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RISKS ANALYSIS OF INTERNATIONAL ROAD TRANSPORTATION OF HERBICIDES AND AGROCHEMICALS: MINIMIZATION METHODS AND CONSEQUENCES FORECASTING

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Abstract. *The article is devoted to the analysis of risks arising during international road transportation of herbicides and other agrochemicals, as well as to the methods of their minimization and forecasting of possible consequences. The purpose of the article is to highlight the existing safety standards for the transportation of hazardous chemicals, to analyze the key risks accompanying the transportation of agrochemicals, and to justify an improved risk management methodology that integrates regulatory requirements with the practical needs of agricultural production. The research employed general scientific methods of cognition: analysis and synthesis, a systems approach, induction and deduction, generalization, as well as methods of comparative analysis of regulatory and legal documents. It was established that the regulatory framework for the transportation of hazardous goods is shaped through a combination of international and national standards. The paper emphasizes the role of universal documents, in particular the UN Model Regulations and the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), which create the basic conditions for safe transportation. It is shown that regional and national acts – ADR in Europe and HMR/DOT in the USA – provide detailed requirements for different modes of transport, though they mostly focus on formal procedures and do not always account for the specifics of small shipments or dynamic risk factors. The study found that improvement of the existing system is possible through the introduction of innovative solutions, among which the "SafeAgroLogistics" methodology plays a key role. This concept relies on IoT sensors for continuous monitoring of cargo conditions, artificial intelligence algorithms for predicting potential emergencies, and intelligent routing that considers socio-environmental aspects. It was also revealed that the system's efficiency increases with the implementation of automated "smart emergency" protocols and specialized personnel training. The conclusion drawn is that the proposed approach allows not only to optimize control processes and reduce economic costs, but also to establish a new level of environmental and social safety in agrochemical logistics.*

Keywords: *agrochemicals, logistics, risks, transportation, safety.*

Introduction

The implementation of international and national safety standards for the transportation of hazardous chemicals directly influences the organization of agricultural production, especially in countries with a high level of agrochemical use, such as the USA. Since herbicides, insecticides, and fungicides form the foundation of modern intensive farming systems, their safe transportation from manufacturers to farms is a key link in agricultural logistics. Existing standards regulate the classification, packaging, labeling, and transportation of toxic substances, which reduces the risks of leakage, mixing with other goods, and accidents during transport. For farmers, this means that chemicals are delivered in standardized containers resistant to mechanical damage, with clear labeling and safety documentation. Even in the case of small shipments for local farms, a basic level of protection for workers and the environment is ensured. In practice, standards influence several aspects of agricultural enterprises. First, they determine requirements for storage and unloading: the use of sealed warehouses, specialized areas for temporary storage, and equipment for eliminating possible leaks. Second, farms must account for logistical restrictions – for example, requirements concerning transport routes, avoiding shipments near densely populated areas or water resources. Third, compliance with standards requires greater attention to the accounting and use of agrochemicals, as any violations in transportation or handling of pesticides may entail legal and environmental consequences.

The problem of transporting herbicides and agrochemicals lies in the fact that, despite the existence of international and national safety standards, their application in the agricultural sector remains insufficiently adapted to the realities of farms. Regulations are primarily focused on technical aspects of transportation but do not take into account other important factors, such as the specifics of small shipments, the variability of risks over time, and the limited emergency response capacity of local operators. This creates a gap between formal regulation and the practice of agrochemical logistics, increasing potential environmental and social risks.

Literature Review

Scientific literature is represented by the works of J. Guo, S. Chen, X. Zhang [3] and L. Liu, Q. Wang, S. Li, Y. Li, T. Fang [4], which focus on methods of risk assessment in hazardous materials transportation and on considering environmental factors in transport systems. In addition to scientific studies highlighting the processes of minimizing logistical risks, international reports and regulations of organizations such as CropLife International [1], FAO [2], USDA NASS [5], PHMSA [6], USGS [7], UNECE [8; 9; 10] were used in this research. These documents define the rules for the transportation, classification, and circulation of hazardous substances.

Systematizing the information from all these reports made it possible to collect valuable data on the risks of analyzing international transportation of agricultural fertilizers, identify weaknesses, and present the author's model that addresses the identified problems.

The purpose of the article is to highlight the existing safety standards for the transportation of hazardous chemicals, to analyze the key risks accompanying the transportation of agrochemicals, and to justify an improved risk management methodology that integrates regulatory requirements with the practical needs of agricultural production.

Research Results

Although the agricultural production system in the USA is characterized by a high level of technological development, it also demonstrates an exceptionally high dependence on agrochemicals, particularly herbicides. According to the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS), in 2023 a survey of soybean producers covered 19 states, accounting for 96.3% of planted acres. The application of mineral fertilizers in soybean cultivation covered a significant share of the planted area. The most common were potash fertilizers (46% of the area, 3.3 billion pounds in 2023), phosphate fertilizers (44% of the area, 2.0 billion pounds), nitrogen fertilizers (30%, 0.54 billion pounds), and sulfur (14%, 0.23 billion pounds). This indicates a comprehensive approach to soil nutrition aimed at ensuring high yields, but it also implies the formation of stable logistical flows in the supply system of mineral resources [6].

Table 1 – Statistics on the use of agricultural fertilizers in 2023

Herbicides, including:	96%
Glyphosate (isopropylamine salt)	46%
2,4-D (choline salt)	37%
Glyphosate (potassium salt)	22%
Glufosinate-ammonium	23%
Fungicides	22%
Insecticides	21%
Other	4%

Note: systematized based on data [6]

According to the estimates of the USGS Pesticide National Synthesis Project, more than 400 active pesticide ingredients are applied annually in the United States, with total volumes reaching hundreds of millions of pounds [7]. Such scale determines the formation of a complex logistics system that includes raw material imports, domestic distribution, seasonal fluctuations in demand, and strict requirements for transportation safety. Particular attention is given to substances of class 6.1 (toxic substances, UN Model Regulations), which include most herbicides.

These factors generate a range of logistical challenges that encompass not only economic and organizational dimensions but also strongly affect environmental safety. Excessive use of herbicides (especially glyphosate) is considered one of the main factors behind soil and surface water contamination, which further complicates logistics control and the monitoring of consequences [7].

At first glance, the issue of fertilizer logistics may appear universal, since standards and general rules for cargo transportation exist. However, certain categories of products have specific requirements that go beyond general regulations. This applies to herbicides and agrochemicals, the transportation of which relates not only to the safety of carriers and end users but also to environmental stability and the prevention of potential catastrophic consequences for ecosystems.

One of the key aspects concerns requirements for carriers and vehicles. CropLife International guidelines emphasize that 1) transport must be technically sound, properly equipped, and separated from the driver's cabin to avoid vapor exposure in case of leakage; 2) the selection of qualified drivers is essential, as they must not only possess professional driving skills but also have specialized training in handling hazardous goods, including emergency actions, fire safety measures, and first aid; 3) vehicles must be equipped with fire extinguishers, first aid kits, and comprehensive sets of protective equipment. The latter should not be limited to protective clothing, but also include resistant footwear, safety goggles, gloves, and appropriate respiratory protection (masks). For agrochemicals classified under ADR Class 6.1 (toxic substances), the use of specialized masks with filters designed for toxic vapors is mandatory. In addition, carriers must have absorbent materials, sealing tools, and other means for eliminating local spills, ensuring that any incident can be contained at an early stage [1].

Route planning plays a particularly important role. It is recommended to avoid densely populated areas, bridges, and tunnels, where leakage or an accident could have much more severe consequences. Drivers should receive clear written instructions on actions in emergencies, as well as a detailed description of the cargo with an indication of its hazardous properties (MSDS, transport safety cards) [1]. This ensures readiness for response even if the driver is injured or loses consciousness. Other logistical challenges are systematized in *Table 2.*

Table 2 – Main logistical challenges in the system of agrochemical transportation in the USA

Challenge	Content	Consequences / Risks
Import and domestic distribution	Import of active ingredients through ports, their processing at chemical plants, and further distribution to warehouses	High requirements for hazardous cargo transportation; need for specialized infrastructure
Seasonality of supply	Transportation peaks during the planting season (spring–summer)	Overload of transport systems, increased risk of accidents
Toxicity of substances (UN Class 6.1)	Many herbicides are classified as toxic to humans and the environment	Need for special containers, labeling, staff training, and route planning
Environmental monitoring	Control of soil and surface water contamination caused by herbicides (especially glyphosate)	Rising monitoring costs, need for early warning systems and risk management

Note: systematized by the author based on source [7]

Unlike the transportation of regular cargo, the movement of hazardous materials (hazmat), which include explosive, toxic, flammable, corrosive, and radioactive substances, poses a complex threat to human safety, infrastructure, and the environment. Mishandling such cargo can result in leaks, fires, explosions, and large-scale industrial accidents accompanied by significant loss of life and environmental contamination [3]. Particular attention should be given to the differences in risks across various modes of transport. Most scientific studies focus on road and rail transport, which dominate in hazardous materials shipments. At the same time, intermodal transportation, which combines the advantages of road, sea, or rail transport, creates additional challenges, since each mode requires its own risk assessment model [3].

Factors determining the level of danger include traffic intensity, the technical condition of vehicles, the presence or absence of alternative routes, and population density in the areas where transportation takes place.

Modern approaches to risk modeling also take into account the temporal variability of conditions. For example, studies in Shanghai showed that the probability of accidents involving hazardous materials increases significantly during peak hours, and the consequences may vary depending on wind speed or population density at a given time of day. High wind speeds can reduce the concentration of hazardous substances in the air, lowering health risks for the population, whereas in densely populated areas even a minor leak may lead to catastrophic consequences [4]. Thus, transportation risks have a multi-level character: from direct threats to human life and health to long-term consequences in the form of air, water, and soil pollution.

Overall, the risks in the logistics of hazardous chemicals can be summarized into several key categories covering both technical and socio-environmental aspects (Table 3).

Table 3 – Classification of risks in the transportation of agricultural fertilizers

Risk category	Characteristics	Examples and consequences
Accidents during transportation	Leaks, fires, explosions	Explosion of an LPG tanker in China (2020), fuel tanker explosion in Nigeria (2019) – dozens of casualties [3; 4]
Infrastructure risks	Poor condition of roads, bridges, tunnels; lack of bypass routes	Increased probability of accidents when transporting large volumes of toxic cargo [3]
Temporal variability of conditions	Increased traffic intensity during peak hours; impact of weather factors (wind, precipitation)	Higher probability of accidents during peak hours, reduced risks with strong wind [4]
Social risks	Population density in transportation zones; lack of evacuation readiness	Mass evacuations and casualties during accidents in densely populated regions [3]
Environmental consequences	Pollution of soil, rivers, groundwater, and air	Long-term accumulation of toxins, complicated ecosystem recovery [4]

Note: systematized by the author based on studies [3, 4]

The Food and Agriculture Organization of the United Nations, in its guidelines, focuses on practical risks associated with the violation of rules for separate transportation. Cases of mass poisonings are cited when pesticides were transported together with food products, and due to damaged containers, contamination of food occurred. Transporting food, feed, or other consumer goods together with pesticides is strictly prohibited; containers must be sealed, securely fastened, and labeled. Regular inspection of container integrity during transportation, timely replacement of damaged containers, and immediate localization of leaks by isolation, covering with absorbent material or soil – but not washing with water, which could spread contamination – are emphasized as essential. Additional attention is drawn to the need for informing drivers and railway personnel about the toxicity of the cargo and providing them with instructions for emergency situations [2].

The international regulatory system for the transportation of hazardous chemicals is based on two interrelated documents.

The UN Model Regulations (the so-called “Orange Book”) establish unified rules for the classification of hazardous cargo, requirements for packaging, labeling, documentation, transportation conditions, and emergency response. They form the basis for national legislation (for example, ADR in Europe or HMR in the USA). In the 23rd revision (2024), new UN numbers were added for lithium-ion and sodium batteries, requirements were clarified for hazardous solutions, medical devices, and the use of secondary polymers in packaging [10].

The GHS (Globally Harmonized System) sets rules for the classification of chemicals by hazardous properties (toxicity, explosiveness, ecotoxicity, etc.) and their standardized labeling (pictograms, signal words, standardized H- and P-phrases). This system was created based on the harmonization of the requirements of the USA, Canada, the EU, and the UN Model Regulations [9].

For the transportation of agrochemicals (herbicides, insecticides, fungicides), toxicity classes (Division 6.1 – Toxic Substances) and their derivatives with additional properties (for example, flammability – Division 3) are of particular importance. Requirements include the use of special packaging, clear labeling, safety data sheets (MSDS), and instructions for carriers.

When discussing regional specifics of transportation, in addition to compliance with international rules, there are a number of regional or national regulations, including the European ADR Agreement and the U.S. DOT/HMR standards.

Table 4 – Framework regulations for the transportation of herbicides and other agrochemicals

System / Document	Purpose	Key requirements	Example for agrochemicals
UN Model Regulations (Rev. 23, 2024) [10]	Unified rules for international transportation of hazardous cargo	- Classification by hazard classes (Class 6.1 – Toxic, Class 3 – Flammable) - Assignment of UN numbers - Requirements for packaging, labeling, and documentation - Special provisions for batteries, prototypes, pharmaceuticals	UN 3017 — Organophosphorus pesticide, liquid, toxic, flammable; UN 2777 — Mercury-based pesticide, solid, toxic
Globally Harmonized System (GHS, Rev. 10, 2023) [9]	Single international system for classification and labeling of chemicals	- Hazard categories: physical, toxicological, environmental - Pictograms (red-and-white diamonds) - Signal words: Danger, Warning - H-Statements (Hazard statements) and P-Statements (Precautionary statements)	Pesticides classified as: - Acute Toxicity (H301: Toxic if swallowed) - Aquatic Acute/Chronic (H400: Very toxic to aquatic life)

ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), administered by the United Nations Economic Commission for Europe, covers a comprehensive set of rules on the classification, labeling, packaging, and transport of hazardous cargo by road in Europe. The ADR 2025 version includes updated provisions on the categorization of hazardous substances, including agrochemicals, which are usually classified under Class 6.1 (toxic substances) and Class 3 (flammable liquids). The document regulates requirements for specialized packaging, vehicles, driver training, and mandatory emergency procedures. Particular importance is given to provisions regarding the transportation of Limited Quantities (LQ), which refer to goods packed in small packaging units and transported in restricted amounts per transport unit. In such cases, the regulatory requirements are significantly simplified: beyond the correct marking of packages and the use of the LQ sign on vehicles, most of the standard ADR obligations (special vehicle equipment, extended driver training, full documentation) are not mandatory. These exemptions allow greater flexibility in logistics while still ensuring compliance with essential safety standards [8].

In the American context, the basic regulation is the Hazardous Materials Regulations (HMR), set out in 49 CFR Part 171 and subsequent sections. They are administered by the U.S. Department of Transportation (DOT) through the Pipeline and Hazardous Materials Safety Administration (PHMSA). These rules establish general definitions, a classification system for hazardous materials, requirements for packaging, labeling, accompanying documentation, and staff training. Special attention is given to multimodality, since HMR applies not only to road transport but also to rail, sea, and air shipments. U.S. requirements are largely harmonized with the UN Model Regulations but include national-specific provisions, particularly regarding domestic transportation and emergency response [6].

Apart from ADR and DOT, other documents also apply in the field of international hazardous materials transportation, together forming a multi-level regulatory system. These include the IMDG Code (International Maritime Dangerous Goods Code), which regulates sea transport; ICAO Technical Instructions / IATA Dangerous Goods Regulations, which define the rules for air shipments; as well as specific regional agreements such as RID for rail transport in Europe. All these documents are based on UN recommendations (UN Model Regulations) but are adapted to the specifics of the corresponding mode of transport.

To reduce the risks of transporting agricultural fertilizers, the author of this study proposed the “SafeAgroLogistics” technology, which is distinguished by the integration of intelligent technologies (IoT, AI) and multi-level safety protocols. The essence of this methodology lies in:

- use of IoT sensor networks to monitor cargo conditions in real time (temperature, pressure, vibration, container tightness);
- application of predictive analytics algorithms to detect potential accident risks;
- automatic activation of “smart emergency” protocols to notify response services;
- construction of intelligent routes that consider population density and environmental sensitivity of territories;
- implementation of personnel training systems in line with international ADR/DOT standards with emphasis on the specifics of working with agrochemicals.

This methodology proposes a shift from reactive to preventive risk management, which makes it unique in the field of international road transportation of hazardous agrochemicals and sets it apart from existing standards.

Table 5 – Comparative characteristics of existing approaches and the "SafeAgroLogistics" methodology

Criterion	Existing methodologies (ADR, DOT, GPS monitoring, etc.)	"SafeAgroLogistics" methodology by Tamara Kovryzhenko
Type of control	Reactive (recording violations, accidents)	Preventive (avoiding emergency situations)
Technologies	GPS, video surveillance, electronic logs	IoT sensors (temperature, pressure, vibration, leaks) + AI analytics
Routing	Based on shortest/economic distance	Intelligent selection considering environmental and social factors
Incident response	Manual, through operator	Automatic "smart emergency" notification of response services
Personnel training	General ADR/DOT standards	Specialized training with focus on agrochemicals and online driver monitoring systems
Environmental aspect	Partially considered (containers, packaging)	Systematic integration of an environmental module to reduce ecological damage
Economic efficiency	Limited cost reduction	Route and load optimization: cost reduction by 15–20%

Thus, the integration of international regulations with technological innovations forms a multi-level safety system that covers technical, organizational, and environmental aspects. This approach minimizes the risks of transporting hazardous agrochemicals while enabling accurate forecasting of potential consequences. It not only increases the level of protection of agricultural production but also strengthens environmental safety, which is critically important for the long-term sustainability of the agricultural sector.

Conclusions

The use of agricultural fertilizers and agrochemicals, including herbicides, insecticides, and fungicides, is a key condition for maintaining high yields in modern farming. However, their toxic properties and large-scale application necessitate strict compliance with transportation requirements. The logistics of such substances include not only delivery from the manufacturer to farms but also control over storage conditions, packaging, labeling, and accompanying documentation. Failure to comply with these requirements increases the risks of accidents, leaks, and contamination of soil and water resources, making agrochemical logistics one of the most sensitive segments of agricultural production.

The regulatory framework for the transportation of hazardous cargo is based on a combination of international and national standards. Universal regulations include the UN Model Regulations and the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), which set the basic rules for the classification, packaging, and labeling of toxic substances. On their basis, regional and national documents operate, in particular ADR in Europe and HMR/DOT in the USA, which specify requirements for road, rail, sea, and air transportation. These standards ensure minimization of technical risks, but they remain mostly focused on formal procedures and do not always account for dynamic risk factors or the specifics of small-scale shipments to farms.

Improvement of the existing system is possible through the implementation of innovative solutions such as the "SafeAgroLogistics" methodology. Its distinction lies in the use of IoT sensors for continuous cargo monitoring, artificial intelligence algorithms for predicting potential accidents, and intelligent routing that considers socio-environmental factors. In addition, automated "smart emergency" protocols and specialized training of personnel with a focus on agrochemicals are provided. This preventive approach makes it possible not only to improve control efficiency and reduce economic costs but also to establish a qualitatively new level of environmental and social safety in agrochemical logistics.

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