

A Systematic Literature Review on Safety of Ammonia as a Marine Fuel

Nicoleta Pocitarencu^a, Olga Aneziris^{b*}, Ioanna Koromila^b, Zoe Nivolianitou^b, Marko Gerbec^c, Vladislav Maras^d, Ernesto Salzano^a

^a Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna 40131, Italy

^b Systems Reliability and Industrial Safety Laboratory, National Center for Scientific Research DEMOKRITOS^{*}, Terma Patriarchou Grigoriou, Aghia Paraskevi 15310, Greece

^c Department for inorganic chemistry and technology, Jožef Stefan Institute, Jamova 39, Ljubljana 61000, Slovenia

^d Faculty of Transport and Traffic Engineering, University of Belgrade, Vojvode Stepe 305, Belgrade 11000, Serbia
 olga@ipta.demokritos.gr

In this paper a systematic literature review on safety and risk assessment at ports storing and transferring ammonia is performed. Regulations and ISO standards for ammonia safety have been considered. In addition, various classification societies have issued guidelines for assessing hazards and risks of ammonia storage at ports and during bunkering, such as DNV and ABS. International and regional maritime organizations have also contributed to the systematic understanding and enforcement of risk assessment methodologies. The European Maritime Safety Agency (EMSA) provided an overview of the challenges and opportunities with particular focus on safety regulations and risk assessment of fuel merchant ships. The Green Shipping Programme (GSP), provided the regulatory framework and a comparison between ammonia and LNG as a marine fuel. Companies such as Alfa Naval, Hafnia, Haldor Toso, Vestas and Siemens have collaborated to explore the potential of ammonia as a marine fuel and have provided an industrial vision and a roadmap. The Seveso directive on the control of major-accident hazards involving dangerous substances, which has been applied to ammonia on land based installations since 1982, is also a valuable regulation for ports, where large quantities of ammonia may be stored. A literature review regarding scientific papers concerning risk assessment of ammonia at ships has also been performed and the aim is to investigate scientific and harmonization gaps of ammonia safety in the marine sector, within the EU.

1. Introduction

The use of anhydrous ammonia has gained significant attention in the maritime industry as a potential long-term solution for decarbonisation, particularly among alternative fuels. However, due to its toxicity and corrosiveness, ammonia poses risks to human health, infrastructure, and the environment, making it crucial to implement stringent safety measures during its storage, handling, and bunkering operations on ships and in port areas.

Anhydrous ammonia is a carbon-free compound composed of nitrogen and hydrogen, and it is a colourless gas with a strong, sharp, irritating odour. The benefit of its low odour threshold (2-5 ppm) is that it can be detected by smell long before reaching hazardous concentrations (about 300 ppm).

Ammonia is easily liquefied due to strong hydrogen bonds between molecules, making it more convenient for transport and storage. At atmospheric pressure, ammonia becomes a liquid below -33.5°C. Although it is classified as a non-flammable gas by the United Nations, it can ignite at a temperature of 651°C within a concentration range of 15-28% vol. The concentrations required for ignition are relatively high, and ammonia vapour disperses rapidly in the air due to its relative density of 0.589 compared to dry air. While it tends to dissipate as it rises in open environments, ammonia is particularly dangerous in confined spaces. Its flammability range is narrower than those of methane, propane, propylene, gasoline, diesel, and butane, which is a significant factor to consider in enclosed areas.

When using ammonia as a fuel in marine internal combustion engines, the emissions of sulphur dioxide, carbon monoxide, heavy metals, hydrocarbons, and polycyclic aromatic hydrocarbons (PAH) drop to zero; harmful particulate matter (PM) emissions would also be substantially lower than for conventional fossil fuels, this is because ammonia has no carbon, sulphur and other contaminants typically seen in conventional residual or distillate fuels. Particulate matter emissions will mainly come from the combustion of pilot fuel and cylinder lubrication oil. Engine developments related to the use of ammonia are ongoing. Issues related to concerns about nitrogen oxide (NO_x) and nitrous oxide (N₂O) emissions, along with the harmful effects of ammonia slip from engines, would need to be thoroughly addressed to ensure compliance with environmental regulations, minimize environmental impact, and maintain the safe and efficient operation of the system (ABS, 2020). Ensuring safety onboard ships fueled with ammonia, as well as during bunkering operations, is critical. This paper aims to contribute to this effort by examining the relevant regulatory framework governing the safe use of ammonia as a marine fuel. Additionally, it reviews existing literature on quantitative risk assessments.

2. Regulatory framework

2.1 International legislative bodies

The safe transport of bulk ammonia on ships is covered in specific codes depending on its form. For aqueous ammonia, the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code) is applicable. This code (IMO, 2004) outlines safety requirements for the design, construction, and operation of ships transporting dangerous chemicals in bulk, including aqueous ammonia. It focuses on the safe handling and containment of these substances during transport. For anhydrous ammonia, the relevant regulation is the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). The IGC Code (IMO, 2014) provides guidelines for the construction and safety of ships transporting liquefied gases, such as anhydrous ammonia, which is carried under pressure or at low temperatures. Both codes are part of the regulations set by the International Maritime Organization (IMO), ensuring that vessels are built to meet safety standards and that appropriate procedures are followed to minimize risks to crew, the environment, and the public.

However, there are no international regulations for the use of ammonia as a fuel. The most relevant code is the IGF Code (IMO, 2015) which provides requirements and focuses mainly on liquefied natural gas (LNG). International organizations such as IMO, IACS and Classification Societies have been working to develop and update the rules and regulations specific to ammonia fueled ships. Interim Guidelines for Ships Using Ammonia as Fuel have been recently finalized by IMO Safety Committee MSC 109 (Lloyds, 2024) and published (IMO, MSC.1/ Circ. 1687, 2025). Cargo ships weighing 500 gross tons or more and passenger ships using non-cargo ammonia as fuel can now use the guidelines as a basis for vessel design and systems layout.

The International Organization for Standardization (ISO) has published a range of standards related to the use of anhydrous ammonia in industrial or land-based sectors, which may be suitable for marine applications. The ISO standards are key references for the management, transfer, and quality control of liquefied anhydrous ammonia, a chemical widely used in industrial and agricultural applications. ISO 7105 (ISO, 1985) defines requirements for the transport, handling, and purity of ammonia, including analytical techniques such as the Karl Fischer method for determining water content, which is crucial for ensuring optimal product performance. ISO 5771 (ISO, 2024) specifies technical requirements for rubber hoses and hose assemblies designed for safe transfer of liquid or gaseous ammonia, focused on pressure resistance, low-temperature flexibility, and ozone durability. Finally, ISO 7106 (ISO, 1985) outlines analytical methods, both gravimetric and spectrometric, for determining residual oil content in ammonia, ensuring compliance with quality standards necessary for industrial applications. Together, these ISO standards provide a comprehensive framework for the safe and efficient management of ammonia.

2.2 Classification societies

Ammonia as a marine fuel presents a promising pathway toward achieving the International Maritime Organization's (IMO) 2050 greenhouse gas reduction targets, but its adoption faces significant technical, operational, and regulatory challenges. According to DNV's white paper on ammonia as a marine fuel (DNV, 2020), its toxicity and corrosiveness necessitate stringent safety measures, including advanced leak detection systems and specialized storage solutions, while NO_x emissions from combustion require effective mitigation through technologies like selective catalytic reduction. DNV also emphasizes the critical need for scaling up the production of green ammonia produced via renewable energy sources to enhance environmental benefits, alongside substantial investments to improve electrolyser efficiency and reduce production costs. ABS has issued requirements for Ammonia-Fuelled Vessels (ABS, 2023) and has outlined technical and safety standards for the design, construction, and operation of ammonia-fuelled ships, addressing issues such as ammonia slip mitigation, double-walled piping, and compliance with IMO emission regulations. Additionally, the ABS report on

ammonia bunkering (ABS, 2024) provides guidance on the challenges of ammonia bunkering, emphasizing the need for rigorous safety measures due to ammonia's toxicity. The advisory outlines the design of bunkering infrastructure, risk assessment, and safety procedures, highlighting the importance of ammonia bunkering plans that ensure safe operations in line with regulatory standards. It also stresses the need for advanced control systems, emergency shutdown mechanisms, and appropriate personal protective equipment (PPE) to protect personnel during ammonia transfers. ABS includes emergency procedures, both preventive and mitigation measures and also the importance of crew training programs. Although ammonia's lower energy density necessitates larger storage tanks and infrastructure development, its potential for scalable production and zero-carbon emissions positions ammonia as a viable long-term solution for maritime decarbonisation.

2.3 International and European associations

International and regional maritime organizations have sought not only to enhance knowledge on the application of ammonia in the shipping industry but also to contribute to the systematic understanding and enforcement of risk assessment methodologies. The European Maritime Safety Agency (EMSA) has published a report that explores the use of anhydrous ammonia as a fuel in the maritime sector (EMSA, 2023). The document highlights that, although ammonia is not currently used as a fuel for ocean-going ships, recent analyses have identified potential solutions for its adoption. This study assesses several designs for ammonia-fuelled ships from the risk and safety perspectives. In particular, two cargo ships (an oil tanker and a bulk carrier) and a Ro-Pax ship have been analysed, and it has been demonstrated that the main safety concerns are ammonia toxicity and gas-dispersion properties. While solutions are available, additional research and studies are needed to further reduce or fully mitigate the associated risks. This study also contains a detailed regulatory gap analysis for ammonia bunkering, use, and consumption. EMSA also published two reports in 2024 regarding the safety of ammonia in ships, as follows: a) it focuses on ammonia hazards and the current onshore and offshore regulatory framework (EMSA, 2024a), and b) it performs a qualitative evaluation of the reliability of ammonia systems (EMSA, 2024b).

The "Ammonia as a Marine Fuel Safety Handbook" developed by the Green Shipping Programme (GSP) provides comprehensive guidelines focused on ensuring the safe use of ammonia as a marine fuel (GSP, 2023). This handbook, stemming from Colorline's ammonia pilot project, addresses crucial aspects such as risk management, ship design integration, operational procedures, and crew training. It emphasizes the identification and assessment of risks associated with ammonia, offering strategies for safe fuel system integration within ship designs. Additionally, it provides standardized operating procedures for on board ammonia handling and outlines training programs for crew members. The primary objective of this handbook is to serve as a foundational document for the development of ammonia-powered vessels that are both safe and efficient, tackling the unique challenges associated with using ammonia as a marine fuel. These guidelines are essential in ensuring the safe adoption of ammonia in the maritime industry, paving the way for the future of sustainable shipping.

Safety considerations associated with the use of ammonia as a marine fuel are crucial for its widespread adoption. Experience from other industries, such as agriculture and refrigeration, provides a solid foundation for establishing safe practices for handling ammonia as a fuel of ships. The maritime industry has significant opportunities to integrate safety as a key parameter in the design of ammonia-fuelled fleets. Furthermore, companies like Alfa Laval have developed solutions to ensure safe ammonia fuel use, such as the FCM (Fuel Conditioning Module) and ammonia fuel supply systems, which ensures controlled and secured operation of ammonia as a marine fuel (Alfa Naval et. al, 2020). Alfa Laval suggests that storing ammonia refrigerated, rather than under high pressure, is safer on ships. Refrigeration reduces the risks associated with high-pressure storage, as ammonia remains stable at lower temperatures and reduces the likelihood of dangerous leaks in case of accidents.

Finally, the Society for Gas as a Marine Fuel (SGMF) has released two documents for ammonia as a marine fuel: a) "Ammonia as a marine fuel- an introduction" (SGMF, 2023) and b) "Ammonia as a marine fuel- Safety and operational Guidelines- bunkering", (SGMF (2024), which focuses on ammonia bunkering during design, preparation, and operation and also includes risk assessment.

2.4 European legislative bodies

The Seveso Directive of the European Parliament (European Commission, 2012) establishes stringent requirements for controlling the risks of industrial accidents involving hazardous substances, including ammonia. Ammonia is classified as a hazardous substance due to its potential risks to human health and the environment in the event of an incident. The directive defines thresholds for the quantities of hazardous substances, such as ammonia, above which companies are required to implement specific safety measures. These thresholds are divided into two categories: a) the lower threshold, which is 50 tonnes of ammonia, and mandates basic prevention measures, and b) the upper threshold, which is 200 tonnes of ammonia, and more rigorous risk

assessment studies are required, including emergency planning and communication with local authorities. Companies handling ammonia are obligated to assess risk, so as to identify potential hazards associated with its use, storage, and transport. Preventive and mitigation measures must also be adopted to minimize the likelihood and consequences of accidents. Additionally, the directive mandates the creation of emergency response plans that must be coordinated with local authorities, ensuring an effective and swift response to incidents. Public information on the risks associated with ammonia is another crucial aspect, ensuring that communities are aware of the potential dangers and can take appropriate action in case of emergencies. The Seveso Directive, which may be applied to ports storing ammonia, aims to safeguard human health and the environment by ensuring that the risks associated with hazardous substances, such as ammonia, are managed effectively and that competent authorities are equipped to handle emergencies.

3. Literature review

Ammonia, as a marine fuel, is still in its early stages of development, requiring extensive safety investigations in both the design and operational phases of a ship's lifecycle. The safety challenges associated with ammonia, particularly its toxicity and chemical corrosion, require rigorous risk assessments. Table 1 presents the scientific papers identified for ammonia safety when used as a marine fuel. A study by Jang et al., (2023) has compared safety regulations and guidelines from classification societies and international codes, highlighting gaps in current approaches. Risks such as ammonia leakage during bunkering, in fuel preparation rooms, and in engine rooms have been critically analysed, with recommendations for better safety management frameworks.

The scientific community has contributed to systematic research into the safe use of ammonia for land use industries, such as for fertilizers, but the first risk assessment studies for ammonia as a marine fuel appeared in 2020. Quantitative risk assessment for ammonia ship-to-ship (STS) bunkering by using a Bayesian Network (BN) framework evaluated potential hazards associated with ammonia transfer operations (Fan et al., 2022). The proposed method integrated the Event Tree analysis and provided a comprehensive depiction of possible accident scenarios. Within this framework, the BN approach modelled causal relationships between various risk factors, such as leaks, spills, fires, and their consequences, enabling the calculation of associated probabilities. By incorporating data from operational practices, historical incidents, and safety measures, the BN framework provides a dynamic and probabilistic risk assessment. This approach allows for real-time update of probabilities as new data becomes available, ensuring continuous evaluation and refinement of safety measures. This study identified critical risk contributors and proposed mitigation strategies, including enhanced safety protocols, emergency response plans, and advanced monitoring systems.

Quantitative risk assessment (QRA) has been used to estimate the risks on ammonia-powered ships (Abubakirov et al, 2024). This study showed that ammonia-powered vessels pose higher individual risks for the engineering crew, particularly in fuel preparation areas, when compared to conventional LNG powered ships. Increased risk highlights the need for effective management of human-machine interactions, enhanced system reliability, and safety management to mitigate these safety concerns. In addition to the flammability, the high toxicity of ammonia, especially in storage conditions, emphasizes the importance of thorough risk evaluation.

Quantitative risk assessment has been performed (Franks et al, 2024) for two ship designs that use ammonia as fuel (a containership and a tanker). It is shown that risk changes with vessel arrangement, operating conditions and application of risk reduction measures. Risk criteria are also discussed. The method enables identification and evaluation of a risk reduction measure that is not currently mandated within the design requirements for such vessels.

Several studies have simulated accidental ammonia release and dispersion during bunkering (Ng et al., 2023). Various scenarios for large-scale release of ammonia during bunkering were simulated (Ng et al., 2023), and the behaviour of ammonia over the sea surface and on land was identified, with various weather parameters specific to Singapore. Yang and Lam (2024) also performed a risk assessment of ammonia bunkering operations for the port of Singapore. Ammonia consequence analysis was performed in case of ship-to-ship collisions of ammonia-fueled vessels, under semi-refrigerated and refrigerated configurations (Masia et al., 2024). This analysis was based on the results obtained from the integral models, such as PHAST software tool, and showed that semi-refrigerated tanks generally result in more severe health risks than refrigerated tanks.

Finally, a comparative analysis of vapour cloud dispersion during ship-to-ship bunkering has been performed (Duong et al., 2023). It is shown that due to the high toxicity of ammonia, the required distances for safe dispersion in the ambient air are greater compared to liquefied natural gas (LNG) under similar operational conditions. Weather conditions, leak rates, and leak hole diameters were found to be critical factors influencing the extent of the safety zone. These findings provide valuable insights for establishing safety protocols and improving emergency management during ammonia bunkering, offering essential data for both qualitative and quantitative risk assessments.

This literature research underscores the importance of continued research, development, safety measures, and regulations to ensure the safe adoption of ammonia as a marine fuel.

Table 1: Literature review for ammonia safety as a marine fuel

Reference	Document Title
Abubakirov et al, 2024	Towards risk-informed design and operation of ammonia-powered ships: Critical aspects and prospective solutions
Duong et al., 2023	Comparative analysis on vapor cloud dispersion between LNG/liquid NH ₃ leakage on the ship to ship bunkering for establishing safety zones
Fan et al., 2022	Quantitative risk assessment for ammonia ship-to-ship bunkering based on Bayesian network
Franks et al, 2024	Use of quantitative risk assessment to enhance the safety of ships using ammonia as fuel, <i>Journal of Safety and Sustainability</i>
Jang et al., 2023	Regulatory gap analysis for risk assessment of ammonia-fueled ships
Masia et al., 2024	Risk Assessment of Ammonia Fueled Ships: Consequences on Human Health of Ammonia Releases from Damaged Fuel Storage Tanks
Ng et. al., 2023	Accidental release of ammonia during ammonia bunkering: Dispersion behaviour under the influence of operational and weather conditions in Singapore
Yang and Lam, 2024	Risk assessment of ammonia bunkering operations: Perspectives on different release scales

4. Conclusions

This paper provides a literature review on the safety of using ammonia as a marine fuel. It discusses the key regulations, standards, and classification society guidelines relevant to the handling of ammonia in ports and on board ships. Additionally, studies involving QRAs to assess ammonia safety in shipping were collected and reviewed. The literature on the use of ammonia as a fuel, particularly in the maritime sector, is still in its early stages compared to other alternative fuels. While ammonia has been extensively studied for land-based applications, research dedicated to its use in port facilities and marine operations is relatively scarce. Most of the studies conducted so far focus on the design of ammonia-fuelled ships, adhering to alternative design requirements and safety guidelines. However, QRAs for ammonia storage and handling in port areas are largely absent, and there is a significant gap in research regarding the risks associated with bunkering operations for ammonia. This includes the lack of comprehensive studies for various bunkering methods, such as ship-to-ship, tank-to-ship, and truck-to-ship, all of which present unique risks and safety considerations specific to ammonia's properties.

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References

- Abubakirov R., Yang M., Scarponi G. E., Moreno V. C., Reniers G., 2024, Towards risk-informed design and operation of ammonia-powered ships: Critical aspects and prospective solutions, *Ocean Engineering*, 314,2, 1-16, doi: 10.1016/j.oceaneng.2024.119753.
- ABS, 2020, Sustainability Whitepaper Ammonia as Marine Fuel, American Bureau of Shipping.
- ABS, 2023, Requirements for Ammonia Fuelled Vessels, American Bureau of Shipping.
- ABS, 2024, Ammonia Bunkering: Technical and Operational Advisory, American Bureau of Shipping.
- ALFA LAVAL, HAFNIA, HALDOR TOSOA, VESTAS, SIEMENS GAMESA, 2020, Ammonfuel – An industrial view of ammonia as a marine fuel, <https://www.alfalaval.com/globalassets/documents/industries/marine-and-transportation/marine/fcm-lff/ammonia-as-fuel/ammonfuel-report-version-09.9-august-3.pdf>.
- Masia B. Yang M. Cozzani V., 2024, Risk Assessment of Ammonia Fueled Ships: Consequences on Human Health of Ammonia Releases from Damaged Fuel Storage Tanks, *ACS Chemical Health and Safety*,31,6,503-520, doi: 10.1021/acs.chas.4c00044
- Duong P.A., Ryu B. R., Jung J., Kang H., 2023, Comparative analysis on vapor cloud dispersion between LNG/liquid NH₃ leakage on the ship to ship bunkering for establishing safety zones, *Journal of Loss Prevention in the Process Industries*, 85, 105167, doi:10.1016/j.jlp.2023.105167.

- DNV, 2020, Ammonia as Marine Fuel Whitepaper.
- EMSA, 2023, Potential of Ammonia as Fuel in Shipping, European Maritime Safety Agency, Lisbon, <https://emsa.europa.eu/publications/reports/download/7620/4833/23.html>
- EMSA, 2024a, Safety of Ammonia for use in Ships, Part 1- Ammonia: properties, regulations and accidents review, Lisbon, <https://www.emsa.europa.eu/publications/download/7881/5264/23.html>
- EMSA, 2024b, Safety of Ammonia for use in Ships, Part 2- Safety assessment and reliability analysis of main components, equipment, sub-systems and systems, Lisbon. <https://www.emsa.europa.eu/publications/download/7985/5264/23.html>
- European Commission , 2012, Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.
- Fan H., Enshaei H., Jayasinghe S.G., Tan S. H., Zhang C., 2022, Quantitative risk assessment for ammonia ship-to-ship bunkering based on Bayesian network, *Process Safety Progress*,41(2):395-410 doi:10.1002/prs.12326.
- Franks A., Parkar S., Han C.R., 2024, Use of quantitative risk assessment to enhance the safety of ships using ammonia as fuel, *Journal of Safety and Sustainability*, 1, 3, 127-140,doi:10.1016/j.jsasus.2024.09.004.
- GSP, 2023 Ammonia as a Marine Fuel Safety Handbook <https://grontskipsfartsprogram.no/wp-content/uploads/2022/03/Ammonia-as-Marine-Fuel-Safety-Handbook-Rev-01.pdf>.
- IMO, 2004 Amendments to the International code for the construction and equipment of ships carrying dangerous chemicals in bulk (IBC code), Resolution Maritime Environment Protection Committee (MEPC), 119(52), International Maritime Organisation.
- IMO, 2014, Amendments to the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), adopted by resolution MSC. 370 (93), International Maritime Organisation.
- IMO, 2015, Resolution MSC.391(95), Adoption of the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), International Maritime Organization.
- IMO, 2025, MSC.1/ Circ. 1687, Interim Guidelines for the safety of Ships using ammonia as fuel.
- ISO, 2024, ISO 5771:2024: Rubber Hoses and Hoses Assemblies for Transferring Anhydrous Ammonia – Specification, International Standardisation Organisation.
- ISO, 1985, ISO 7105: Liquefied Anhydrous Ammonia for Industrial Use – Determination of Water Content – Karl Fisher Method, International Standardisation Organisation.
- ISO, 1985, ISO 7106: Liquefied Anhydrous Ammonia for Industrial Use – Determination of Oil Content – Gravimetric and Infra-Red Spectrometric Methods, International Standardisation Organisation.
- Jang H., Mujeeb-Ahmed M.P., Wang H., Park C., Hwang I., Jeong B., Zhou P., Mickeviciene R., 2023, Regulatory gap analysis for risk assessment of ammonia-fuelled ships, *Ocean Engineering*, 287, 2, 115751. doi: 10.1016/j.oceaneng.2023.115751
- Lloyds, 2024, IMO Maritime Safety Committee (MSC 109), Summary Report. <https://maritime.lr.org/MSC-109-Summary-Report>.
- Ng C.K.L.; Liu M.; Lam J.S.L.; Yang M., 2023, Accidental release of ammonia during ammonia bunkering: Dispersion behaviour under the influence of operational and weather conditions in Singapore, *Journal of Hazardous Materials*, 452, 131281, doi: 10.1016/j.jhazmat.2023.131281
- SGMF, 2023, Ammonia as a marine fuel- an introduction.
- SGMF, 2024, Ammonia as a marine fuel- Safety and Operational Guidelines- bunkering.
- Yang, M., Lam, J.S.L., 2024, Risk assessment of ammonia bunkering operations: Perspectives on different release scales, *Journal of Hazardous Materials*, doi: 10.1016/j.jhazmat.2024.133757