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REVIEW

Global Regulatory Landscape in Renewable E-Fuel and Fertilizer Pathways: The Case of Ammonia and Hazardous Chemicals

[version 1; peer review: 1 approved with reservations]

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Abstract

Background

The transition to renewable energy sources offers significant benefits for public health, environmental sustainability, and climate change mitigation. Ammonia, while widely used in fertilizers and emerging as a clean energy carrier, is classified as s hazardous chemical, demanding strict regulatory oversight. This dual role of ammonia - both as a risk and a solution – presents unique challenges for sustainable integration into energy and agricultural systems.

Methods

As part of the Horizon Europe project "Versatile and Direct E-fuel and Fertilizer Generation from Renewable Electricity" (VERGE), we conducted a systematic review of global regulations related to ammonia. The study analyzed 75 distinct regulatory frameworks from multiple jurisdictions, covering the synthesis, storage, and transportation of ammonia. The review focused on legal consistency, safety standards, and process control across national and international systems.

Results

The findings revealed major disparities between jurisdictions, especially in classification, compliance obligations, and safety protocols. Despite fragmentation, several high-performing regulatory models were identified, particularly within the European Union.

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Common features of effective frameworks included real-time monitoring, harmonized labeling systems, and risk-based controls. Furthermore, integration of digital technologies and life-cycle assessment methodologies was found to be growing in regulatory design.

Conclusions

Ammonia has significant potential to serve as both a renewable fuel and fertilizer component, provided that legal systems evolve to support its safe use. Harmonized global regulation, informed by best practices and technological progress, is essential to unlock ammonia's role in decarbonizing industry and agriculture. Coordinated policy efforts can facilitate the transition to sustainable ammonia pathways and accelerate the global shift toward low-carbon systems.

PLAIN LANGUAGE SUMMARY

The growing demand for clean energy combined with the ever-increasing climate crisis we face are increasingly driving the search for new technologies. Through the VERGE project our goal was to produce ammonia (a very promising ingredient for fertilizers and future sustainable fuels) using air, water, and electricity from renewable sources. However, the fact that ammonia is a hazardous substance means that its production process is subject to a series of strict regulations. The same applies to its transportation and storage. In this study, our main concern was to examine global legal frameworks related to ammonia, finding 75 in total. From these 75, we identified the most effective practices and ways to harmonize them. At the end of the research, it emerged that green ammonia could be a viable substance, a tool that would contribute decisively to a cleaner and more sustainable planet, in accordance with the right policy and technology.

Keywords

Ammonia, greenhouse gas emissions, e-fuels, regulatory framework, safety standards, transport emissions, chemicals, hazardous substances.

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Introduction

Modern technological advancements are revolutionizing the production of essential resources, setting the stage for a more sustainable and climate-neutral future. Among the most innovative breakthroughs is the creation of liquid ammonia using clean electricity, air, and water. This state-of-the-art method not only transforms traditional ammonia production but also significantly reduces the emissions linked to its use in fertilizers and marine fuels.

The potential impact is profound: this cleaner approach to ammonia synthesis has the capacity to drastically cut industrial greenhouse gas emissions, a key driver of global warming potential. As the technology advances, research efforts continue to focus on enhancing electrolytic systems for nitrogen reduction, striving to boost efficiency and ensure lasting operational reliability. Ultimately, these innovations have the power to redefine the global chemical industry and open up new pathways for sustainable progress and development.

Ammonia is a key component of the agricultural sector because it is used as a foundation for nitrogen fertilizers. When used in mineral fertilizers, its application raises soil fertility and plant nourishment, promoting global food security. However, ammonia releases from agriculture have prompted issues that have influenced the enforcement of stringent environmental policies. Global policies are being modified to establish safer production, storage, and transport regulations to guarantee that ammonia remains a viable product of global industries. Also, as the need for alternative fuels grows, ammonia's potential to be used as a shipping fuel presents an opportunity to decarbonize shipping. While there are technical and regulatory challenges, sustained research and new structures are leading the way towards ammonia-powered vessels, in line with international objectives for clean energy transitions. Through the applications of regulatory systems and technological advancements, ammonia can be at the center of seeking environmental sustainability and effective management of resources[1].

Three areas in the ammonia sector that are considered of utmost importance for the protection of human health and the environment are: the safety measures taken when dealing with it, its production process, and its proper transportation process. Each of these has specific standards that must be met in accordance to the related global legislation. Laws, Directives, Frameworks, etc. are included, diverse and differ depending on the area of their application.

Discussion/analysis of the recent literature

Safety standards

Initially, safety standards are important because they protect human health and the environment and enable the utilization of chemicals like ammonia, which, although useful in various uses, poses tremendous risk due to its toxicity, corrosiveness, and reactivity. Safety frameworks are structured in three levels. First are the **Safety Fundamentals**, which set out the underlying principles and the general objective of safety procedures—to protect people, property, and the environment. They are followed by **Safety Requirements**, binding standards that specify what must be done to ensure safety in practice. Lastly, **Safety Guides** provide technical guidance and best practices to ease implementation and adherence to the general safety goals. Together, these layers form a solid foundation for ensuring safety in diverse industries and applications[2].

Globally, safety is driven by conventions and organizations that ensure harmonized norms. The International Labour Organization (ILO) sets international standards of safe working conditions, while conventions such as the Basel and Rotterdam Conventions regulate safe transportation, trade, and dumping of hazardous chemicals and wastes. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) publish widely adopted technical standards that ensure consistency of safety measures across boundaries.

Chemical safety legislation within the European Union is extremely comprehensive and precautionary. Major laws such as REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) make sure chemicals imported or manufactured are registered and tested for safety. The CLP Regulation also puts in place uniform criteria for the classification, labeling, and packaging of substances to warn and protect users. Parallel to these is the General Product Safety Directive, which requires all consumer products to comply with general safety standards. Moreover, sector-specific directives like Seveso III aim to prevent industrial accidents involving dangerous substances by requiring risk assessment and emergency planning.

The European Standard EN 378 is particularly applying in the VERGE project. It is specifically addressing the design, operation, and disposal of refrigeration equipment based on hazardous substances such as ammonia. It places strict limits on quantities of ammonia in systems and requires best practices in leak detection, emergency ventilation, and system design to reduce public alarm from ammonia odor even when present at non-hazardous concentrations[3].

Recent developments focus on improving safety through technological advancements. This includes integrating digital monitoring systems, utilizing advanced risk assessment tools such as HAZOP and PHA, and improving emergency preparedness through systematic planning and simulation. Significant endeavors are also made to harmonize international safety standards, primarily by the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), which aims to standardize hazard classification and communication worldwide, although its adoption varies across different countries[2].

Overall, the safety criteria reflect a comprehensive and global approach to managing chemical risks. They emphasize prevention, real-time monitoring, and preparedness, particularly in the case of ammonia. Rooted in European and international legal frameworks, these criteria are increasingly influenced by innovation, sustainability priorities, and the need for harmonization, especially amid growing cross-border industrial

activities and environmental concerns. Adhering to these principles is not only essential for regulatory compliance but also critical in fostering a resilient, sustainable, and safe chemical industry.

Chemical production process

The process of chemical production is governed by a combination of legal frameworks, environmental considerations, and technical practices, particularly in the case of ammonia production. Chemical production regulations intend to guarantee the safe handling, use, storage, and disposal of chemical compounds and consider their broader implications on health, safety, and the environment. These frameworks are typically enforced by both national and global legislation, which sets requirements for risk assessment, labeling, classification, and reporting of safety data. Examples of such are REACH within the EU and TSCA in the US, both demanding registration and testing of chemical substances so that they can be declared safe and their environmental effects ascertained.

Environmental laws are also closely connected with chemical production and aim to minimize emissions, regulate hazardous waste, and implement proper wastewater treatment processes. International agreements such as the Stockholm Convention on Persistent Organic Pollutants (POPs) and the Rotterdam Convention on Prior Informed Consent (PIC) promote international cooperation in managing hazardous chemicals. At the industrial level, ammonia is produced via the well-established Haber-Bosch process, developed in the early part of the 20th century. This method synthesizes ammonia by combining nitrogen and hydrogen under high pressure and temperature in the presence of a catalyst. While energy-intensive, the process is vital in modern industry and agriculture since it enables large-scale production of fertilizers. The ecological cost of the Haber-Bosch process is significant, and it consumes around 1–2% of all energy on earth and contributes a large amount of global CO_2 emissions (roughly 1,8% to 2,0% of global CO_2 emissions, or 0,8 of around 40 billion metric tons of CO_2 annually)[4]. Consequently, there is increasing interest in transitioning to low-carbon or green ammonia production methods that use renewable energy to power electrolysis and produce hydrogen required for ammonia synthesis. Green ammonia is grouped with other low-carbon alternatives like blue ammonia, which captures and stores carbon emissions of conventional processes, with pink or yellow ammonia, which uses nuclear energy to produce hydrogen, and turquoise ammonia, which is produced by methane pyrolysis, resulting in solid residues of carbon that can be recycled[5].

Harmonization of chemical production standards worldwide remains a challenge due to disparate regulatory approaches and enforcement systems. Efforts like the Globally Harmonized System (GHS) try to offset these disparities by harmonizing chemical labeling and classification globally, although implementation remains extremely variable. With this complex and evolving background, chemical production must balance innovation and industrial necessity with a strong commitment to safety, sustainability, and global cooperation[6].

Ammonia's handling, storage and transport

Ammonia, a corrosive, hazardous, and potentially explosive compound, must be in strict compliance with environmental and chemical safety regulations to minimize the risk it presents to human health, the environment, and infrastructure. Although regulations vary around the world, they all aim to ensure the safe and efficient production, storage, and transportation of ammonia as best as possible. Environmental regulations control emissions standards, spill containment, and discharge practices, while chemical storage law addresses containment structures, emergency shutdown systems, ventilation, and real-time monitoring systems. Where transport is concerned, the regulation addresses packaging, labeling, vehicle design, loading and unloading procedures, along with personnel training, with the U.S. Department of Transportation and the United Nations Economic Commission for Europe being significant bodies regulating it.

Storage processes emphasize the use of double-wall, low-pressure, atmospheric tanks for larger amounts. These tanks typically feature outer or annular insulation and conform to international codes such as API 620 and API 625[7]. The tanks are built on elevated concrete slabs to prevent ground freezing and have been designed with considerations such as resistance to seismic conditions, wind resistance, and thermal stability. Safety aspects in storage include high-level shutdown systems, independent pressure and level indicators, lightning and earthquake protection, and vapor barriers to prevent moisture exclusion. Instrumentation and insulation design is important in maintaining tank integrity and preventing occurrences such as ice formation, structural failure, or stress corrosion cracking. The decommissioning and commissioning processes are also tightly regulated with nitrogen and ammonia purging, temperature management, sampling of gases, and meticulous checking for the sake of safety before and after operating cycles[8].

For transport, ammonia is shipped primarily by ship or pipeline, both of which are proven and mature means of transportation. Approximately 170 vessels are converted to carry ammonia, and as many as 200 ports worldwide have infrastructure to support transport today. Ammonia loss in shipping at sea is minimal, typically under 1%, and expanded utilization of low-carbon or blue ammonia has meant shipments all over regions of the world like between the Middle East, Japan, and Europe. Pipes, such as the 2,470 km Russia-to-Ukraine pipeline, previously have conducted successful ammonia shipment, and similar infrastructures are located in the United States where pipelines carry nearly 2 million tons annually within 11 states. However, geopolitical volatility and shifting energy conditions spurred increasing activity toward the reopening of LNG facilities and the new-build ammonia pipe installations to facilitate increasing demand for clean energy carriers.

Ammonia bunkering as a marine fuel is also underway, with concepts of ship-to-ship, truck-to-ship, and floating storage unit-based refueling. Safety during bunkering is ensured through dispersion simulations, leakage detection schemes, and wind-affected emission simulation. Computational fluid

dynamics simulations and advanced technologies are employed to predict the behavior of ammonia on leakage in terms, thereby enabling design toward safer handling systems. Additionally, ongoing risk management entails emergency planning, systems for detecting ammonia leaks, standby refrigeration facilities, reduction of venting, and flare systems for major emergencies. Overall, the storage, handling, and transportation of ammonia are founded on an integrated safety approach, which unites engineering standards, regulatory needs, environmental responsibility, and technological advancements to support industrial application as well as the transition to low-carbon energy systems[9].

ECHA & PFAS

The European Chemicals Agency (ECHA), (presented in Figure 1), has taken a leading role in tightening the regulatory landscape for hazardous substances, - most notably through its proposed restriction of per- and polyfluoroalkyl substances (PFAS). Although PFAS are not used directly in renewable e-fuels or ammonia-based fertilizers, the debate around them illustrates a broader regulatory trend under the EU's REACH framework toward restricting substances of very high concern[10].

PFAS comprise a diverse family of over 10,000 synthetic chemicals with widely varying properties. Only certain subgroups (for example, long-chain perfluoroalkyl acids) are well documented for their persistence, bioaccumulation potential, and toxicity[11]. Scientific articles have been published about PFAS exposure and health effects, and while it is difficult to prove direct causation in humans, studies suggest that exposure to some PFAS may be linked to harmful health effects in humans and animals—though more research is needed to clarify these relationships.

ECHA's proposal—one of the largest chemical-group restrictions ever undertaken in the EU—therefore adopts a precautionary approach, aiming to address cumulative environmental and health risks even as toxicological and epidemiological studies continue to identify which PFAS clusters pose the greatest hazards.

Industry experts have raised concerns that regulating all PFAS as a single class may be too broad. They argue that clustering PFAS by similar bioavailability, environmental fate, and reactivity would allow risk-based restrictions focused on the most problematic subgroups, while avoiding unnecessary disruption in sectors such as refrigeration, gas supply systems, and advanced manufacturing—where PFAS currently have no readily available substitutes. In response, industry representatives have proposed targeted exemptions and longer transition periods.

ECHA and the European Commission, supported by the *Chemicals Strategy for Sustainability* (2020)[12], counter that a class-wide restriction is warranted under the precautionary principle, since the extreme persistence of many PFAS means that delaying action could entail irreversible environmental and health impacts.

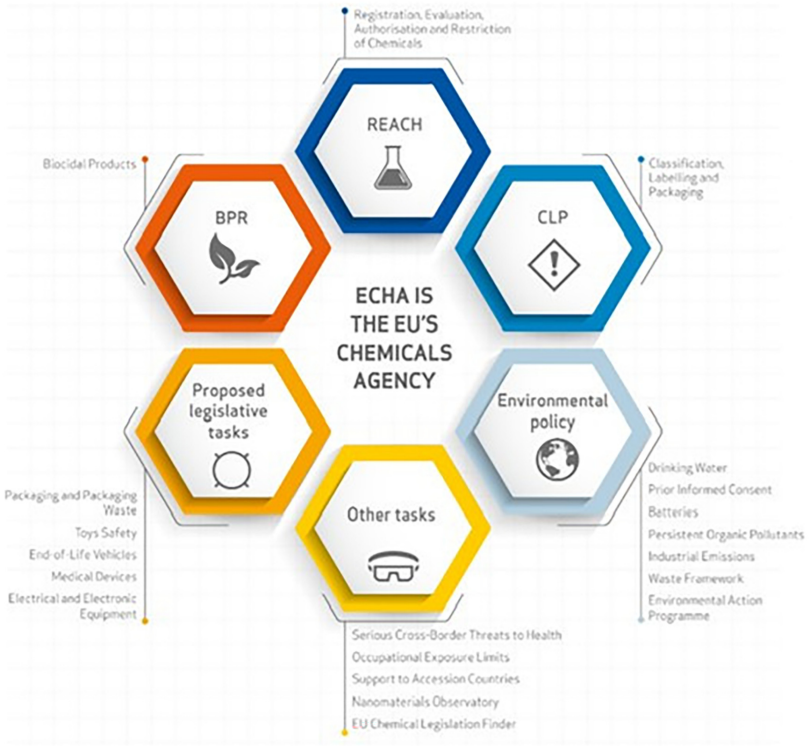

Figure 1. Overview of the European Chemicals Agency (ECHA) and Its Key Responsibilities. (source: 13).

This evolving regulatory tension is particularly relevant to ammonia—another hazardous chemical. Unlike PFAS, where regulators are debating targeted restrictions by chemical clusters rather than an outright prohibition, ammonia is essential for fertilizer production and renewable-energy pathways (including e-fuel development). Consequently, it is more likely to be managed through risk-based controls and exposure limits rather than broad, class-wide restrictions.

Figure 2. (below) illustrates some of the potential health effects reported for certain well-studied PFAS subgroups. It is not intended to imply that all PFAS share these effects, but rather to highlight why regulators and researchers are prioritizing specific PFAS families for further risk assessment and possible restriction.

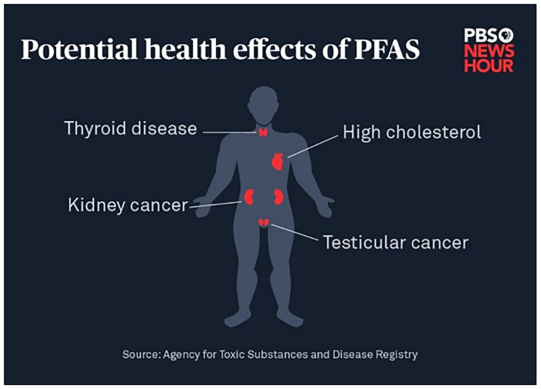

Figure 2. Potential health effects of PFAS. (source: 14).

Regulatory framework analysis

In total, seventy five (75) unique regulatory frameworks were identified in the field of dangerous chemicals, including ammonia. These were categorized based on geographical regions, typology and severity levels. They are briefly presented below.

1. *REACH Regulation (EC 1907/2006):* Aims to ensure the registration, evaluation, authorization, and restriction of chemical substances to guarantee human health and environment protection[15].

2. *CLP Regulation (EC 1272/2008):* Imposes the conditions for the classification, labeling, and packaging of chemical substances and mixtures in line with the UN's system of GHS[16].

3. (*Chemicals Strategy*, n.d.) *EU Chemical Strategy (for Sustainability):* Facilitates the transition to safe and sustainable chemicals through prioritizing innovation and safeguarding the environment[12].

4. *European Green Deal:* Aims for climate neutral EU by 2050, with far-reaching implications for sustainable chemical production and emission cuts[17].

5. *Safe and Sustainable by Design Framework (SSbD):* Sets the assessment methods of chemicals and materials considering health, safety, and sustainability from the design stage[18].

6. *F-Gas Regulation (EU 2024/573):* sets out a stricter phase-down schedule for fluorinated greenhouse gases (F-gases), for minimizing their climate impact and endorse alternatives that include a few or no global warming potential (GWP)[19].

7. *Industrial Emissions Directive (IED 2010/75/EU):* Regulates industrial installations to prevent pollution through the use of permits and the best available technology[20].

8. *Seveso III Directive (2012/18/EU):* Requires protection steps and emergency planning with the aim of preventing serious industrial accidents involving harmful chemicals[21].

9. *Chemical Agents Directive (CAD 98/24/EC):* Protects workers from the dangers caused by hazardous substances in workplaces by defining limit values and protective measures[22].

10. *FuelEU Maritime Regulation (EU 2023/1805):* Establishes mandatory GHG intensity limits for energy used in shipping and encourages the transition to sustainable marine fuels – like ammonia to cut maritime emissions across the EU beginning in 2025[23].

11. *Renewable Energy Directive (EU 2023/2413):* The Renewable Energy Directive (2023/2413/EU) – RED III strengthens the EU's renewable energy framework establishing a mandatory target of at least 42,5% renewable energy in total final energy consumption by 2030, with an ambitious objective of achieving 45%[24].

12. *Commission Delegated Regulation (EU) 2023/1184:* The Act establishes a Union methodology for the production of renewable liquid and gaseous transport fuels of non-biological origin[25].

13. *Commission Delegated Regulation (EU) 2023/1185:* The Act lays down a minimum greenhouse-gas (GHG) savings threshold and the methodology to calculate life-cycle GHG emissions savings[26].

14. *Regulation (EU) 2023/1804:* Has emission limits and reporting obligations for large industrial sectors, including ammonia handling[27].

15. *Regulation (EU) 2023/957:* Has a mainstreaming of climate and sustainability principles in chemical and product safety policy[28].

16. *Carbon Border Adjustment Mechanism (CBAM):* Prevents leakage of carbon by putting a carbon price on imports of a few products like chemical inputs[29].

17. *The National Emission Ceilings (NEC) Directive:* Aims to reduce the health and environmental impacts of air pollution while moving toward the EU's long-term air quality objectives[30].

18. *The Fertilizers Regulation (EU) 2019/1009:* Sets up unified rules for the safety, labeling, and market placement of fertilizers across the European Union,

ensuring high levels of environmental and health protection[31].

19. *Hydrogen and Decarbonized Gas Market Pack:* A 2024 EU legislative package setting common rules both for hydrogen and low-carbon gas markets, involving infrastructure access, certification of renewable gases (like hydrogen and ammonia), and measures for the promotion of integration and decarbonization[32].

20. *ADR:* It works to ensure safe transportation of dangerous goods by road across Europe to safeguard individuals, property, and the environment[33].

21. *PIC Regulation (EU 649/2012):* Uses the Rotterdam Convention in the EU export and import of risky chemicals[34].

22. *International Maritime Organization (IMO):* Develops global standards for safety, security, and environmental performance of global shipping, including the transportation of ammonia[35].

23. *Rotterdam Convention:* Manages international trade in dangerous chemicals and pesticides through prior informed consent processes[36].

24. *Basel Convention:* Limits transboundary movement and disposal of dangerous waste and chemicals[37].

25. *ISO (International Organization for Standardization):* *Creates* optional international guidelines to ensure chemical safety, enhance quality, and promote effective environmental management[38].

26. *Best Available Techniques (BAT):* Provides guidance documents to specific industrial sectors for reducing emissions as well as improving safety[39].

27. *ILO Convention No 174:* A legally binding international convention to prevent major industrial accidents and limit their consequences for workers and the environment[40].

28. *OECD:* Facilitates internationally accepted techniques for determining the safety and environmental impact of chemicals to enable harmonized testing methodologies[11].

29. *WHO for drinking-water Quality:* Seta international guidelines for safe drinking water, addressing chemical, microbiological, and radiological parameters to safeguard human health[41].

30. POPs: A global treaty aimed at eliminating or restricting the production and utilization of persistent organic pollutants, which pose serious environmental and health risks[42].

31. Minamata Convention on Mercury: A global treaty aimed at protecting human health and the environment by controlling emissions and releases of mercury and its compounds[43].

32. *CWC:* Bans the creation, accumulation, and utilization of chemical weapons, mandating their elimination under internationally supervised verification[44].

33. *RID:* Sets safety standards for the rail transport of hazardous goods to prevent accidents and protect the public and the environment[33].

34. *IMDG Code:* Provides advice on safe sea carriage of hazardous and dangerous goods to prevent accidents and marine pollution[38].

35. *ICAO Technical Instructions:* Sets international guidelines to ensure the secure air transport of hazardous materials, supporting the ICAO's broader aviation safety framework[45].

36. *IBC Code:* Defines the requirements for the design, construction, and equipment of ships transporting bulk hazardous chemical cargoes, prioritizing safety and environmental preservation[46].

37. *GHS for Chemicals:* A globally harmonized system for the classification and labelling of chemicals to ensure safe production, handling, and use worldwide[6].

38. *Toxic Substances Control Act (TSCA - USA):* Supervises the import and use of new chemical substances in the[47].

39. *Occupational Safety and Health Act (OSHA - USA):* Provides worker health and safety in operations involving hazardous chemicals like ammonia[48].

40. *Clean Air Act (CAA - USA):* Handles air pollution control such as chemicals industries emissions and ammonia production[49].

41. *U.S. Environmental Protection Agency (EPA):* Manages environmental policies like chemical emissions, waste, and industrial processes[50].

42. *RMP Rule (40 CFR Part 68):* A U.S. regulation requiring facilities that handle threshold amounts of hazardous chemicals, like ammonia, to create a Risk Management Plan (RMP) addressing accidental release prevention, emergency response, and hazardous analysis[51].

43. *EPCRA:* Mandates reporting by industries of hazardous chemicals storage and releases to increase community safety and emergency preparedness[52].

44. *Work Health and Safety Act (WHS Act – Australia):* Sets out employer and employee responsibilities for ensuring a safe workplace, such as the control of hazardous chemicals like ammonia[53].

45. *Safe Work Australia Guidelines:* Provides national model codes of practice and guidelines on the control of chemical hazards and occupational health and safety[54].

46. *The Australian Dangerous Goods (ADG) Code:* Oversees the transport of hazardous materials by setting guidelines for packaging, labeling, and emergency protocols for substances such as ammonia[55].

47. *The National Environment Protection Council (NEPC – Australia):* Develops and maintains national environmental conditions and state and territory measures for things like air and soil pollution[53].

48. *NOHSC:1005 (1994):* An Australian Code of Practice that lays down the rules for labeling hazardous stuff in workplaces, helping everyone handle chemicals safely[48].

49. *Workplace Hazardous Materials Information System (WHMIS):* Canada's nationwide system to provide information regarding hazardous workplace chemicals through labeling and safety data sheets to protect employees[56].

50. *Transportation of Dangerous Goods Act (Canada):* Regulates the safe transportation of dangerous substances, like ammonia, by all transport methods, railway, airline, and ship- within Canada[57].

51. *The Fertilizers Act (Canada):* Regulates the registering, labeling, and safeness of fertilizers used to sell in Canada, that they are efficient and safe to the consumers and environment[58].

52. *Canadian Environmental Protection Act (CEPA):* Provides a legal framework to evaluate and manage toxic substances and pollutants like ammonia to protect human health and the environment[59].

53. *Industrial Safety and Health Act (ISHA-South Korea):* Aims to prevent industrial accidents and disease by controlling dangerous substances and enforcing occupational safety standards[60].

54. *The Act on the Prevention of Air Pollution (South Korea):* Sets regulations and mitigation strategies for controlling air pollutants generated by industrial processes, including those related to ammonia emissions[61].

55. *The Green Growth Strategy (South Korea):* Encourages environmentally conscious, low-carbon growth by embedding sustainability into industrial and economic strategies with a reference on green ammonia[62].

56. *Chemical Substances Control:* A Japanese law for the production, importation, and assessment of chemical substances to mitigate environmental and health hazards[63].

57. *Factories Act of 1948 (India):* Enforces labor safety and hazardous waste management in industry, including ammonia[64].

58. *Manufacture, Storage and Import of Hazardous Chemicals:* Regulations under India's Environment Protection Act designed to manage industrial activities involving hazardous chemicals by enforcing standards for registration, labeling, and safety measures[64].

59. *Fertilizer (Control) Order, 1985:* A piece of legislation of India dealing with the quality, production, sale, and supply of fertilizers for ensuring agricultural efficiency and farm safety[64].

60. *China's Environmental Protection Law (2014):* Regulates air, water, and ground pollution, bringing ammonia use and emissions under strong controls[65].

61. *Air Pollution Prevention and Control Action Plan (China):* Focuses on major polluting sectors by enforcing strict emissions regulations and encouraging the adoption of cleaner production methods, such as those for ammonia[66].

62. *Decree No. 591:* Regulates the safe management of hazardous chemicals in China, covering classification, registration, and emergency response measures[67].

63. *Law on Chemical Substances (L. 4412/2016 – Greece):* It regulates labeling, packaging, and classification of chemical products in Greece based on EU standards like REACH and CLP for safe handling and use[68].

64. *Law on Industrial Emissions (L. 4014/2011 – Greece):* Sets the framework for environmental permits and emissions management in industrial plants, implementing the EU's Industrial Emissions Directive in Greece[69].

65. *The Health and Safety at Work Act 2015 (HSWA – New Zealand):* Core occupational health and safety legislation requiring risk management of chemicals and a safety-first culture[70].

66. *The Resource Management Act (New Zealand):* New Zealand's principal environmental law, regulating the sustainable management of natural and physical resources, including chemical process emissions and discharges[71].

67. *Environmental Conservation Acts in South Korea:* Includes a number of laws to protect water, air, and soil quality from industrial pollution, with ammonia emissions listed as a priority field[72].

68. *Industrial Safety and Health Act (Japan):* Ensures safety at work by regulating the management of dangerous chemicals, training, marking, and control stipulations[60].

69. *Brazilian Institute of Environmental and Renewable Natural Resources (IBAMA):* Places environmental approval and regulation of ammonia emissions in Brazil's manufacturing industry[73].

70. *Policy on Solid Waste (No. 12,305/2010):* A Brazilian law that establishes rules and tools for sustainable environmentally friendly solid waste management, such as hazardous industrial and chemicals waste[74].

71. *The Control of Major Accident Hazards (COMAH - UK):* UK application of Seveso III with safety reporting and emergency preparation for high-hazard industries[75].

72. *No. 7-FZ:* Establishes the fundamental regulations and principles for ensuring environmental safety and using natural resources sustainably in Russia[76].

73. *Royal Decree No. M/34:* Establishes fertilizer quality and standards in Saudi Arabia to promote safe farming practices and ensure compliance with market regulations[77].

74. *No 107 of 1998:* Sets rules for registering, selling, and using fertilizers, farm feeds, and agricultural remedies so we can be sure they are safe and good quality[78].

75. *ASEAN Agreement on Haze Pollution:* A regional agreement between ASEAN countries for the prevention, monitoring, and mitigation of haze pollution resulting from land and forest fires[79].

Their classification according to type, geographical distribution, and severity is presented in Table 1 and is depicted in Figure 3, Figure 4, and Figure 5.

Table 1. A categorization of the 75 Regulatory Frameworks. Types: ***Regulation:*** A binding act made in law directly enforceable throughout all the EU member states or within a member state, with no need for national implementation legislation. ***Act:*** A law passed by a legislative assembly to govern behavior within a country or area. ***Agency:*** A government agency or organization responsible for governing and imposing policies, laws, or rules. ***Directive:*** An act of the EU that sets out to achieve objectives for the member states, but gives them the flexibility to create their own legislation to attain the objectives. ***Law:*** A rule formally enacted by a governing authority that must be followed within its jurisdiction. ***Strategy:*** A plan or policy designed to achieve specific objectives, often over a long period of time, but not legally binding. ***Treaty:*** A formal, legally binding agreement between international organizations or states. ***Framework:*** A general plan or set of guidelines that specifies principles, aims or processes, but which has no legally binding force on its own. ***Guidelines:*** Non-binding guidance or recommendations that specify a course of action but are not mandatory. ***Decree:*** An authoritative direction issued by a head of state or government by virtue of a statute, usually without the intervention of the legislature ***Order:*** A specific order issued by an authority (for instance, a court, a minister, or an agency) which must be followed. ***Rule:*** A technical direction or routine issued under an act or law. ***Code:*** A systematic collection of regulations or rules on a specific subject. ***Standard:*** A technical standard, normally voluntary but utilized by most or sometimes mentioned in legislation. ***Convention:*** An international agreement, usually concluded under the UN, to which nations subscribe, usually needing ratification. ***Agreement:*** An authoritative agreement between parties (nations, bodies) that can be or can fail to be legally enforceable. Severity Levels: ● Very High - High: Mandatory, strict regulations with severe penalties for non-compliance. ◕ Moderate to High: Comprehensive frameworks with strong enforcement but some flexibility. ◔ Moderate: Guidelines or frameworks with limited enforcement or voluntary adherence.

S/N	Name	Geographical Boundaries	Type	Stringency/ Severity
1	REACH	EU	Regulation	● Very High
2	CLP	EU	Regulation	● High
3	Chemical Strategy (for Sustainability)	EU	Strategy	● High
4	European Green Deal	EU	Strategy	● High
5	SSbD	EU	Framework	◕ Moderate to High
6	No 2024/573	EU	Regulation	● High
7	Industrial Emissions Directive (IED)	EU	Directive	● High
8	No 2012/18/EU – SEVESO III	EU	Directive	● High
9	Chemical Agents Directive (CAD)	EU	Directive	● High
10	Fuel Maritime Regulation 2023/1805	EU	Regulation	● High
11	Regulation 2023/2413	EU	Directive	● High
12	Regulation (EU) 2023/1184	EU	Regulation	● High
13	Regulation (EU) 2023/1185	EU	Regulation	● High
14	No 2023/1804	EU	Regulation	● High
15	No 2023/957	EU	Regulation	● High

S/N	Name	Geographical Boundaries	Type	Stringency/ Severity
16	CBAM	EU	Regulation	High
17	NEC Directive	EU	Directive	High
18	Fertilizers Regulation (EU) 2019/1009	EU	Regulation	Very High
19	Hydrogen and Decarbonized Gas Market Pack	EU	Policy Pack	Moderate to High
20	ADR	EU	Agreement	Very High
21	No 649/2012 – PIC Regulation	International	Regulation	High
22	IMO	International	Agency	High
23	Rotterdam Convention	International	Treaty	High
24	Basel Convention	International	Treaty	High
25	ISO	International	Agency	Moderate
26	Best Available Techniques (BAT)	International	Framework	High
27	ILO Convention No 174	International	Convention	Moderate to High
28	OECD	International	Guideline	Moderate to High
29	WHO for drinking-water Quality	International	Guideline	Moderate
30	POPs	International	Treaty	Very High
31	Minamata Convention on Mercury	International	Treaty	Very High
32	CWC	International	Treaty	Very High
33	RID	International	Regulation	High
34	IMDG Code	International	Code	Very High
35	ICAO Technical Instructions	International	Regulation	Very High
36	IBC Code	International	Code	Very High
37	GHS for Chemicals	International	System	High
38	TSCA	US	Act	Moderate
39	OSHA	US	Agency	Moderate
40	CAA	US	Law	Very High
41	EPA	US	Agency	High
42	RMP Rule (40 CFR Part 68)	US	Rule	Very High
43	EPCRA	US	Act	High
44	WHS Act	Australia	Act	Moderate to High
45	Safe Work Australia Guideline	Australia	Guideline	Moderate
46	ADG Code	Australia	Regulation	Moderate to High
47	NEPC	Australia	Agency	Moderate to High
48	NOHSC:1005(1994)	Australia	CoP	Moderate to High
49	WHMIS	Canada	Regulation	High
50	TDGA	Canada	Act	High
51	The Fertilizers Act	Canada	Act	High
52	CEPA	Canada	Law	High

S/N	Name	Geographical Boundaries	Type	Stringency/ Severity
53	ISHA	Japan	Act	High
54	Act on the Prevention of Air Pollution	Japan	Act	High
55	The Green Growth Strategy	Japan	Strategy	High
56	Chemical Substances Control	Japan	Act	Very High
57	Factories Act of 1948	India	Act	Moderate
58	Manufacture, Storage and Import of Haz.Chems	India	Rule	High
59	Fertilizer (Control) Order, 1985	India	Order	High
60	Environmental Protection Law (2014)	China	Law	High
61	Air Pollution Prevention & Control Plan	China	Strategy	High
62	Decree No. 591	China	Decree	High
63	Chemical Substances (L. 4412/2016)	Greece	Law	High
64	Industrial Emissions (L. 4014/2011)	Greece	Law	High
65	HSWA	New Zealand	Act	High
66	RMA	New Zealand	Act	High
67	Environmental Conservation Acts	South Korea	Act	High
68	ISHA	South Korea	Act	High
69	IBAMA	Brazil	Agency	High
70	Policy on Solid Waste (No. 12,305/2010)	Brazil	Law	Moderate
71	COMAH	UK	Regulation	High
72	No. 7-FZ	Russia	Law	High
73	Royal Decree No. M/34	Saudi Arabia	Decree	Moderate to High
74	No. 107 of 1998	South Africa	Law	Moderate
75	ASEAN Agreement on Haze Pollution	ASEAN Reg.	Treaty	Moderate

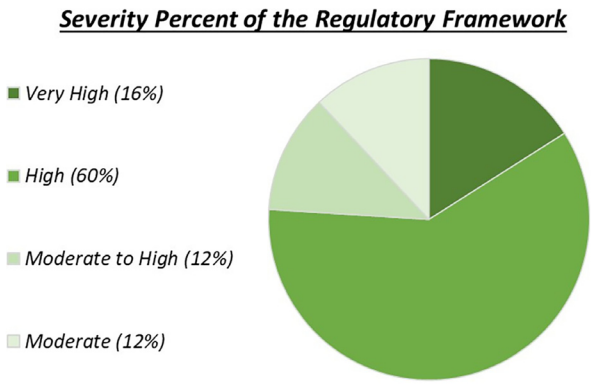

Figure 3. Severity Levels allocation of the Global Regulatory Framework.

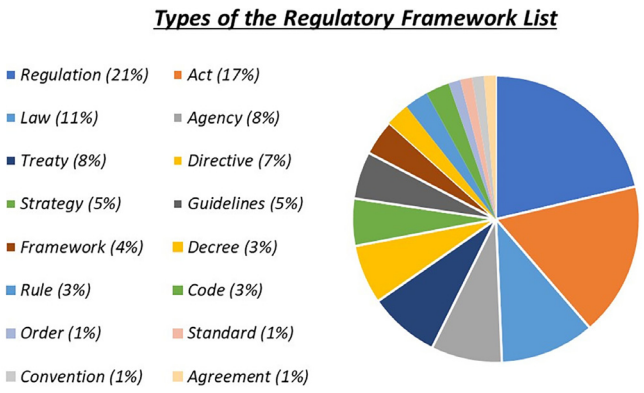

Figure 4. Types allocation of the Global Regulatory Framework.

While ammonia is the primarily focus of our analysis, the other chemicals are considered secondary. Additionally, we categorized all 75 regulatory frameworks based on their relevance to ammonia, as shown in the following Figure 6.

Conclusions

Ammonia is a cornerstone of modern agriculture and an emerging player in renewable fuel economies, subject to complex regulatory frameworks. It is an essential yet hazardous substance, widely used but subject to intense regulatory scrutiny. The Horizon Europe VERGE project is tackling this duality by exploring the potential of utilizing ammonia more effectively through new production technologies and ensuring risks are kept in check by adhering to thorough regulation compliance.

Throughout the European Union and globally, legislative frameworks such as REACH, CLP, the Industrial Emissions Directive, and more recently introduced legislation focused on renewable fuels of non-biological origin (RFNBOs) have placed stringent requirements for the safe handling, storage, and transportation of chemicals. These are complemented by international agreements, such as the Rotterdam Convention and national regulations that reinforce a shared commitment to chemical safety.

The regulation of ammonia signifies a substantial policy transformation in several key ways:

1. Reframing an industrial chemical as part of circular economy solutions rather than just a pollutant
2. Recognizing the dual nature of ammonia as both an environmental challenge (through emissions) and a potential climate solution (as green ammonia)
3. Creating regulatory frameworks that address both the risks and opportunities
4. Demonstrating how traditional industries can be reimagined for a low-carbon future

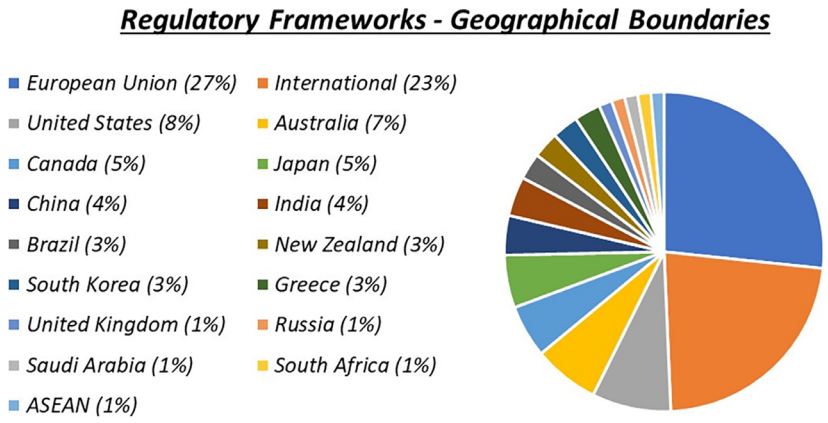

Figure 5. Geographical Boundaries of the Global Regulatory Framework.

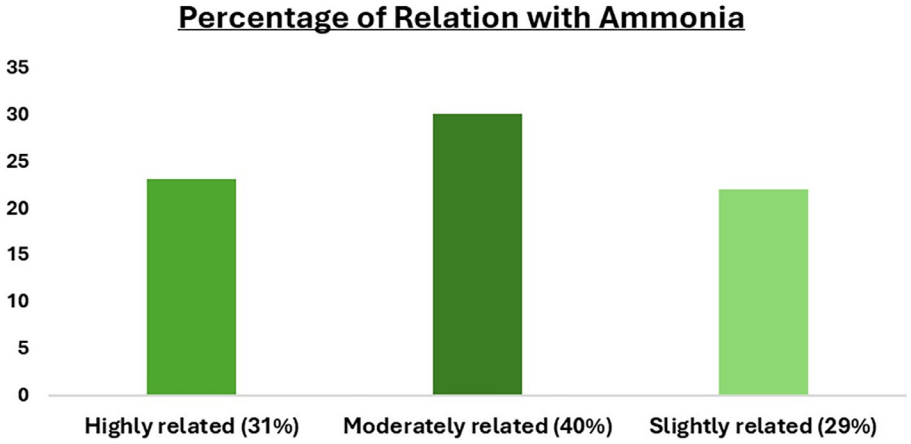

Figure 6. Percentage of relevance of legislation to ammonia.

5. Linking previously separate policy areas, including agricultural emissions, industrial policy, and energy transition.

This shift represents broader changes in environmental governance where regulations increasingly seek to balance pollution control with innovation pathways. Ammonia regulation exemplifies how policymakers are working to transform linear production models into circular systems that minimize waste and environmental impacts while maximizing resource efficiency.

As ammonia emerges as both a staple fertilizer and a green energy carrier, regulatory frameworks must adapt to evolving production technologies. Producing green ammonia with renewable electricity offers both an opportunity and a challenge: on the one hand, it holds great promise to decarbonize shipping, heavy industry, and agriculture, but, on the other, it requires coherent and harmonized standards if it is to deliver environmental integrity and operational safety. Future policy will therefore have to strike a careful balance - fostering innovation while ensuring robust safeguards for both human well-being and environmental health.

Horizon Europe initiatives such as VERGE contribute positively to this discussion by bridging scientific research and policy experience. By mapping the global regulatory landscape, this study helps to identify gaps or inconsistencies and facilitate the safe development of new technologies. The path forward will rest on continued cooperation among public institutions, industry, academia, and civil society. It is only through such coordinated efforts that Europe and the world can transition towards an authentically sustainable an secure economy, where chemicals like ammonia are seen not only as risks, but also as acceleration drivers of the green transition.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Underlying data

Zenodo: VERGE Project – Global Regulatory Landscape in Renewable E-Fuel and Fertilizer Pathways.

https://doi.org/10.5281/zenodo.16571437[80].

The project contains the following underlying data:

- Table_1._Regulatory_Framework.pdf (PDF version of the master table presenting the 75 global regulatory frameworks categorized by geography, type, and severity).

Extended data

Zenodo: VERGE Project – Global Regulatory Landscape in Renewable E-Fuel and Fertilizer Pathways. https://doi.org/10.5281/zenodo.16571437[80].

This project contains the following extended data:

- Figure_1.jpg (Overview of the European Chemicals Agency and its key responsibilities)
- Figure_2.jpg (Illustration of potential health effects of PFAS)
- Figure_3.jpg (Severity levels allocation of the global regulatory framework)
- Figure_4.jpg (Types allocation of the global regulatory framework)
- Figure_5.jpg (Geographical distribution of the global regulatory framework)
- Figure_6.jpg (Percentage of relevance of legislation to ammonia).

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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Zhefei Pan
Chongqing University, Chongqing, China

The manuscript titled "Global Regulatory Landscape in Renewable E-Fuel and Fertilizer Pathways the Case of Ammonia and Hazardous Chemicals" focuses on the global regulatory framework of "ammonia as a renewable fuel/fertilizer", which has clear value for open science, policy transparency, and interdisciplinary research. However, the methodological transparency and depth of the results in the article are insufficient. Therefore, I suggest making minor revisions to the current manuscript. The specific suggestions are as follows:

1. The methodology of the article is insufficient. It is suggested to include a complete search formula, database, inclusion and exclusion criteria, and quality assessment tools, and provide a corresponding flowchart.
2. The depth of the regulations in the article is insufficient. It is recommended to add a "horizontal comparison matrix" in the results section, such as differences in classification thresholds; emergency response requirements for leakage/accidents; licensing procedures; penalty intensity, etc.
3. The conclusions and policy recommendations in the article are rather general. It is necessary to provide specific and operational policy roadmaps in the conclusion.

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Renewable Energy Research

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.