

The Italian ports of the Trans-European Transport Network (TEN-T): sustainability, climate resilience and public health implications

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Abstract

Background. The Trans-European Transport Network (TEN-T) represents a key instrument for achieving sustainable and climate-resilient mobility within the European Union. Seaports, as multimodal nodes connecting maritime, rail and road transport, play a strategic role in this framework, particularly in coastal and densely populated urban areas.

Methods. This study provides a policy-oriented analysis of the TEN-T structure, with specific reference to the 46 Italian seaports included in the network. Based on a review of European legislation, institutional documents and scientific literature, the paper examines the geographical distribution of Italian TEN-T ports, their environmental context and their relevance to public health and climate change adaptation.

Results. Particular attention is given to ports located near contaminated sites and to the growing exposure of coastal infrastructure to climate-related risks. The analysis highlights the need to integrate environmental sustainability, climate resilience, exposure monitoring and public health considerations into TEN-T port governance.

Conclusions. Such integration may contribute to reducing health-related exposures among port workers and surrounding communities.

Key words

- Trans-European Transport Network
- port sustainability
- Italian seaports
- climate change
- contaminated sites
- public health

INTRODUCTION AND OBJECTIVES

The Trans-European Transport Network (TEN-T) is a multimodal network of railways, inland waterways, short-sea shipping routes and roads that are interconnected to link urban hubs, ports and airports. It is a central aspect of the European Union's (EU) transport infrastructure policy, helping to achieve the objectives of the European Green Deal, which sets a target of achieving climate neutrality in the Union by 2050, as well as reducing net greenhouse gas emissions by at least 55% by 2030 [1]. It also supports the sustainable mobility strategy [2]. The TEN-T policy is based on the EU Regulation 2024/1679 [3], which defines the network and sets out infrastructure requirements to ensure consistent quality throughout the EU. This Regulation replaces the previous one, Regulation (EU) n. 1315/2013 [4].

The revised TEN-T is organised into three layers. The Core Network comprises the most strategically important transport nodes and links and is scheduled

for completion by 2030. The Extended Core Network forms an intermediate layer that expands and strengthens the priority network and is scheduled for completion by 2040. The Comprehensive Network encompasses the wider network of existing and planned transport infrastructure, ensuring accessibility and connectivity across all EU regions, and is scheduled for completion by 2050 [3].

The TEN-T network not only improves connections between different European regions but also plays a key role in reducing the environmental and climate impact of transport while enhancing the safety and resilience of infrastructure.

Although transportation is a source of economic development, the intensification of traffic flows also has negative impacts on public health, the environment and the climate, including air and noise pollution, greenhouse gas emissions, land consumption, road accidents, traffic congestion and loss of biodiversity. Therefore, the search for alternative measures to enhance the sustain-

ability, liveability and healthiness of cities [5-7] through effective urban and transport planning is a crucial aspect to prioritise.

A growing number of studies, particularly in European cities, have started to look at the additional health benefits of transport policies that also address climate change mitigation [8]. The promotion of sustainable and active mobility, together with traffic reduction, represents a strategic opportunity to achieve significant health benefits.

Within this framework, seaports emerge as particularly critical nodes of the TEN-T. As multimodal interfaces between maritime, rail and road transport, ports concentrate transport activities, energy use and emissions, and are often located near urban areas. As a result, port areas represent places where transport policies, environmental sustainability and public health concerns intersect most clearly, especially in coastal and densely populated areas.

The primary objectives of the TEN-T fall into four categories: sustainability, cohesion, efficiency and benefits for all users. With regard to sustainability, the Network promotes five major objectives aimed at reducing emissions from mobility, improving sustainable transport, enhancing environmental protection and energy security, and decreasing negative environmental and health impacts.

Despite the growing body of literature on transport sustainability, port environmental performance and TEN-T governance, limited attention has been paid to the explicit integration of public health considerations and climate change adaptation within port areas, particularly in the context of Italian seaports included in the TEN-T network.

This paper, based on a review of available information, aims to examine how the structure and governance processes of the network, with specific reference to seaports, may contribute to reducing environmental exposures and protecting public health. In particular, it pursues three main objectives: 1) to describe the structure of the TEN-T, with particular attention to Italian seaports included in the network; 2) to analyse how the sustainability of port areas aligns with the environmental and health objectives of the TEN-T; and 3) to examine how the growing threat of climate change requires the adaptation of port infrastructure.

Accordingly, the study does not seek to establish a causal relationship between TEN-T governance and health outcomes, but rather to identify the policy and environmental mechanisms through which TEN-T-related port interventions may influence exposure conditions and potentially affect public health.

Existing studies have mainly examined port environmental performance and sustainability indicators, or TEN-T corridor governance, as separate areas of research. This study generates new knowledge by integrating the revised TEN-T governance framework with a national-level analysis of the 46 Italian TEN-T seaports, their geographical overlap with municipalities containing National Priority Contaminated Sites, and the pathways linking port decarbonisation and climate adaptation to environmental exposures and potential

public health implications. This integrated perspective provides a basis for identifying where environmental monitoring, health surveillance and climate-risk assessment could be incorporated into TEN-T port planning and investment decisions.

Seaports in the Trans-European Transport Network (TEN-T)

The TEN-T node structure includes urban and transport nodes, such as airports, seaports and inland ports, rail-road terminals, and terminals along inland waterways. Seaports are fundamental geostrategic transport nodes that facilitate the interconnection of maritime, land, and rail transport networks. They represent cross-border multimodal hubs and entry and exit points for the network's land infrastructure. They are also important access points for trade, industry and the military, as well as energy hubs [3].

Seaports are a vital part of the multimodal transport infrastructure. This includes the port infrastructure for transport operations and the connections between ports and the main European transport network, as well as the Motorways of the Sea, regular maritime connections that facilitate the transfer of goods and passengers by sea, thereby reducing road congestion and emissions.

Regulation (EU) 2024/1679 defines the European maritime space as the maritime dimension of the TEN-T, comprising seaports, maritime routes and their multimodal connections with the hinterland. Its purpose is to ensure the efficient, sustainable and resilient integration of maritime transport into the wider European transport network [3].

From an environmental sustainability perspective, ports play a key economic role. However, their infrastructural and functional complexity means they are critical contexts where measures must be implemented to mitigate negative environmental and health impacts, using an integrated One Health approach that reconciles economic competitiveness with European sustainability, resilience and environmental health protection objectives [9]. For this reason, an increasing number of ports are committing to sustainable development pathways, in line with the United Nations 2030 Agenda and its Sustainable Development Goals (SDGs), while also developing infrastructure capable of withstanding climate change.

In the context of TEN-T maritime infrastructure projects, particular attention is therefore paid to environmental protection and port health and safety measures. These include the introduction of new technologies and innovations, the use of renewable and low-carbon fuels, noise reduction measures, improvements in energy efficiency, the promotion of zero- and low-emission ships, and actions aimed at strengthening the resilience of logistics chains and international maritime trade.

In this regard, the effects of climate change are now evident across Europe. Consequently, the TEN-T framework places increasing emphasis on ensuring the resilience of transport infrastructure to extreme weather events, which in the past have caused extensive damage to transport systems, with serious repercussions on the economy and human life [10].

Several studies, systematic reviews and technical reports highlight trends in environmental performance, sustainability and port performance in European ports [11-16]. Other studies focus specifically on TEN-T ports and the governance of major transport corridor development [17-20].

This conceptual and regulatory framework provides the basis for analysing the role, distribution and characteristics of Italian seaports within the TEN-T network, as discussed in the following sections.

DATA SOURCES AND ANALYTICAL APPROACH

This study adopted a policy-oriented documentary review and descriptive analytical approach. It combined an examination of the regulatory and policy framework governing the TEN-T with a national-level analysis of the Italian seaports included in the network.

European legislation and policy documents concerning the TEN-T, sustainable mobility and climate policy were examined to describe the structure, governance and infrastructure requirements of the network [1-4]. Institutional reports and scientific publications addressing port sustainability, environmental performance, public health and climate change adaptation were also reviewed to support the interpretation of the regulatory and descriptive analysis. The literature search was narrative rather than systematic and was intended to identify relevant evidence and conceptual frameworks, rather than to provide an exhaustive review of all available publications.

The 46 Italian seaports listed in Annex II to Regulation (EU) 2024/1679 constituted the analytical set for this study [21]. For each port, information was collected on its geographical location, corresponding Italian region and TEN-T classification. Additional information on corridor membership, rail connectivity and environmental or infrastructural characteristics was examined where relevant to the analysis and publicly available.

The list of TEN-T ports was cross-referenced with the municipalities included in the sixth *Report of the Italian epidemiological study of residents in national priority contaminated sites* (SENTIERI) [22]. This comparison was used to identify ports located in municipalities that contain National Priority Contaminated Sites, including cases in which the port area lies within or near the boundaries of the contaminated site. This geographical overlap was treated as contextual information on the environmental and public health relevance of these areas. It does not establish that port activities caused the contamination or the health outcomes observed in the corresponding municipalities.

Information on port environmental priorities and sustainability practices was obtained from reports published by the European Sea Ports Organisation (ESPO) and other European and national institutional sources [23, 24]. Evidence concerning climate-related hazards, vulnerability and adaptation was obtained from European Commission studies, assessments published by the Intergovernmental Panel on Climate Change, and Italian climate indicators reported by the Istituto

Superiore per la Protezione e la Ricerca Ambientale (ISPRA) [10, 25, 26]. Information from Italian Port System Authorities and other institutional websites was used to provide specific examples of port infrastructure, connectivity and adaptation initiatives.

Descriptive counts were used to summarise the geographical distribution of the ports and their classification within the TEN-T. The regulatory, institutional and scientific information was organised and narratively synthesised across four predefined dimensions: TEN-T governance and connectivity, port environmental sustainability, climate change mitigation and adaptation, and potential implications for public health.

Based on this synthesis, a conceptual framework was developed to organise the evidence into four linked components: TEN-T and port interventions; environmental improvements; changes in health determinants and exposure conditions; and potential public health outcomes. The framework represents plausible policy and exposure pathways identified in the reviewed sources and is not intended as an empirically validated causal model.

ANALYSIS OF THE AVAILABLE INFORMATION

TEN-T network structure

The TEN-T consists of linear infrastructure for rail, road and inland waterway transport, as well as point infrastructure comprising urban nodes, airports and ports. Transport and urban nodes act as multimodal connection points between long-distance traffic and regional and local transport networks. As described above, the TEN-T is structured into the Core, Extended Core and Comprehensive Networks. The Core and Extended Core Networks constitute the priority layers of the TEN-T, while the Comprehensive Network provides broader territorial coverage and connectivity across the EU.

The completion of the TEN-T is supported by nine European Transport Corridors and two horizontal priorities. The European Transport Corridors are defined on the Core Network and aim to ensure strategic continuity along the main trans-European axes. While the Comprehensive Network is not directly structured around these corridors, it provides territorial coverage and connectivity to the Core Network. In some cases, sections of the Extended Core Network are included in the corridors to ensure continuity and improve connections. In addition to ensuring efficient and reliable infrastructure, TEN-T infrastructure requirements promote more sustainable transport modes, contribute to reducing transport-related emissions and enhance resilience to the impacts of climate change.

The TEN-T includes two horizontal priorities: the European Maritime Space and the European Rail Traffic Management System (ERTMS), the common European system for railway signalling and traffic management. Given the focus of this study, particular attention is paid to the European Maritime Space, which is directly related to seaports. Within the TEN-T, the European Maritime Space supports the development and improvement of short-sea shipping routes, seaports and

their connections to the hinterland, including in the outermost regions. By improving the connectivity of maritime transport with rail, road and inland waterway networks, it contributes to a seamless, sustainable, efficient and resilient multimodal transport system across Europe [3].

To be included in the TEN-T, seaports must fulfil the criteria set out in Regulation (EU) 2024/1679. The network's infrastructure requirements are designed to ensure efficient and reliable infrastructure, promote more sustainable transport solutions with reduced emissions, and increase resilience to the impacts of climate change [3].

Italian ports in the TEN-T network

Italy is part of the TEN-T through both linear infrastructure (railways, roads and inland waterways) and

point infrastructure, including urban nodes, seaports, inland ports and airports. Five of the nine European Transport Corridors cross the Italian peninsula:

- Baltic-Adriatic;
- Mediterranean;
- Scandinavian-Mediterranean;
- Rhine-Alpine;
- Western Balkans-Eastern Mediterranean.

A total of 46 Italian seaports are included in the TEN-T and are distributed across 12 different regions. Of these, 15 ports belong to the Core Network, representing the most strategically important nodes, while 31 ports are part of the Comprehensive Network [21] (Table 1).

Each Italian region covered by the TEN-T includes no more than two Core ports (as in Liguria, Puglia and Sicily). When Core and Comprehensive ports are con-

Table 1
List of the Italian seaports in Core and Comprehensive Network

n	Port name	Core/comprehensive	Region	Corridor
1	Ancona	Core	Marche	Scandinavian-Mediterranean
2	Augusta	Core	Sicilia	Scandinavian-Mediterranean
3	Bari	Core	Puglia	Scandinavian-Mediterranean
4	Brindisi	Comprehensive	Puglia	
5	Cagliari	Core (Porto Foxi, Cagliari)	Sardegna	Scandinavian-Mediterranean
6	Capri	Comprehensive	Campania	
7	Carloforte	Comprehensive	Sardegna	
8	Casamicciola-Porto di Ischia	Comprehensive	Campania	
9	Catania	Comprehensive	Sicilia	
10	Chioggia	Comprehensive	Veneto	
11	Civitavecchia	Core	Lazio	Scandinavian-Mediterranean
12	Fiumicino	Comprehensive	Lazio	
13	Gaeta	Comprehensive	Lazio	
14	Gela	Comprehensive	Sicilia	
15	Genova	Core	Liguria	Rhine-Alpine
16	Gioia Tauro	Core	Calabria	Scandinavian-Mediterranean
17	Golfo Aranci	Comprehensive	Sardegna	
18	La Maddalena	Comprehensive	Sardegna	
19	La Spezia	Core	Liguria	Scandinavian-Mediterranean
20	Livorno	Core	Toscana	Scandinavian-Mediterranean
21	Marina di Carrara	Comprehensive	Toscana	
22	Messina	Comprehensive	Sicilia	
23	Milazzo	Comprehensive	Sicilia	
24	Monfalcone	Comprehensive	Friuli-Venezia Giulia	
25	Napoli	Core	Campania	Scandinavian-Mediterranean
26	Olbia	Comprehensive	Sardegna	
27	Palau	Comprehensive	Sardegna	
28	Palermo	Core (Palermo, Termini Imerese terminal)	Sicilia	Scandinavian-Mediterranean
29	Piombino	Comprehensive	Toscana	
30	Ponza	Comprehensive	Lazio	

Continues

Table 1
Continued

n	Port name	Core/comprehensive	Region	Corridor
31	Porto Empedocle	Comprehensive	Sicilia	
32	Porto Levante	Comprehensive	Veneto	
33	Porto Santo Stefano	Comprehensive	Toscana	
34	Porto Torres	Comprehensive	Sardegna	
35	Portoferraio (Elba)	Comprehensive	Toscana	
36	Portovesme	Comprehensive	Sardegna	
37	Procida	Comprehensive	Campania	
38	Ravenna	Core	Emilia-Romagna	Baltic-Adriatic
39	Reggio Calabria	Comprehensive (Reggio Calabria-Villa San Giovanni)	Calabria	
40	Salerno	Comprehensive	Campania	
41	Savona-Vado	Comprehensive	Liguria	
42	Siracusa	Comprehensive (Siracusa-Santa Panagia)	Sicilia	
43	Taranto	Core	Puglia	Scandinavian-Mediterranean
44	Trapani	Comprehensive	Sicilia	
45	Trieste	Core	Friuli-Venezia Giulia	Baltic-Adriatic/Mediterranean
46	Venezia	Core	Veneto	Baltic-Adriatic/Mediterranean

Core ports are highlighted in white.

sidered together, the regions with the highest concentration of ports are Sardinia and Sicily (8 ports each), followed by Tuscany and Campania (5 ports each). Regulation (EU) 2024/1679 added seven new Comprehensive ports and designated the Port of Civitavecchia as a Core port. Ports in *Table 1* are listed in the same order as in the official TEN-T list.

Some Core ports, particularly those serving island territories, play a crucial role in ensuring territorial continuity. Ports such as Livorno, Civitavecchia, Cagliari, Naples and Palermo provide regular and reliable passenger and freight connections, thereby reducing the logistical isolation of island regions.

Most Italian TEN-T ports have direct rail connections to the main railway network, and several are equipped with internal rail terminals. This facilitates intermodal sea-rail transport and increases logistical efficiency along European Transport Corridors. Examples include Trieste, Genoa, La Spezia, Venezia, Livorno, Taranto, Ancona, Ravenna, Gioia Tauro and Naples. Other ports, however, are connected to railway infrastructure only outside the port area or lack dedicated rail branches serving port operations [27].

The Port of Civitavecchia recently completed the Fast Track to the Sea Project, aimed at improving last-mile rail connectivity within the port area. The project involved the construction of new tracks and the upgrading of existing infrastructure, resulting in enhanced logistical efficiency, operational resilience and transport sustainability. These developments strengthened the role of Civitavecchia as a key logistics hub within the TEN-T network.

Several TEN-T ports are located in environmentally and health-critical areas, where port activities coexist

with industrial facilities, landfills, military arsenals and shipyards. Sixteen of these ports are situated in Italian municipalities included in the contaminated sites of national concern for environmental remediation analysed by the SENTIERI Project [22]. The main objective of SENTIERI is to implement permanent epidemiological surveillance of populations residing in these sites. Its periodic updating enables the monitoring of changes in the health profiles of local populations. However, these changes cannot be attributed specifically to mobility, port or TEN-T interventions without dedicated exposure assessments and longitudinal evaluation designs. Some of the contaminated areas in Italy are, in fact, located along the coast, often coinciding with major ports. These are areas that are currently or have historically been affected by human activities that have resulted in environmental chemical contamination with potential impacts on human health. Port areas themselves may represent sources of contamination, and even ports located outside the boundaries of contaminated sites can contribute to environmental and health pressures in surrounding areas [9].

A relevant example is the Port of Trieste, one of the main commercial, industrial and logistical hubs for strategic traffic in the EU. The port is part of both the Mediterranean and Adriatic-Baltic TEN-T corridors, which connect Austria and Slovenia with the Northern Adriatic and Eastern Europe. The Trieste National Site of Interest (SIN) also includes the port area and is covered by a Programme Agreement aimed at environmental remediation and redevelopment. These interventions are functional to sustainable development objectives for both the productive system and the port infrastructure within the site.

Due to its central position in the Mediterranean, Italy represents a strategic hub for European maritime traffic. This geographical advantage has supported the development of ports and coastal areas. The European maritime space, which encompasses coastal shipping routes and Motorways of the Sea, is strategically and multifunctionally important for Italy, as it connects its ports to major European and international trade routes. For Europe, and Italy in particular, the use of maritime transport is a vital strategic asset for economic development and integration with the TEN-T, promoting more sustainable, efficient and safer mobility. Shifting suitable freight and passenger flows from road to maritime transport can reduce road congestion and related air and noise pollution. However, these benefits depend on vessel efficiency, fuel choices and the carbon intensity of maritime energy sources [28]. Ports can also reduce emissions from ships at berth through cold ironing, also known as onshore power supply (OPS) or shore-side electricity. This system supplies electricity from the shore to ships at berth, allowing them to switch off their auxiliary engines and thereby reducing local emissions of air pollutants and noise. Its contribution to greenhouse gas mitigation depends on the carbon intensity of the electricity supplied [29, 30].

Within this framework, the TEN-T offers Italy an opportunity to accelerate the development of greener ports and more resilient infrastructure, as discussed in the following sections.

Sustainability, emissions and public health in TEN-T ports

The TEN-T network aims to make all modes of transport more sustainable, recognising that, within the framework of sustainable development, ecological, economic, and social dimensions are complementary and interdependent. Regulation (EU) 2024/1679 aims to reduce the environmental and climate impacts of transport while increasing the safety and resilience of the network. These objectives are in line with the European Green Deal, which calls for a 90% reduction in transport-related greenhouse gas emissions by 2050 [1, 3].

Transport accounts for approximately one quarter of total greenhouse gas (GHG) emissions in the European Union, underlining the urgent need to transition towards a sustainable mobility system compatible with climate-neutrality objectives. These emissions, particularly carbon dioxide (CO₂), contribute to global warming and climate change, with wide-ranging environmental and potential public health implications.

Within this context, maritime transport accounted for 14.2% of EU transport-sector CO₂ emissions in 2022. Since 2014, sulphur oxide (SO_x) emissions from shipping in Europe have fallen by around 70%, largely due to the introduction of Sulphur Emission Control Areas (SECAs) in the north of the continent. The Mediterranean Sea officially became an Emission Control Area for sulphur oxides and particulate matter on 1 May 2025 and is expected to contribute to further emission reductions in Southern Europe. In contrast, nitrogen oxide (NO_x) emissions increased by an aver-

age of 10% across the EU between 2015 and 2023, remaining a significant challenge for air quality and public health [24].

Environmental objectives applied in ports, including those within the TEN-T network, may have direct and indirect implications for human health. Improvements in environmental performance can reduce pollution-related exposures among port workers and populations living in surrounding urban areas, potentially generating public health co-benefits. *Table 2* presents the conceptual framework developed in this study, linking four components: 1) TEN-T and port interventions; 2) environmental improvements; 3) changes in health determinants and exposure conditions; and 4) potential public health outcomes for port workers and surrounding communities. The relationships shown represent plausible pathways identified in the reviewed literature rather than causal effects demonstrated by the present study.

Building on this framework, ports can be understood as complex socio-technical systems where transport, logistics, energy production, industrial activities and urban functions intersect. Port sustainability therefore extends beyond reducing emissions from ships and cargo-handling operations and encompasses ecosystem protection, energy transition, occupational health and safety, and relationships with local communities. Within the TEN-T framework, ports are strategic nodes where European transport, environmental and public health policies converge.

Mitigation actions aimed at reducing emissions remain a core element of port sustainability. European ports increasingly act as energy hubs, supporting the decarbonisation of maritime transport through the provision of alternative fuels such as liquefied natural gas (LNG), biofuels, hydrogen and ammonia, as well as through the electrification of port operations. Among these measures, shore-side electricity is particularly relevant to local air quality because it reduces emissions of nitrogen oxides, sulphur oxides and particulate matter from auxiliary engines while ships are at berth, as well as noise exposure in surrounding port areas [29, 30].

To monitor progress and guide decision-making, ports increasingly rely on environmental performance indicators. At the European level, the environmental top 10 priorities identified by the European Sea Ports Organisation (ESPO) in its annual ESPO environmental report [16] provide a widely adopted reference framework for port environmental management (*Table 3*). These priorities reflect both long-standing environmental concerns, such as air and water quality, noise and waste management, and policy areas that have progressively gained prominence and become structurally embedded in port environmental agendas, including climate change, energy efficiency and relationships with local communities.

Beyond the ESPO priorities, several indicator frameworks have been proposed in the scientific literature to assess port sustainability. Puig *et al.* [31] developed a comprehensive framework of environmental performance indicators addressing operational, managerial and environmental condition aspects of port activities.

Table 2

Conceptual framework linking Trans-European Transport Network (TEN-T) and port interventions to environmental improvements, health determinants and potential public health outcomes. The relationships shown represent plausible pathways derived from the reviewed literature and should not be interpreted as causal effects empirically demonstrated by this study

TEN-T and port interventions	Environmental improvements	Health determinants/exposure pathways	Potential public health outcomes
Promotion of multimodal transport	Reduced road traffic, congestion, air pollution and noise	Lower exposure to traffic-related air pollutants and noise; reduced collision exposure	Potential reduction in pollution-related and road-injury risks among urban residents, road users and logistics workers
Integrated green-port management	Improved environmental monitoring, management and port-city coordination	Better identification and control of cumulative environmental pressures in port-city areas	Potential reduction in cumulative environmental exposures and associated health risks among port workers and nearby residents
Use of alternative fuels	Potential reduction in lifecycle greenhouse gas emissions and, depending on the fuel and technology, local air pollutants	Reduced climate-related pressures and possible reductions in pollutant exposure	Potential climate and air-quality co-benefits; outcomes depend on the fuel pathway used
Shore-side electricity at berth	Reduced NO _x , SO _x , particulate matter and noise from auxiliary engines	Lower exposure to port-related air pollutants and noise while ships are at berth	Potential respiratory, cardiovascular and noise-related co-benefits for port workers and nearby residents
Renewable energy in port operations	Reduced reliance on fossil energy and lower greenhouse gas emissions	Lower exposure to combustion-related air pollutants and reduced contribution to climate-related health hazards where renewable energy displaces fossil-fuel use	Potential air-quality- and climate-related health co-benefits
Nature-based solutions in port-city areas	Improved microclimate, stormwater management and access to green space	Reduced heat and flood exposure; improved opportunities for contact with green space	Potential reduction in heat-related illness and flood-related injury risks, together with benefits for mental well-being
Climate-proofing of port infrastructure	Reduced exposure to flooding, storm surges, extreme heat and disruption of essential services	Lower vulnerability to climate-related hazards for port operations and communities	Potential reduction in injuries, heat stress and health risks associated with disruption of essential services among port workers and surrounding communities

NO_x: nitrogen oxides; SO_x: sulphur oxides.

Table 3

Environmental top 10 priorities of European ports for 2025

1. Climate change	6. Water quality
2. Air quality	7. Relationship with the local community
3. Energy efficiency	8. Garbage/port waste
4. Port development (land-related)	9. Ship waste
5. Noise	10. Port development (water-related)

Other studies have explicitly adopted a broader sustainability perspective by integrating environmental, economic and social dimensions into port assessment frameworks. For example, Shiau *et al.* [32], through a case study of the Port of Keelung, emphasised the social construction of port sustainability indicators and the role of stakeholder engagement in balancing environmental protection, economic performance and social concerns. Similarly, Lim *et al.* [33], in a systematic review of port sustainability and performance research, highlighted the need to move beyond predominantly environmental assessments towards more integrated frameworks that also account for operational and social dimensions.

From a public health perspective, indicators related to air quality (NO₂, PM2.5, PM10), noise exposure, occupational safety and accident rates are particularly rel-

evant. Several studies have demonstrated associations between port-related emissions and adverse health outcomes in nearby populations, including respiratory and cardiovascular diseases [34, 35]. Integrating health-related indicators into port sustainability assessments can therefore support a more holistic approach, aligning port development with broader societal well-being objectives.

Within the TEN-T context, sustainability indicators also serve an important governance function by supporting transparency, accountability and comparability across ports and corridors. The harmonisation of reporting practices, promoted through EU-funded projects and initiatives, facilitates benchmarking and knowledge sharing among ports. In parallel, digitalisation and smart port technologies enhance the capacity to collect real-time environmental data, supporting adaptive management and evidence-based policy decisions [36].

Italian ports, given their geographical position and exposure to climate risks, represent a critical testing ground for the integration of climate change adaptation and sustainability within the TEN-T framework. Many Italian port authorities have adopted environmental management systems and climate strategies, often aligned with ESPO guidelines and EU climate objectives. However, challenges remain, including uneven implementation across ports (reflecting differences in resources, governance capacity and local priorities), limited availability of comparable data, and the need for

stronger integration of health considerations into port planning and decision-making processes.

Overall, the TEN-T framework provides a strategic opportunity to improve the environmental performance of European ports by linking infrastructure development with emission reduction, environmental monitoring and public health considerations. Regulatory requirements, financial instruments and harmonised indicators can support more transparent and evidence-based port governance, while contributing to reducing health-related exposures among port workers and surrounding communities.

Climate risks and adaptation in Italian TEN-T ports

Mediterranean and Italian ports are particularly exposed to sea-level rise, coastal erosion, storm surges, flooding, extreme precipitation and heat waves [25, 37, 38]. These hazards can damage quays, terminals and transport connections, disrupt logistics chains and essential services, and increase occupational and community risks [39]. Their effects may be especially significant in densely populated coastal areas and among vulnerable population groups.

In Italy, the mean sea-level indicator for Venice shows an accelerating upward trend, with an average rise of 4.8 mm/year during the period 1993-2024. Simulations of mean sea-level anomalies for Italian waters indicate increases of approximately 16-19 cm, with important implications for coastal erosion and flood exposure [26].

Recent extreme events further illustrate these risks. In January 2026, Cyclone Harry caused heavy rainfall, very strong winds and exceptional waves along the Ionian and Tyrrhenian coasts, damaging coastal towns and infrastructure [40]. The event illustrates how Mediterranean cyclones can disrupt port operations, affect transport connections and expose workers and coastal communities to compound environmental and safety risks.

Adaptation requires a combination of structural and non-structural measures. Structural interventions include the reinforcement or elevation of quays, terminals and breakwaters, the redesign of drainage systems, and the construction of seawalls and storm-surge barriers. Non-structural measures include climate-risk assessments, emergency preparedness plans and the integration of climate risks into port governance and investment decisions. In this context, climate-proofing refers to incorporating current and future climate risks throughout the planning, design, construction, operation and maintenance of port infrastructure, with the aim of ensuring its long-term resilience and operational reliability [41, 42].

Italian examples include the MOSE (Modulo Sperimentale Elettromeccanico) flood-barrier system in Venice and the new breakwater in the Port of Genoa, designed to protect port basins and infrastructure. Adaptation strategies may also incorporate circular-economy principles, such as the reuse of dredged materials for coastal protection works, as reported in ports including La Spezia and Marina di Carrara.

Enhancing the climate resilience of TEN-T ports

is therefore not only an economic and infrastructural necessity but also has important public health implications, particularly for vulnerable coastal communities exposed to climate-related hazards.

DISCUSSION AND CONCLUSIONS

This study examined how the structure and governance of the TEN-T, with specific reference to seaports, may contribute to reducing environmental exposures and protecting public health. It described the structure and geographical distribution of Italian TEN-T ports, analysed how port sustainability relates to the environmental and health objectives of the TEN-T, and considered the need to adapt port infrastructure to climate-related hazards.

By combining the classification and geographical distribution of Italian TEN-T ports with evidence on contaminated-site municipalities, port sustainability priorities and climate-related risks, this study develops an integrated, governance-oriented perspective linking TEN-T implementation with environmental exposures and public health. Its original contribution is not a quantitative estimation of health impacts, but the identification of points at which environmental monitoring, health surveillance and climate-risk assessment could be more systematically incorporated into port planning and decision-making.

The main objective of TEN-T is to develop a sustainable and resilient multimodal transport network. In this context, short sea shipping can substantially contribute to decarbonising transport by carrying more freight and passengers by sea. This would reduce road congestion, including in Italy. Its actual climate benefits, however, depend on fleet modernisation, fuel choices and the decarbonisation of maritime energy sources. Proper design and planning provide opportunities to develop policies that prevent and mitigate negative impacts on health and the environment. By adopting sustainable technologies and environmentally responsible practices, TEN-T ports may reduce environmental pressures and health-related exposures among port workers and surrounding communities.

Ports are complex infrastructures that are often closely integrated into urban fabric, with neighbourhoods bordering the port area. This spatial configuration raises specific challenges for port governance, particularly in relation to environmental pressures and public health concerns. Awareness of ports located in environmentally critical areas, such as contaminated sites, further underlines the importance of continuous assessment and monitoring of environmental conditions to support sustainable development strategies aimed at protecting public health. From this perspective, different approaches can be identified to assess the potential environmental and health impacts of such improvements. A promising tool is to implement *ad hoc* health surveillance systems coupled with environmental and ecosystem monitoring in port areas. An integrated One Health approach could build on surveillance initiatives such as SENTIERI by combining environmental, ecosystem, occupational and population-health data. Before-and-after assessments of major mobility, land-

management and port-infrastructure interventions could help evaluate changes in exposure to noise, air pollution and other relevant risk factors.

Italy's extensive and highly urbanised port system is particularly exposed to climate-related coastal hazards. The evidence reviewed indicates that adaptation should be integrated into port planning, infrastructure investment and emergency preparedness rather than treated solely as an emergency-management issue.

The impacts of Cyclone Harry, described above, illustrate the operational, infrastructural and public health consequences that extreme coastal events may generate in Mediterranean port cities [40].

While major ports are already investing in protective infrastructure and adaptation planning, further technical knowledge and implementation capacity are needed across the Italian port system. Particular attention should be paid to smaller and island ports, which play important roles in territorial continuity, tourism and local trade but often have more limited human and financial resources for climate-risk assessment and adaptation.

This study has several limitations. First, it is based on secondary and publicly available sources, which vary in scope, date and reporting quality. Second, the identification of TEN-T ports located in municipalities containing National Priority Contaminated Sites included in the SENTIERI study provides information on their geographical and environmental context, but does not establish port-specific exposures or causal relationships between port activities and health outcomes. Third, the study does not include primary environmental measurements, port-level climate-risk modelling or a quantitative health impact assessment. Finally, differences in the availability and comparability of information among ports limit systematic port-to-port assessment. These limitations highlight the need for harmonised port-level environmental, exposure and health indicators, as well as longitudinal or before-and-after assessments of TEN-T interventions.

Areas where urban, industrial and port activities overlap may face multiple and interacting environ-

mental pressures, representing a complex public health challenge. The coexistence of refineries, petrochemical and chemical plants, container terminals, logistics hubs and urban transport can contribute to combined environmental exposures affecting both port workers and nearby urban communities. Addressing these pressures requires multisectoral strategies that integrate environmental protection, occupational health, public health and port-city planning. By incorporating environmental standards, climate resilience and performance monitoring, the TEN-T can serve as an important policy framework for addressing environmental exposures and public health concerns in port cities. In the context of Italian TEN-T ports, our analysis highlights the need to incorporate environmental monitoring, health surveillance and climate-risk assessment into port planning and investment decisions. An integrated approach should combine technological and logistical improvements, targeted spatial planning and appropriate mitigation measures. Harmonised indicators and longitudinal evaluations will be essential to determine whether TEN-T interventions translate into measurable reductions in environmental exposures and improved protection of port workers and surrounding communities.

Authors' contributions

AF: conceptualization, methodology, data collection and analysis, writing original draft, review and editing; MP: methodology, data collection and analysis, writing, review and editing; II: methodology, data collection and analysis, writing, review and editing. All Authors have revised the manuscript, supervised the overall work and approved its final version.

Conflict of interest statement

The Authors declare no conflicts of interest regarding this manuscript.

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