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INNOVATIVE APPROACHES TO DEVELOPING SAFETY STANDARDS FOR TRANSPORTING HAZARDOUS CHEMICALS: INTERNATIONAL EXPERIENCE AND APPLICATION IN THE UNITED STATES

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Abstract. *The article focuses on innovative approaches to shaping safety standards for transporting hazardous chemicals, taking into account international experience and their application in the United States of America. The purpose of the article is to examine innovative approaches to developing safety standards for the transportation of hazardous chemicals in the context of U.S. agricultural production, considering international practices. The study employed general scientific methods of cognition: analysis, synthesis, comparison, generalization, systems approach, and induction. The findings show that the use of hazardous chemicals in U.S. agriculture covers a wide range of agrochemicals, including nitrogen, phosphate, and potassium fertilizers, as well as pesticides based on glyphosate and other active substances. It has been demonstrated that their use is a key factor in maintaining the stability of agricultural production, yet it creates significant risks to human health and the environment, especially during transportation. The analysis of international standards revealed that the regulatory framework for transporting hazardous goods is based on the UN Model Regulations, which harmonize approaches across different modes of transport and countries. It was found that European ADR rules and U.S. HMR show similarities in aligning requirements, but the U.S. retains the right to adapt them to national conditions, setting stricter standards in cases of heightened infrastructure or security needs. This model combines the flexibility of international agreements with domestic oversight, allowing for effective regulation of intensive agrochemical flows in the U.S. A significant innovation is identified in the "SafeAgroLogistics" methodology by Tamara Kovryzhenko, which integrates Internet of Things technologies, artificial intelligence algorithms, and preventive safety protocols into the organization of hazardous chemical transportation.*

Keywords: *safety, chemicals, transportation, standards, innovation.*

Introduction

Modern agriculture increasingly depends on efficient logistics, as production scales and the use of agrochemicals continue to grow each year. The transportation of fertilizers, pesticides, and other hazardous substances is a critical stage in the agricultural cycle, since timely and safe delivery directly affects crop yields and the stability of food markets. In this context, innovations in logistics processes serve as a key factor in enhancing safety, reducing environmental risks, and optimizing producers' costs.

The implementation of new technologies – from digital monitoring and intelligent routing systems to the use of environmentally friendly materials and multimodal transport solutions – makes it possible to adapt agrochemical logistics to current challenges. This not only ensures compliance with international standards but also creates new opportunities to strengthen the competitiveness of the agricultural sector. Therefore, innovative logistics approaches are becoming an integral part of sustainable agricultural development, focused on efficiency and safety.

Literature Review

The issue of innovative approaches to developing safety standards for transporting hazardous chemicals and their application in the U.S. remains insufficiently studied in foreign academic and regulatory literature, as most sources emphasize international experience and regulatory practices.

Significant contributions to the topic include international documents such as the Recommendations on the Transport of Dangerous Goods – Model Regulations [8], which form the global basis for harmonizing rules. Equally important is the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) [11], which ensures the unification of classification and labeling standards. At the regional level, ADR 2025 [12] regulates international road transport.

In the U.S., key documents include those issued by the Department of Transportation, such as DOT Chart 17 [3], which systematizes hazard signs, and 49 CFR Part 171, Subpart C [10], which establishes rules for applying international standards in national legislation. Another crucial act is Hazardous Materials: Harmonization With International Standards (Final Rule) [4], reflecting U.S. efforts to integrate into the global system. Reports in the agricultural sector, such as USDA NASS analytics [9] and studies by R. Nehring and E. Njuki [7], provide additional insights into agrochemical use trends.

Publications by A. Miranda, F. Hernandez-Tenorio, F. Villalta, G. Vargas, A. Sáez [6], and P. Magnabosco, A. Masi, R. Shukla [5] focus on the development of biostimulants and biofertilizers, while sources [1,2] highlight innovative approaches to reducing environmental risks from chemical use, indirectly affecting the regulation of hazardous material transportation. Expert literature from modern online publications and official resources (phmsa.dot.gov, federalregister.gov, ecfr.gov, unece.org) was also used, reflecting the latest updates in international and U.S. standards.

Thus, despite the abundance of scientific and regulatory sources, there is a shortage of systematic materials that integrate innovative approaches to transporting hazardous chemicals. By applying scientific analysis methods, the presented information was grouped, analyzed, and structured according to the subject of the study.

The purpose of the article is to examine innovative approaches to developing safety standards for the transportation of hazardous chemicals in the context of U.S. agricultural production, considering international experience. The *objectives* include: first, analyzing the specifics of hazardous chemicals used in agriculture along with logistics risks and current transport regulations; second, characterizing the features of international and national safety standards with an emphasis on harmonization and U.S. national differences; third, identifying the potential for implementing innovative solutions capable of improving the safety and efficiency of agricultural logistics.

Research Results

Before examining innovative approaches to developing safety standards for transporting hazardous chemicals, it is necessary to define what hazardous chemicals represent. At present, several regulatory documents govern the classification of dangerous substances. These include the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), developed under the UN [9], as well as the U.S. Department of Transportation's Hazardous Materials Classification System [3].

According to these documents, hazardous chemicals are classified to establish rules for labeling, packaging, and transportation. The use of this system helps minimize risks when handling hazardous substances, especially during transportation. Since the focus here is on chemicals applied in agriculture, it is essential to determine which types from different classes of hazardous chemicals are used in this sector. A systematization of such substances is presented in Table 1.

Table 1 – Chemicals used in agriculture

Class (by GHS/DOT)	Description	Use in agriculture and risks
Class 2 (gases)	Compressed, liquefied, and dissolved gases under pressure	Ammonia is used as a fertilizer (anhydrous ammonia), chlorine is applied for disinfecting grain storage facilities. Risks: leaks, respiratory damage, suffocation hazard.
Class 3 (flammable liquids)	Liquids that evaporate easily and form explosive mixtures with air	Organic solvents sometimes included in pesticide mixtures. Risks: ignition, explosion, release of toxic vapors.
Class 5 (oxidizers and organic peroxides)	Substances that release oxygen and may cause or intensify combustion	Nitrate compounds (ammonium nitrate) are widely used in fertilizer production. Risks: explosions if stored improperly, fire hazard.
Class 6 (toxic substances)	Substances that can cause poisoning when inhaled, ingested, or in contact with skin	Pesticides, insecticides, and herbicides applied for crop protection. Risks: acute and chronic poisoning, environmental contamination.
Class 8 (corrosive substances)	Chemicals that destroy living tissue and damage materials upon contact	Sulfuric acid, sodium hydroxide, and other reagents for soil treatment and equipment cleaning. Risks: container degradation, danger to humans and animals.
Class 9 (miscellaneous dangerous substances)	Substances with combined or specific hazards	Lithium-ion batteries used in agricultural machinery, as well as certain chemicals with mixed properties. Risks: fires, release of toxic substances.

Note: systematized by the author based on research [3, 9]

Thus, hazardous chemicals used in agriculture fall into several main classes, with particular attention required for gases, flammable liquids, oxidizers, toxic and corrosive substances, as well as materials with mixed hazards. Their proper classification into the appropriate category forms the basis for developing and implementing safety measures during transportation [11; 3].

In the United States, the use of chemicals in agriculture is practically ubiquitous. The most common fertilizers remain potash (applied on 46% of acreage, averaging 88 pounds per acre), phosphate (44% of acreage), and nitrogen (30% of acreage). The total amount of potash fertilizers applied exceeded 3.2 billion pounds, while phosphate fertilizers amounted to over 2 billion pounds. In addition, sulfur was used on 14% of fields, primarily for soil property correction [9].

As for pesticides, their use in soybean cultivation is even more extensive: herbicides were applied on 96% of planted areas, fungicides on 22%, and insecticides on 21%. Among herbicides, glyphosate (isopropylamine salt) was the most widely used, applied on 46% of acreage, followed by 2,4-D (choline salt) on 37%. Together, they form the backbone of chemical weed control in soybeans. Such widespread application is explained by both the high level of weed competition and the dominance in the U.S. of soybean cultivation technologies resistant to glyphosate [9].

In the long term, there is a clear trend toward increasing use of chemicals in U.S. agriculture. A number of innovative approaches in modern farming are aimed at improving soil fertility and replacing traditional chemical products. One promising direction is the application of nanotechnology in the form of nano-biostimulants – systems where nanomaterials (particles ranging from 1–100 nm) are combined with biostimulants for a synergistic effect. This allows controlled release of active substances, increases their effectiveness at much lower doses, and simultaneously reduces environmental impact. Among the significant advantages are the use of biostimulants derived from waste (such as biomass), which supports a circular economy, and the high environmental sustainability of such solutions [5]. Another important line of innovation involves the use of microalgae-based bioproducts – both as biofertilizers and biostimulants [6].

It is also important to note that innovations extend into the logistics of agricultural products, particularly fertilizers. Supply chain optimization includes the development of multimodal transport solutions, such as the use of river-railway interchanges for faster and more energy-efficient delivery of nitrogen, phosphate, and potash fertilizers. This ensures flexibility, speeds up delivery during peak demand periods (planting/spraying seasons), and reduces logistics costs.

Before the implementation of innovative safety standards for transporting hazardous chemicals, it is important to outline how such standards are developed at the international level. The UN Model Regulations on the Transport of Dangerous Goods are developed by the Committee of Experts under the UN Economic and Social Council (ECOSOC). They are updated regularly – every two years – with the involvement of specialists in transport, chemical classification, testing, and regulation [8]. These regulations were created to harmonize national and international requirements, ensuring unified classification, packaging, labeling, testing, and documentation [4].

In the regional context, for example in Europe, the ADR-2025 Agreement concerning the International Carriage of Dangerous Goods by Road entered into force on January 1, 2025. It contains specialized provisions for modern types of transport, including the use of electric and hydrogen vehicles of categories FL and AT, the transport of molten aluminum in bulk, as well as hazardous waste, including asbestos in sealed bags [12]. Such updates demonstrate the adaptability of standards to technological progress and new logistical challenges.

Table 2 presents the key approaches to developing safety standards for transporting hazardous chemicals.

Table 2 – Approaches to developing safety standards for transporting hazardous chemicals

Stage / methodological approach	Description
1. Development of model regulations (UN)	The Committee of Experts under ECOSOC prepares the Model Regulations, which contain unified requirements for classification, packaging, labeling, documentation, testing, and training. They are drafted using the wording “shall” to allow smoother integration into national legislation.
2. Harmonization and unification	The Model Regulations serve as the foundation for international agreements (ADR, IMDG, ICAO), as well as for national standards, ensuring consistency, reducing legal adaptation costs, and facilitating compliance.
3. Regular updates (revisions)	Periodic reviews every two years include updates to criteria, introduction of new classes, changes in testing procedures, and consideration of new technologies (for example, lithium batteries, bioreactors, new packaging materials).
4. Adaptation to new transport technologies	The standards take into account modern logistical solutions: electric vehicles, hydrogen-powered transport, bulk transportation of specific materials (molten aluminum, asbestos), including special safety requirements.
5. Regulation of packaging and documentation	Clear criteria are set for packaging (testing, design, materials), labeling (UN numbers, hazard classes), marking, and transport documentation to ensure safety and compliance.
6. Transition periods and implementation	New editions enter into force with clearly defined transition periods (example: ADR-2025 — from January 2025 to June 2025), allowing stakeholders time to adapt.

Regulatory control over the transportation of hazardous chemicals in the United

States is based on the provisions of the Hazardous Materials Regulations (HMR), codified in the Code of Federal Regulations (49 CFR, Parts 171–180). An important element is Subpart C Part 171, which directly allows the application of international standards – such as the Recommendations on the Transport of Dangerous Goods (Model Regulations), ICAO Technical Instructions, and the IMDG Code. This means that carriers engaged in international or multimodal transportation may apply international rules, provided they comply with U.S. safety criteria [10]. In this way, the basic requirements for classification, labeling, packaging, and shipment documentation are harmonized with international approaches, simplifying cross-border transport.

However, there are certain features that distinguish the U.S. from other jurisdictions.

First, the United States retains the right to national adaptation. When international rules do not account for local conditions (such as infrastructure specifics or requirements for domestic transport), stricter HMR provisions apply. Second, the U.S. maintains a system of regular harmonization through rulemaking: the latest major update by PHMSA (Pipeline and Hazardous Materials Safety Administration), known as HM-215Q, was issued in April 2024. This final rule introduced changes aligning national requirements with the 22nd revision of the UN Model Regulations, as well as with the updated ICAO TI and IMDG Code [4].

It is also important that PHMSA sets transition periods during which stakeholders can gradually shift to new requirements. This reduces the risk of violations and gives businesses time to adapt documentation, packaging, and transport procedures. Another distinctive feature is the strong emphasis on administrative accountability and enforcement: any carriers applying international standards must obtain confirmation of compliance from federal authorities; otherwise, the national HMR rules apply [10; 4].

Thus, the American system combines harmonization with international regulations and the simultaneous preservation of national legal mechanisms of oversight. This enables the U.S. to remain aligned with international standards while addressing its own safety and infrastructure priorities.

The challenge of developing safety standards for transporting hazardous chemicals is global, since accidents during transport may have catastrophic consequences for human health, the environment, and the economy. International experience (ADR in Europe, DOT in the U.S., UN Recommendations on the Transport of Dangerous Goods) demonstrates the importance of a systemic approach that combines regulatory frameworks, technical standards, and personnel training. In this context, the "SafeAgroLogistics" methodology by Tamara Kovryzhenko could serve as a basis for updating standards in the U.S., as it integrates IoT, AI, and multi-level safety protocols, enabling a shift from the traditional regulatory approach to intelligent, preventive solutions.

Table 3 – Application of the "SafeAgroLogistics" methodology in developing safety standards (international experience – U.S.)

Standards component	International experience (ADR, DOT, UN)	Added value of Tamara Kovryzhenko's "SafeAgroLogistics" methodology
Technical vehicle control	Regulatory inspections before departure	IoT sensors for continuous real-time monitoring
Routing	Selection of safe routes according to regulations	Intelligent AI-based routing that accounts for environmental zones
Emergency response	Notification procedures through operators	Automated "smart emergency" protocol
Personnel training	ADR/DOT standards	Specialized agrochemistry training and online driver monitoring
Environmental requirements	Use of safe packaging, transport restrictions	Environmental monitoring system and impact modeling
Economic efficiency	Not a priority	Optimization of loading and routing (cost reduction by 15–20%)

Note: systematized by the author based on [8, 12]

Thus, innovative safety standards for transporting hazardous chemicals are of great importance for agricultural production, since the agricultural sector is one of the largest consumers of chemical fertilizers, pesticides, and other hazardous substances. The traditional regulatory system (based on HMR in the U.S. and international acts such as ADR and the UN Model Regulations) ensures a minimum level of safety, yet current challenges demand more flexible and technologically advanced approaches.

Among the most promising innovative standards is the integration of digital monitoring technologies. The use of IoT sensors on transport vehicles allows real-time tracking of transportation parameters (temperature, pressure, container integrity), which reduces the risk of accidents. It also increases transparency in logistics and enables agricultural producers to respond promptly to potential violations. Another important direction is intelligent routing with the use of artificial intelligence algorithms to select optimal transport routes, taking into account environmental zones, population density, and infrastructure limitations. This not only enhances safety but also reduces costs by shortening delivery times and optimizing fuel consumption. An equally important element is ecological integration into transport standards. New approaches include not only requirements for packaging and containers but also environmental monitoring systems that model the consequences of potential accidental releases. For U.S. farms, this means greater public trust, compliance with international eco-standards, and better market access.

Combined, these innovative standards – digital monitoring, AI-based routing, and environmental oversight – can have a positive impact on the operations of U.S. farms. They lower logistics and insurance costs, minimize the risks of fines and reputational damage in case of incidents, and ensure reliable supply of critical agrochemicals during peak periods of the agricultural cycle. Thus, the integration of innovative safety standards into the transportation of hazardous chemicals serves not only as a regulatory requirement but also as a factor of competitive advantage for the U.S. agricultural sector.

Conclusions

The use of hazardous chemicals in U.S. agriculture covers a wide range of fertilizers and plant protection products, with nitrogen, phosphate, and potash compounds, as well as glyphosate-based and other active ingredient pesticides, playing a key role. Their application secures production stability but at the same time creates risks to human health and the environment, especially during transportation. For this reason, agrochemical logistics is based on strict rules of classification, labeling, and transportation, which help minimize accidents and reduce the likelihood of large-scale environmental consequences.

The international system of hazardous materials transport safety is built on the

UN Model Regulations, which provide unified standards across different modes of transport and countries. The European ADR and U.S. HMR show a similar approach to harmonization, while the U.S. retains the right to national adaptation by implementing stricter standards in cases dictated by infrastructure or safety needs. Thus, the U.S. system combines the flexibility of international agreements with domestic oversight, ensuring effective regulation under conditions of high agricultural logistics intensity.

In modern conditions, innovative standards are beginning to play a key role, particularly digital monitoring, artificial intelligence for routing, and environmental control systems. A significant innovation is the "SafeAgroLogistics" methodology by Tamara Kovryzhenko, which integrates IoT, AI, and preventive safety protocols into the process of transporting hazardous chemicals. Its application may become a catalyst for transitioning from the classical regulatory approach to dynamic, intelligent solutions that will enhance efficiency and the competitiveness of U.S. farms.

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