38; 95% CI: 1.165–1.631) among residents near the harbor (Mei et al., 2023). The

International Agency for Research on Cancer (IARC) classifies outdoor air pollution and diesel engine exhaust as Group 1 (carcinogenic to humans) (IARC, 2014, 2016). Port emissions contribute to population exposure to particle-bound PAHs (e.g., benzo[a]pyrene), certain metals (As, Cr-VI), and diesel particulate matter. Epidemiological studies performed by Kærlev et al. (2005; 2014) on occupationally exposed populations (seafarers, dockworkers) supported elevated lung cancer risk. National-scale USA air toxics assessments identify port areas as cancer risk hotspots, with approximately 4 million people living where diesel PM confers cancer risk exceeding 100 per million (US EPA, 2025).

3.4.4. Adverse Pregnancy, Birth, and Developmental outcomes

Scientific literature links maternal exposure to traffic-related $PM_{2.5}$, NO_2, and PAHs with increased risks of preterm birth, low birth weight, small for gestational age infants, and congenital anomalies (Shah and Balkhair, 2011; Stieb et al., 2012). Mechanisms include placental inflammation, oxidative stress, endocrine disruption, and impaired nutrient transport (Bové et al., 2019). Moreover, prenatal and early childhood exposure to traffic-related UFP and PAHs is increasingly linked to cognitive deficits, attention-deficit/hyperactivity disorder (ADHD) symptoms, autistic traits, and lower academic achievement (Calderón-Garcidueñas et al., 2016; Perera et al., 2009). While not specific to port emissions, high concentrations in port-adjacent areas raise significant concerns for child development.

3.4.5. Mental and cognitive health impacts of noise and air pollution

The World Health Organization (WHO) estimated that at least one million healthy life years were lost annually in Western Europe due to environmental noise, with transportation sources including shipping representing major contributors (WHO, 2011). Monitoring near Dublin Port showed that night-time noise levels at nearby homes consistently exceeded the WHO night-noise guideline of 40 dB (A), indicating a significant noise problem for local residents (Murphy and King, 2014).

Chronic noise exposure activates the hypothalamic–pituitary–adrenal axis, leading to elevated cortisol, hypertension, and increased cardiovascular disease risk (Babisch, 2011; Münzel et al., 2014). Mental health impacts include sleep disturbance, cognitive impairment in children, increased anxiety and depression, and reduced quality of life (Basner et al., 2014). Port communities experience these burdens alongside air pollution, creating cumulative health risks requiring integrated assessment.

3.4.6. Health risks from waterborne and Seafood-Mediated exposures

Although air pollution dominates the port health literature, the waterborne and marine discharges characterized in Section 3.1 translate into distinct human-health risks that warrant separate consideration. The US New Bedford Harbor Superfund site, contaminated with PCBs from industrial discharges, resulted in fish consumption advisories eliminating traditional fishing activities in affected communities (Bolnick et al., 2023).

Ballast water introduces invasive species and pathogens. Thus, it was reported that introductions of *Vibrio cholerae* through ship ballast contributed to disease outbreaks in South American ports (Ruiz et al., 2000). Sediment contamination with heavy metals, PAHs, and persistent organic pollutants (POPs) accumulates in benthic organisms and biomagnifies through marine food webs, creating human exposure pathways through seafood consumption (Barbieri et al., 2025; Storelli et al., 2011).

3.5. Vulnerable populations and environmental justice

Port-related pollution exposures are not distributed equitably. Children, elderly individuals, pregnant women, people with pre-existing cardiopulmonary conditions, and socioeconomically disadvantaged communities face disproportionate risks (Newman et al., 2020). Children are particularly vulnerable due to higher ventilation rates per body mass, immature immune and metabolic systems, and longer remaining lifespans to manifest chronic disease (Vrijheid et al., 2016).

In the United States, environmental justice analyses have proven that Black and Hispanic populations are significantly over-represented in census tracts with highest port-related diesel PM exposures and cancer risks (Gao et al., 2021: Pastor et al., 2002; Rosenbaum et al., 2011; Wu and Batterman, 2006). These disparities reflect historical residential segregation, zoning decisions placing polluting facilities in minority neighborhoods, and economic constraints limiting housing choices. Port workers, who experience occupational exposure exceeding that of nearby residents, are disproportionately immigrants and people of color in many jurisdictions (Miraftab, 2004; Schnake-Mahl et al., 2021). Addressing port-related health burdens requires explicit environmental justice attention, community engagement, and targeted interventions protecting the most vulnerable. This synthesis treats vulnerability and environmental justice as cross-cutting dimensions of all exposure–outcome pathways. The same uncertainties in source attribution, exposure assessment, and co-located emissions that complicate risk evaluation also influence how burdens are distributed. Therefore, equity considerations should be integrated into exposure assessment, health-impact estimation, and subsequent planning responses, rather than addressed separately.

4. Illustrative synthesis for the Tarragona Port-Industrial complex (Catalonia, NE Spain)

Tarragona Port complex, located in the Spanish Mediterranean coast, is an extensively studied port-industrial area. Decades of multidisciplinary research, notably through projects like HADA (Harbour Area Diffuse Atmospheric emissions), provide comprehensive examination of source-to-exposure-to-impact pathways. Table 4 summarizes the key research findings from Tarragona Port area, organized by study focus and primary outcomes. This complex was selected as an integrative example because it is one of the most extensively studied port-industrial areas in the Mediterranean, with over two decades of research covering source apportionment,

environmental contamination, biomonitoring, health impacts, and social perception. Its close co-location of a major port and petrochemical cluster also makes it representative of the attribution challenges common to many port cities. Notably, it is also the reference port for the Camp de Tarragona area, where the Universitat Rovira i Virgili (URV) is located. This institutional connection, combined with over two decades of local research engagement, provides the authors with unique access to primary literature and contextual understanding that informs this illustrative synthesis. The material here presented is a synthesis of existing studies, not new analyses. Tarragona is used to illustrate processes and approximate magnitudes, and reported findings reflect the broader Camp de Tarragona area rather than impacts attributable solely to port activities. The applicability of these observations to other settings is discussed in Section 4.8.

4.1. Port Characteristics and emission inventory

Tarragona is a multi-purpose port integrated with one of the largest petrochemical clusters in Southern Europe. This co-location creates unique, complex emission profiles: petrochemical industry emitting SO_2, NO_x, VOCs (ethylene, propylene, benzene), dry bulk terminals for major coal imports and cereals, liquid bulk terminals for crude oil and refined products, and general cargo/container traffic. This combination yields pollutant mixes encompassing industrial vapors, ship exhaust, and substantial fugitive dust.

4.2. Environmental contamination and air quality impact

It has been shown that harbor and industrial activities significantly degrade local air quality (Durán-Grados et al., 2022). Harbor sources contributed 7–25% to ambient PM_{10} concentrations in adjacent neighborhoods, with contributions dependent on wind direction and specific industrial activity (Amato et al., 2016). Advanced receptor modeling (PMF) identified key factors: “fuel-oil combustion” (enriched with V and Ni), “coal handling” (rich in Al, Si, Fe, and As), and urban/industrial combustion factors (Viana et al., 2008; Pandolfi et al., 2011). In turn, recent studies have also confirmed elevated presence of UFP in areas influenced by port and petrochemical complex, with significant contributions from industrial nucleation processes and traffic (Ridolfo et al, 2024; Wang et al., 2023).

On the other hand, Rovira et al. (2018) reported significant soil contamination by coal dust in El Serrallo, a neighborhood closest to the coal terminal, with As, lead (Pb) and PAHs showing exponential decay with distance from the source. This provided *clear* evidence of atmospheric deposition as persistent secondary exposure pathway. In February 2017, residents of La Pineda (~3.5 km west-southwest of the harbor) experienced dramatic coal dust contamination blackening buildings, a recurring event affecting ~ 3,000 residents (Rovira et al., 2018). Ambient monitoring has also detected plumes of specific VOCs, notably benzene and toluene, attributable to petrochemical activities. These carcinogenic compounds add significantly to the overall toxic burden (Lee et al., 2025; Domingo et al., 2020).

4.3. Port water quality and oil Spill risk assessment

Mestres et al. (2010) conducted a hydrodynamic modeling study which proved that pollution inside Tarragona Port tended to remain confined due to limited water exchange, while oil spills from the nearby offshore monobuoy would likely affect neighboring beaches. Valdor et al. (2015) developed a comprehensive environmental risk analysis method for oil–handling facilities that combines hazard identification, meteorological and oceanographic characterization, scenario analysis, and probabilistic assessment, thereby supporting both routine monitoring and emergency response planning.

4.4. Human exposure and biomonitoring evidence

Biomarkers of internal dose measured in biomonitoring studies help link environmental contamination with human exposure. For example, numerous investigations have found higher urinary 1–hydroxypyrene in workers occupationally exposed to PAHs, with

Table 4
Synthesis of Key Research Findings from the Tarragona Port Area.

Research Domain	Key Finding	References
Air Quality and Source Apportionment	Harbor/industrial activities contribute substantially to local PM_{10}. Distinct PM sources identified: fuel–oil combustion (V, Ni), coal dust (Al, Si, As, Fe).	Pandolfi et al. (2011); Viana et al. (2008)
Soil/Dust Contamination	Exponential decay of coal-derived As, Pb, and PAHs in soil with distance from coal terminal; evidence of atmospheric deposition.	Rovira et al. (2018)
Water Quality and Oil Spill Risk	Pollution inside harbor tends to remain confined; oil spills from offshore monobuoy could affect neighboring beaches. Integrated risk analysis method developed.	Mestres et al. (2010); Valdor et al. (2015)
Human Biomonitoring	Elevated urinary vanadium and 1-hydroxypyrene in local population vs. controls; higher manganese in children's hair in impacted zone.	Esplugas et al. (2019); Domingo et al. (2020); González et al. (2021)
Health Risk Assessment and Burden of Disease	Reducing $PM_{2.5}$ to WHO guidelines would prevent 23–297 premature deaths annually in Camp de Tarragona; burden of disease approximately 80 DALYs/100,000 population per year.	Rovira et al. (2018, 2020)
Social Perception and Environmental Justice	High environmental risk perception in neighborhoods of port-industrial complex; inequitable burden on lower-SES communities.	Bustamante Picón et al. (2023)

lower but still elevated levels in environmentally exposed populations compared with reference groups (Jongeneelen, 2001). In addition, recent studies on urinary vanadium indicate increased internal exposure in populations living near industrial sources, supporting its use as a biomarker of metal exposure (González et al., 2021). In addition, studies focusing on children have reported higher Mn levels in hair and urine from children in the port-adjacent zone versus control areas, highlighting early-life exposure potential (Esplugas et al., 2019).

4.5. Health risk assessment and burden of disease

Rovira et al. (2020) conducted a comprehensive health impact assessment of air pollution in Camp de Tarragona County (2005–2017), integrating temporal/spatial air quality analysis, population attributable fraction calculations (WHO AirQ + model), and burden of disease quantification (DALYs). These were the key findings: reducing $PM_{2.5}$ to WHO annual guidelines (10 μg/m^3) would prevent 23–297 premature deaths annually (0.5–7% of all mortality in the area), while burden of disease for specific causes (lung cancer, ischemic heart disease, stroke, COPD): 240 DALYs, equivalent to ~ 80 DALYs per 100,000 population annually. While EU air quality standards were generally met, WHO guideline values, health-based rather than politically negotiated, were frequently exceeded. This gap between regulatory compliance and health protection is a recurring issue in port city environmental management.

4.6. Air pollution and COVID-19 in Tarragona Province

During the COVID-19 pandemic, Marquès et al. (2021) investigated associations between air pollution and COVID-19 transmission/mortality. The industrialized/urban area of Camp de Tarragona experienced higher COVID-19 incidence and mortality than the agricultural zones of Terres de l'Ebre (south of Tarragona Province). The authors hypothesized that chronic respiratory system stress from long-term air pollution exposure near the petrochemical complex and port might increase severe COVID-19 risk, with correlations observed between PM_{10} and COVID-19 cases in some municipalities. Nevertheless, it must be noted that COVID-19 is an acute viral infection, not a chronic disease associated with long-term port emissions. The cited findings are ecological and preliminary, focused only on suggesting that pre-existing air pollution can influence susceptibility, not to demonstrate a port-specific effect. Anyway, these results are subject to major confounding and ecological limitations and should be interpreted cautiously.

4.7. Social Perception, risk Communication, and environmental justice

Scientific data on environmental contamination aligns with sociological research on community perceptions. Some studies have shown heightened environmental risk perception and dissatisfaction with local environmental quality among residents of neighborhoods closest to the port-industrial complex (Bustamante Picón et al., 2023; O'Neill et al., 2007). These communities often have lower average socioeconomic status, illustrating environmental justice patterns, where pollution burdens and health risks are disproportionately borne by vulnerable populations (Miraftab, 2004; Pastor et al., 2002), a pattern common in port cities worldwide (Greenberg, 2021).

A 2023 Public Participation Geographic Information Systems (PPGIS) study found residents clearly identified main chemical risk sources on maps and predicted affected areas, demonstrating high spatial awareness of industrial hazards (Bustamante Picón et al., 2023).

4.8. Lessons and Generalizability

Tarragona case offers universal lessons: (1) industrial co-location needs integrated “port-industrial complex” assessment rather than isolated port emission studies, (2) fugitive dust from bulk material handling requires stringent, continuously evaluated engineering controls, (3) multi-media (air, soil, dust, water), multi-pathway (inhalation, ingestion, dermal absorption) assessment is essential, (4) biomonitoring validates exposure models, and (5) environmental justice is a core concern, so research and mitigation should clearly focus on the unequal impacts faced by the most affected communities.

5. Mitigation strategies and assessment of health Co-Benefits

5.1. Technological and Fuel-Based interventions

Onshore Power Supply (OPS, also termed cold ironing) enables vessels to connect to shore-based electricity grids during port calls, eliminating engine exhaust emissions at berth. Health modeling studies indicate that widespread OPS deployment could substantially reduce premature mortality, cardiorespiratory hospital admissions, and asthma exacerbations in port-adjacent communities (Tichavska and Tovar, 2014). However, OPS faces obstacles such as high installation costs, technical compatibility between ships and ports, and the lack of common international standards (Le, 2024).

Transition to liquefied natural gas (LNG), methanol, ammonia, or green hydrogen offers pathways to zero-sulfur and substantially lower NO_x and PM emissions (Brynolf et al., 2014; Gilbert et al., 2018). Life-cycle assessments and near-port health co-benefit studies are active research frontiers, while exhaust Gas Cleaning Systems (scrubbers) are effective at removing SO_2 from ship exhaust, open-loop scrubbers transfer pollution from air to water, creating acidification and contaminant concerns. Their net environmental and health benefit is highly contested (Hassellöv et al., 2013; Stathatou et al., 2025).

The IMO 2020 global fuel sulfur cap (0.5% S, reduced from 3.5%) was projected to prevent approximately 34% of shipping-related premature deaths and 54% of childhood asthma cases compared to pre-regulation scenarios (Sofiev et al., 2018). Even more, stringent 0.1% sulfur limits in Emission Control Areas have dramatically reduced SO_2 and PM emissions in North America and Northern Europe (Johansson et al., 2013). Coastal area fuel controls (0.5% or 0.1% sulfur within 200 nautical miles) could prevent 33,500–43,500 premature deaths annually (Winebrake et al., 2009).

Emerging post-implementation evidence broadly supports the anticipated SO_2 and PM reductions at port level: observational studies have confirmed sharp declines in V and Ni concentrations in port-adjacent $PM_{2.5}$, the characteristic tracers of HFO combustion, following fuel transitions (Moreira et al., 2024), and satellite monitoring has confirmed reduced SO_2 near major shipping routes in European ECAs (Contini and Merico, 2021; Van Roy et al., 2023). However, NO_x emissions have not reduced according to predictions, and they have actually increased in some areas due to limited Tier III NO_x engine compliance, attenuating the cardiovascular and secondary PM health benefits (Van Roy et al., 2023). Post-2020 monitoring in Mediterranean ports further confirms that organic carbon and black carbon now dominate ship-emitted PM, with uncertain but potentially significant toxicological implications (Shi et al., 2025).

5.2. Operational and Logistical measures

Programs that take advantage of the non-linear relationship between speed and fuel use/emissions show measurable local NO_x and PM reductions (Khan et al., 2012; Psaraftis and Lagouvardou, 2023). In turn, electrification (or hydrogen fuel cell conversion) of drayage trucks and cargo handling equipment directly reduces community NO_x and diesel PM exposure along freight corridors. California's Advanced Clean Fleets rule and Zero Emissions 2030 initiatives commit major ports to zero-emission cargo handling by 2030 (California Air Resources Board, 2022).

5.3. Spatial Planning, Policy, and Community-Focused instruments

Creating mandatory buffer zones that prevent new homes, schools, and hospitals from being sited too close to heavy industrial port areas is a key primary prevention strategy (Ontario Ministry of the Environment, Conservation and Parks, 2021). Including port-specific emissions in regional air quality management plans and implementing market-based instruments (emission trading schemes, differentiated port fees based on environmental performance (e.g., the Environmental Ship Index) drive fleet-wide improvements (Miola and Ciuffo, 2011). Moreover, proactive engagement with port-adjacent communities, transparent real-time air quality data sharing, and directing mitigation benefits (green job training, community investment) to most affected neighborhoods are essential for equitable solutions (Ducruet et al., 2024; Hooks, 2024).

5.4. Assessing health Co-Benefits

Evaluating strategy success must be extended beyond emission reductions to quantified health improvements. Integrated modeling frameworks link: Emission Scenario → Atmospheric Dispersion and Chemistry → Population Exposure → Concentration-Response Function → Health Burden (DALYs, premature deaths, cases avoided). Studies applying this framework have consistently shown substantial potential health gains from aggressive port decarbonization, electrification, and operational improvements (Nunes et al., 2021; Sofiev et al., 2018).

As an illustrative exercise, published estimates for Tarragona can be combined under explicit assumptions. Rovira et al. (2020) reported substantial mortality reductions associated with lowering $PM_{2.5}$ to WHO guidelines, while source-apportionment studies attribute a limited share of particulate matter to harbor activities (Amato et al., 2016). A first-order combination suggests that eliminating this harbor-related fraction could yield modest health benefits, although this estimate is highly uncertain and intended only as an approximation. Important limitations include assumptions of linearity, inconsistencies between PM metrics, and the inability to distinguish harbor emissions from other co-located sources. Evidence from Barcelona indicates relatively small port-specific contributions to mortality (Mueller et al., 2024), suggesting the lower end of the estimated range may be more plausible. This calculation is therefore illustrative, and it does not replace a dedicated, source-resolved health-impact assessment.

5.5. Health-Informed port planning and Design: Translating evidence into action

The health and exposure evidence consolidated in this review has direct implications for how ports are planned, designed, expanded, and managed. Established frameworks for integrating health considerations into transport infrastructure planning (Nieuwenhuijsen and Khreis, 2016; Mueller et al., 2017) are directly applicable to the port context. The conceptual framework presented in Fig. 2 illustrates how these planning and management interventions fit within the broader pathway from port activities to population health. The following subsections organize these implications around five planning domains actionable by port authorities, urban planners, transportation agencies, and regulators.

5.5.1. Mandatory health impact assessment in port masterplanning and expansion

Health Impact Assessment (HIA) is a structured, evidence-based process that evaluates the potential health consequences of proposed policies, plans, programs, or projects using quantitative dose–response functions, population exposure estimates, and burden-of-disease metrics such as disability-adjusted life years (DALYs) (Nieuwenhuijsen et al., 2017a). Although HIA has been

extensively applied to urban transport planning scenarios (Mueller et al., 2017; Iungman et al., 2021), its systematic use in port masterplanning and Environmental Impact Assessment (EIA) procedures remains largely absent. The evidence reviewed here, demonstrating that port-adjacent communities bear quantifiable burdens of premature mortality, cardiovascular and respiratory disease, and reproductive harm, provides the scientific substrate that HIA frameworks require. Mandatory pre-authorization HIA, applied to any significant port expansion or new terminal development, would enable planners to: (a) model the incremental health burden of proposed traffic growth and associated freight corridors before construction; (b) compare the health performance of alternative port layout designs, berth configurations, and hinterland access routes; (c) set binding mitigation requirements as conditions of development consent; and (d) establish a pre-construction baseline against which post-implementation monitoring can be compared. The Tarragona case study (Rovira et al., 2020) illustrates the feasibility of such assessments: the finding of 23–297 preventable premature deaths per year could directly inform health-performance thresholds in port planning instruments. A prospective, mandatory HIA framework for port developments would require applicants to model exposure scenarios under different design configurations and demonstrate compliance with health-protective concentration targets aligned with WHO Air Quality Guidelines, not merely with the less stringent legal limits of EU Directive 2008/50/EC.

5.5.2. *Health-Protective buffer zones and Land-Use separation criteria*

Exposure data reviewed in this paper show sharp distance-decay gradients in $PM_{2.5}$, ultrafine particles, and black carbon concentrations extending 1–3 km from port boundaries (Viana et al., 2014). Soil contamination data from Tarragona demonstrate measurable As, Pb, and PAH deposition in neighborhoods within 3.5 km of the coal terminal (Rovira et al., 2018). These findings directly inform land-use separation standards: new sensitive receptors (homes, schools, hospitals, childcare facilities) should not be permitted within scientifically-derived minimum separation distances from port operational areas, berths handling bulk materials, and high-frequency drayage truck corridors. Several jurisdictions have begun formalizing such standards (Ontario Ministry of the Environment, Conservation and Parks, 2021). Nevertheless, a harmonized European framework remains absent. Port buffer zones should not be static one-size-fits-all distances. Rather, they should be scenario-specific, derived from validated Gaussian or Eulerian dispersion models incorporating local meteorology, terrain, and source-specific emission profiles. The Tarragona case, where regulatory EU air quality standards were met yet WHO health-protective guidelines were repeatedly exceeded, illustrates why buffer zone criteria must be anchored to health-based thresholds, not only legally mandated limits.

5.5.3. *Freight corridor planning and drayage route management*

Heavy-duty drayage trucks are among the largest contributors of NOx and primary $PM_{2.5}$ in port-adjacent residential areas (Hatzopoulou et al., 2011; Ramirez-Ibarra and Saphores, 2023). The creation of "pollution highways" through existing neighborhoods is, in a significant part, a planning failure. Thus, freight access routes frequently result from inadequate integration between port masterplans and urban land-use plans. Therefore, port expansion planning must include mandatory freight corridor routing assessments that minimize cumulative residential exposure. This entails: (a) mapping current and projected drayage trip densities on all potential route options using emissions dispersion modeling, (b) quantifying the population health impact of each routing scenario, disaggregated by socioeconomic status to identify environmental justice dimensions, (c) prioritizing routes along existing major arterials with minimal fronting residential use, and (d) where re-routing is not feasible, accelerating electrification of the drayage fleet. In their life-cycle-based systems analysis of the Port of Oakland, Greer et al. (2024) demonstrated that integrating supply chain emissions accounting into port air quality planning substantially changes the ranking of mitigation priorities, with drayage electrification yielding greater per-dollar health benefits than many vessel-side interventions. This type of analysis should become standard practice in port expansion EIAs.

5.5.4. *Real-Time air quality monitoring linked to operational management*

Emerging research on port sustainability (Alamoush et al., 2021; Lam and Notteboom, 2014) highlights Green Port Master planning as a framework that integrates environmental performance into core design principles from project inception. Within this framework, health protection should be addressed as a parallel objective to climate mitigation and biodiversity conservation. This approach implies several design imperatives with direct health co-benefits: (a) integrating Onshore Power Supply (OPS) as standard in new berth designs to reduce air pollution–related morbidity and mortality (Tichavska and Tovar, 2014); (b) optimizing terminal layouts to enhance emission dispersion by locating high-emission berths at greater distances from residential zones and aligning them with prevailing winds; (c) mandating enclosed and covered infrastructure for dry bulk handling to control dust emissions, with performance tied to ambient PM_{10} compliance levels; and (d) embedding multimodal connectivity, rail and inland waterway links, into masterplans to minimize road-based freight traffic and associated exposure along transport corridors (Psaraftis and Lagouvardou, 2023).

Conventional regulatory air quality networks in port areas are often too sparse and lack the temporal resolution needed to capture short-term emission peaks from specific operations, such as vessel berthing or bulk unloading (Huber et al., 2025). Establishing dense, dedicated monitoring systems that combine fixed reference instruments with low-cost sensor arrays around port perimeters would deliver two core benefits: (i) real-time situational awareness supporting adaptive operational management (e.g., pausing bulk handling during PM_{10} exceedances or rescheduling high-emission activities), and (ii) high-resolution spatial datasets for validating and refining dispersion models used in planning. The Tarragona HADA case study (Pandolfi et al., 2011; Viana et al., 2008;) illustrates how robust monitoring can attribute emissions to specific sources, assess community impacts, and inform management decisions. Port authorities should therefore be mandated to implement and publicly disclose perimeter air quality monitoring data, as transparency mechanisms (similar to the Environmental Ship Index) can drive operator accountability and empower affected communities during pollution episodes.

Table 5 synthesizes the principal planning and policy recommendations derived from the health evidence reviewed, organized by planning domain, with indicative implementation instruments and real-world examples. It is intended as an operational reference for port planners, transport agencies, and regulators seeking to embed health-protective criteria in port governance frameworks.

6. Limitations, knowledge Gaps, and conclusions

6.1. Strengths and limitations of the review

This review integrates a broad body of evidence within a source–to–exposure–to–impact framework, incorporates post-IMO 2020 findings, and uses the Tarragona port–industrial complex to illustrate a full causal chain in a well-characterized setting. Its main limitation is that neither the primary studies, nor this synthesis, can clearly separate the effects of port operations from those of co-located petrochemical, traffic, and urban background sources. Therefore, in Tarragona, the environmental and health findings reflect the integrated industrial–port complex rather than port activities alone (Amato et al., 2016; Ducruet et al., 2024; Mueller et al., 2024). Additional limitations include reliance on proxy exposure metrics in many epidemiological studies, the narrative (non-registered) nature of the review without formal *meta*-analysis or risk-of-bias scoring, and the use of published burden-of-disease and source-contribution estimates (e.g., Rovira et al., 2020) that were not recalculated here. Thus, the illustrative scenario in Section 5.4 should be viewed as an order-of-magnitude example rather than an original quantitative assessment, which highlights the need for dedicated, source-resolved monitoring and epidemiological research.

Table 5
Port Planning and Policy Recommendations Derived from Health Evidence.

Planning Domain	Health Evidence Base	Planning/Policy Recommendation	Implementation Examples
Port Masterplanning and EIA	$PM_{2.5}$ exposure in port-adjacent areas associated with 23–297 preventable deaths/year in Camp de Tarragona); port proximity linked to cardiovascular and lung cancer excess mortality (Ducruet et al., 2024; Mei et al., 2023)	Mandate Health Impact Assessment (HIA) as statutory requirement in port expansion EIA; require health performance scenarios for alternative layout designs; set health-based approval thresholds aligned with WHO AQGs	Barcelona port HIA (Mueller et al., 2024); UTOPHIA tool applied to urban transport (Mueller et al., 2017); WHO HIA guidance
Buffer Zones and Land-Use Separation	Distance-decay gradients in UFP and BC extend 1–3 km from port boundaries; soil As, Pb, PAH contamination at 3.5 km from Tarragona coal terminal (Rovira et al., 2018); higher biomonitoring levels in port-adjacent residents (Esplugas et al., 2019)	Establish health-based minimum separation distances between port terminal types (dry bulk, liquid bulk, container) and sensitive receptors (homes, schools, hospitals); anchor criteria to WHO Air Quality Guidelines rather than EU legal limits	Ontario MoECP (2021) land-use compatibility guidelines; California Air Quality and Land Use Handbook; EU SEA Directive application
Freight Corridor Routing and Drayage Management	Drayage trucks create pollution hotspots along freight corridors (Hatzopoulou et al., 2011); life-cycle EJ analysis shows drayage electrification yields highest per-dollar health benefit at Port of Oakland (Greer et al., 2024)	Conduct freight corridor health impact routing assessments; prioritize routes along arterials minimizing residential exposure; require drayage electrification timelines as permit condition; integrate with regional clean truck programs	California CARB Advanced Clean Fleets (2022); Port of Los Angeles Clean Truck Program; Greer et al. (2024) life-cycle planning framework
Green Port Infrastructure Design	OPS eliminates berth emissions and reduces premature mortality and hospital admissions (Tichavska and Tovar, 2014); terminal layout determines proximity of emission sources to residential areas; closed bulk-handling systems reduce fugitive dust	Require OPS capability at all new berths as planning conditions; mandate enclosed conveyor systems and covered stockpiles at dry bulk terminals; orient high-emission berths to maximize distance/wind dispersion from residential areas; incorporate rail/waterway multimodal access	Port of Barcelona OPS + electrification plan; Rotterdam green shipping hub strategy; EU Alternative Fuels Infrastructure Regulation (AFIR) OPS mandates from 2030
Real-Time Monitoring and Operational Triggers	Acute pollution episodes generated by vessel arrivals and bulk operations not captured by sparse regulatory networks; monitoring data from HADA project identified specific port source contributions in Tarragona (Viana et al., 2008)	Require dense perimeter air quality monitoring networks ($PM_{2.5}$, PM_{10}, NO_2, BC) as licence condition; link exceedance thresholds to operational management triggers; mandate public real-time data disclosure via open platforms	Environmental Ship Index (ESI); Green Award scheme; California AB 617 Community Air Monitoring Plans; ESPO EcoPort monitoring standards
Environmental Justice and Community Participation	Lower-SES communities closest to Tarragona port-industrial complex bear disproportionate health burden (Bustamante Picón et al., 2023); racial/ethnic disparities in port diesel PM exposure (Pastor et al., 2002; Wu and Batterman, 2006)	Require EJ analysis in port planning consent procedures; use PPGIS for community exposure mapping; direct green job investment and monitoring resources to most-affected neighborhoods; adopt tiered mitigation requirements targeting highest-exposure communities	California AB 617 (2017); PPGIS study Camp de Tarragona (Bustamante Picón et al., 2023); US EPA Environmental Justice screening (EJScreen); West Oakland Community Action Plan

Note: OPS = Onshore Power Supply; HIA = Health Impact Assessment; EIA = Environmental Impact Assessment; EJ = Environmental Justice; ESI = Environmental Ship Index; WHO AQG = WHO Air Quality Guidelines; PPGIS = Public Participation Geographic Information System; BC = Black Carbon; UFP = Ultrafine Particles.

6.2. Knowledge gaps and future research Directions

Despite there have been significant advances in recent years, existing persistent gaps still must guide future research.

A major lack of targeted, long-term cohort studies in people living near ports makes it difficult to draw firm causal conclusions about chronic diseases (such as dementia, diabetes, and site–specific cancers) or to evaluate impacts across the life course, whereas long-term health implications of PM and emissions from post-2020 VLSFO blends, scrubber wash water, and alternative fuels (methanol combustion products) require urgent investigation.

Research must move beyond single-pollutant models to understand combined health effects of complex, dynamic mixtures (PM of varying sizes/composition, gases, metals, noise, psychosocial stress) in port areas. Systems biology and multi-omics approaches may prove valuable. To date, most research and stringent regulation have been focused on high-income country ports. Health impacts, exposure patterns, and effective mitigation strategies in rapidly growing port cities of Asia, Africa, and Latin America are critically understudied (Ducruet et al., 2024; Hajat et al., 2015).

Robust, independent evaluations of actual air quality and health improvements from IMO 2020, ECAs, and local green port programs using monitoring and health surveillance data are needed, while holistic assessments, considering combined exposures via air, soil, water, and noise in port communities, are necessary for complete risk pictures.

For advancing exposure science, new technologies (low-cost sensor networks, satellite remote sensing, AI/ML for source attribution) for high-spatiotemporal-resolution exposure assessment, and further biomarker development for emerging contaminants, should be used. Future research should be interdisciplinary and collaborative, explicitly focused on protecting health, co-designed with affected communities, and clearly communicated to guide policy and strengthen community advocacy.

In transport planning and port design, important knowledge gaps remain when integrating health into port development. First, standardized methodologies for including Health Impact Assessments in port expansion Environmental Impact Assessments are missing, even though urban transport HIA tools exist, their adaptation to ports −which combine maritime, land-based, and industrial emissions- has not been systematically explored yet. Second, no port-specific guidelines for minimum buffer zones are established in European or international regulations, despite available evidence. Third, the real-world health benefits of Green Port certification schemes like the Environmental Ship Index, EcoPort, or Green Award have not been evaluated using actual health outcomes, only reported emissions. Fourth, the health consequences of port masterplan decisions, such as berth placement, terminal design, and logistics zone location, have rarely been modeled in advance, leaving planners without data-driven insights for long-term structural planning. Closing these gaps requires collaboration between port planners, transportation engineers, urban health researchers, and regulators, along with a political commitment to make health protection a measurable goal in port governance.

6.3. Conclusions

This review consolidates a consistent and substantial body of evidence: residential proximity to ports and harbors is associated with significant, multi-faceted public health risks. Emissions from maritime vessels, cargo handling operations, and land-side logistics degrade local air quality, elevating ambient concentrations of harmful pollutants. This exposure translates into increased population-level risks of premature death from cardiovascular and respiratory causes, higher incidence and exacerbation of chronic diseases (asthma, COPD, lung cancer), and emerging threats to reproductive health and child development.

Specifically, the multi-decadal Tarragona port-industrial complex illustrates the full pathway from the combined emissions of a port and its co-located petrochemical cluster to environmental contamination, human exposure (confirmed by biomonitoring), and associated health burdens. Notwithstanding, the reviewed studies do not allow the contribution of port operations to be isolated from that of the petrochemical complex and other urban sources. These observations sit within a framework of environmental injustice where regulatory compliance with EU standards coexists with frequent exceedance of health-protective WHO guidelines.

Although regulatory and technological measures can clearly cut emissions and related health impacts, they are still not applied consistently, being constrained by economic and political pressures. Moving forward will require a genuine shift toward a “Health in All Port Policies” approach, in which protecting public health is treated as a central goal port planning, expansion, and day–to–day operations. Achieving this requires sustained investment in community-scale environmental and health monitoring, support for longitudinal epidemiological research and biomonitoring programs (needed in Tarragona and other similar locations with ports), development and enforcement of health-protective regulations aligned with WHO guidelines rather than politically negotiated limits, and a strong, consistent focus on environmental justice. The goal must ensure that undeniable economic benefits of global maritime trade are not realized at the expense of health and well-being of millions calling the world's port cities home.

Declaration of AI-assisted technologies

Artificial Intelligence (Skywork AI Smart Slide Tool) was only used to assist in the graphic designs of Figs. 1 and 2.

CRediT authorship contribution statement

Jose L. Domingo: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Joaquim Rovira:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Martí Nadal:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

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

Data availability

This is a review article without data specifically created.

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