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A comprehensive evaluation of grain cargo damage factors in maritime transportation: a neutrosophic perspective

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ABSTRACT

Safe and efficient maritime transportation of grain cargo is essential for food security and global trade. However, grain cargo is vulnerable to risks that may cause qualitative and quantitative losses during transit, while their relative importance remains insufficiently examined. This study applies TNWAA-based neutrosophic AHP to identify and prioritize risk factors contributing to grain damage during maritime transport. By integrating truth, indeterminacy, and falsity, the method enables a more nuanced evaluation of expert judgments than conventional approaches. The expert assessments identified four main risk categories: wet damage, procedural issues, heat damage, and contamination, together with 17 related sub-factors. Wet damage was ranked as the most influential factor affecting grain cargo integrity. The results provide a basis for risk-focused actions, including improved moisture monitoring, stronger operational procedures, and enhanced environmental controls during maritime transport.

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1. Introduction

The number of people globally affected by hunger continues to rise, reaching an estimated range of 702–828 million in 2021 due to various factors such as the COVID-19 pandemic, regional conflicts, natural disasters, water scarcity, population growth, rising food prices, and climate change (Saleh et al. 2013; George et al. 2020; Fan et al. 2021; WFP and UNICEF 2022). Therefore, global food security has emerged as a significant policy concern (Kaur 2019; Mogale et al. 2020). Over the past 40 years, one-third of arable land has been lost, while only 12% of the remaining land is utilized for cultivation (Mogale et al. 2020). Grain products such as rice, wheat, maize, and corn are the most widely cultivated and traded cereals in the world. These products have been a primary source of nutrition for humans, and they continue to play a crucial role in meeting the nutritional needs of people in developing and the poorest countries. Rice, wheat, and corn are the predominant grain crops that play a crucial role in human nutrition, accounting for over 50% of the total calories consumed worldwide (Awika 2011; Shahbazi et al. 2025). Today, maritime transportation plays a crucial role in the global economy by safely and efficiently transporting large volumes of grain between countries and continents. Each year, a significant amount of 200 billion tons of food is transported worldwide, with 35% being transported by land, 60% by sea, and 5% by air (Inamuddin et al. 2021). The war in Ukraine has caused significant disruptions in shipping routes and supply chains, affecting the flow of goods and resources, thereby triggering a food crisis. Ukraine plays a significant role in global wheat and corn production and export. From 2017–2020, Ukraine accounted for 10% of global wheat exports and 15% of corn exports, while the Russian Federation accounted for 20% of global wheat exports during the same period. Ukraine's grain exports, which amounted to around 4.2 million tons per month and a total of 50 million tons annually in 2021, decreased to nearly zero in early March 2022 (UNCTAD 2022; Gilbert 2023). The war has caused grain prices to rise significantly since the start of the conflict.

So, minimizing food loss and waste during the entire process, including harvesting, storage, transportation, processing, and distribution, measures must be implemented to prevent deterioration or contamination that may compromise the quality of the food. Poor practices prior to and following harvesting frequently result in losses that endanger food and nutrition security, despite attempts to raise yields

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(Shahbazi et al. 2025). In India, a significant proportion of agricultural production is lost or wasted due to various factors related to handling, storage, logistics, and transportation, despite its position as the second largest global producer of food grains (wheat and rice), following China (Mogale et al. 2017; Bisheko et al. 2023). In another research study supporting this conclusion, approximately 60% of the entire harvested crop is lost due to post-harvest losses across several African nations, resulting in elevated hunger rates, diminished edible food quantity, poor nutritional quality, reduced farmer income, and threatened food security (Ariyo et al. 2025). As highlighted in the 2019 State of Food and Agriculture report by the Food and Agriculture Organization (FAO), approximately 14% of global food production is estimated to be lost or deteriorates during the post-harvest stages, prior to reaching end consumers, with an estimated value of approximately $400 billion annually (FAO 2019). Grain is a significant cargo of global trade and ranks as the third largest dry bulk cargo in terms of seaborne trade, accounting for approximately 9.5% of the total dry bulk trade worldwide. This accounts for an impressive volume of around 430 million tons traded each year. Despite its economic importance, the sensitivity of grain products to various damage during transportation, such as moisture absorption and self-heating, gives rise to challenges that can lead to significant losses (*Transportation of Grain* 2018). However, despite the operational and economic importance of grain cargo, the factors causing grain damage during maritime transportation have not been sufficiently examined in a structured and prioritization-based framework. The Swedish Club report presents a classification of factors contributing to the damage of grain products during transportation, including shortage (44%), wet damage (13%), contamination (12%), physical damage (2%), and several other factors. However, the report indicates that the most costly cargo damages are attributed to water damage, accounting for 46.99%, followed by shortage at 17.39%. Additionally, the factors contributing to the occurrence of wet damage are ranked as leaking hatch covers at 42.25% and heavy weather conditions at 21.13% (The Swedish Club 2018, 2023). The improper sealing or leakage of hatch covers can result in water ingress, exposing the grain cargo to moisture. Water ingress through hatch covers is typically defined by the formation of distinct columns of mold damage and caked pillars of grain where water leaks directly downwards from the entry point (The Swedish Club 2022). The contact of water with food can lead to caking, promoting microbial activity and the potential formation of mold, which can potentially cause illness or even death. The rate of microbial activity is influenced by various factors such as pH, temperature, and water activity (Vera Zambrano et al. 2019; Sharma et al. 2023). Moreover, the moisture content is a critical factor that significantly influences various aspects of smoldering, including the thresholds for ignition and extinction, as well as the likelihood of transitioning from smoldering to open flame combustion (Huang X and Rein G 2016; Santoso et al. 2019). According to reports, a considerable amount of food loss occurs as a result of rat, fungal, and insect damage caused by poor storage conditions, which is closely related to moisture content (Nath et al. 2024). Furthermore, another important issue contributing to the damage of grain cargo is the presence of fuel tanks around the cargo tanks. When the fuel inside these tanks is heated, the heat released to the surroundings can cause the grain load to warm up, thereby promoting moisture absorption, the formation of mold and malodor, and increasing microbial activity (Khan 2021). The growth of mold and fungi in grains generates toxic byproducts known as mycotoxins (Benbrook 2005; Awuchi et al. 2021). These mycotoxins can pose significant health risks when consumed, as they have the potential to cause various adverse effects on human and animal health. Globally, a significant proportion of cereal grains, ranging from 25% to 40%, are contaminated with mycotoxins produced by storage fungi (Kumar et al. 2007). The environmental conditions, especially temperature and moisture during the storage of grains, directly affect the production of mycotoxins, playing a critical role in their growth (Delgado et al. 2023). Regions with hot and humid climates are more prone to mold growth, making them more susceptible to mycotoxin formation (Gómez-Salazar et al. 2023). However, mycotoxin-producing molds and fungi can also be observed in temperate regions (Benbrook 2005; Neme and Mohammed 2017). During the storage of grains, factors such as humidity, temperature, and relative humidity play a crucial role in influencing the growth of fungi and preserving the quality of the grains. Among these factors, humidity stands out as the most critical control parameter for preventing the formation of mycotoxins (Neme and Mohammed 2017). Moreover, insects are considered another important factor that leads to significant losses (30–40%) in grains. Insects pose a significant threat to the quality and quantity of stored grains, as they can infest storage areas and cause damage and contamination by feeding on the grains (Boxall 2002; Tapondjou et al. 2002; Abass et al. 2014). According to a study conducted by (Compton et al. 1997), each percentage of

insect infestation in corn causes a value loss ranging from 0.6% to 1% (Compton et al. 1997; Baoua et al. 2014). To reduce the risk of insect infestation during grain transportation, it is crucial to implement important strategies and measures. Preventing insect infestation not only helps protect the economic value of grains but also ensures food safety and quality for consumers (Ahsan et al. 2023). Cargo fumigation is an appropriate measure to prevent the introduction and spread of pests on board a ship, which involves the use of chemical substances to exterminate harmful insects and their eggs. The regular cleaning and disinfection of all areas of the ship, including cargo holds, living spaces, storages, and food preparation areas, are implemented as preventive measures for cleanliness and sanitation to mitigate potential damages caused by pests on the cargo (Crossley 2023). Adequate ventilation is essential for effectively eliminating fumigant gases released during fumigation, and it also plays a significant role in reducing the growth rates of insect populations and mold colonies that infest stored grains (Wilson and Desmarchelier 1994). Various factors, including dust and stains, rust, pilferage & broaching, sweepings, and others, are identified as significant factors contributing to the potential damage of grain cargo during transportation (Pepper 2018). Despite the economic significance and food-security relevance of grain cargo, the literature still provides limited insight into the relative importance of the factors causing grain damage during maritime transportation. To address this gap, the present study investigates and prioritizes the critical factors contributing to grain cargo damage during maritime transportation by applying the Neutrosophic Analytical Hierarchy Process (N-AHP). Unlike previous studies that mainly focus on storage-related deterioration, general cargo risks, or isolated quality parameters, this study concentrates specifically on maritime grain transportation and evaluates the relative importance of damage factors under uncertainty. This methodological perspective is necessary because the evaluation of grain cargo damage involves uncertainty, incomplete operational information, and subjective expert judgments. In such contexts, conventional deterministic approaches may fail to capture the complexity of real maritime decision-making. Although previous studies have examined post-harvest grain losses, storage conditions, cargo contamination, moisture-related deterioration, and temperature effects, limited attention has been given to the integrated prioritization of grain cargo damage factors in maritime transportation. This gap is important because maritime grain transport involves multiple interacting operational, environmental, and biological risks that may not be adequately captured by conventional descriptive approaches. Therefore, a structured decision-making framework is needed to identify the most influential damage factors and support more effective preventive strategies in maritime operations.

Neutrosophic sets, which include degrees of truth, indeterminacy, and falsity, extend classic fuzzy and intuitionistic fuzzy methods and provide a more comprehensive framework for describing ambiguity and inconsistency in expert judgments. This adaptability makes the N-AHP ideal for complex decision-making contexts where traditional models often fail to give consistent results. By explicitly modeling uncertainty and disagreement, the method produces a more reliable aggregation of expert opinions and thus enhances the overall robustness of the analysis, enabling a more comprehensive representation of real-world decision-making (Yucesan and Gul 2021; Sahmutoglu et al. 2023; Yalcin and Ayyildiz 2024; Ucak Ozkaya 2025). The findings of this study are expected to contribute to improving practices and strategies in the sea transport of grains, ultimately minimizing losses and ensuring the preservation of grain quantity and quality.

This paper is organized as follows. Section 2 presents the study workflow and elaborates on the methodology, focusing on the application of the TNWAA-based N-AHP approach. Section 3 provides the analysis results, identifying the primary and sub-factors contributing to grain cargo damages during maritime transport. Section 4 discusses the findings, emphasizing their implications for mitigating risks in grain cargo transportation. Finally, the conclusion section concludes the study by summarizing the key outcomes and proposing recommendations for future research and practical applications.

2. Study workflow

This study was conducted in two phases, as illustrated in Figure 1. In brief, the first phase involves constructing the problem-hierarchy structure based on collected data and expert insights. The second phase entails applying the selected method to assess the relative importance of each criterion. The phases and their respective steps are described in the following subsection.

2.1. Identification of grain cargo damage factors

To identify the primary factors directly contributing to the damage of grain cargo during maritime

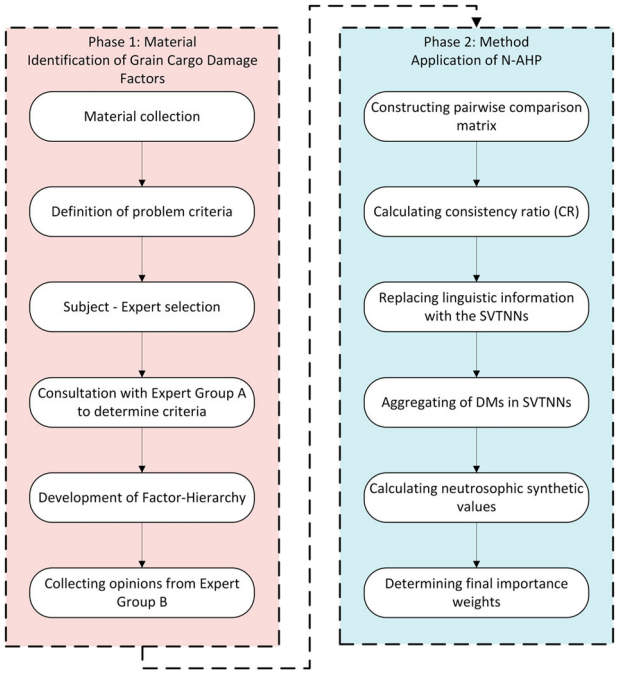


Figure 1. Study workflow and methodological steps. '(This figure is available in color online.)

transportation, a comprehensive review of existing literature and grain cargo claim/damage reports from various Protection and Indemnity (P&I) Clubs was conducted. Based on the initial findings, six experts currently serving on vessels engaged in grain cargo transportation, each with more than ten years of professional experience, were consulted to validate the criteria obtained from the literature. The experts were divided into two groups. The first group (Expert Group A) participated in an online meeting focused on confirming and refining the preliminary list of factors. Following this, individual online meetings were held with each member of the second group (Expert Group B) to explain the selected decision-making approach and to obtain their independent evaluations of the finalized criteria. Through this two-stage consultation process, the factors were verified, categorized, and structured into four main dimensions – heat damage, wet damage, contamination, and procedural issues – forming the foundation for the subsequent phases of the analysis. These primary damage criteria and their corresponding sub-criteria are structured in Figure 2 and are described as follows.

Heat damage (Paulsen et al. 1991; Lirn et al. 2018; Ziegler et al. 2021; Polyvoda and Polyvoda 2023) primarily results from fluctuations in both external and internal temperatures within the cargo. Certain commodities are particularly susceptible to temperature variations or extreme temperatures, which may reduce their shelf life or alter their chemical composition. In maritime grain transport, heat damage can stem from factors such as *self-heating*, elevated *external temperatures*, and proximity to *heated compartments*. Self-heating arises as grains undergo natural respiration, producing heat and moisture that, if unregulated, can accelerate spoilage. This issue is further compounded by external temperatures, especially in tropical climates, which elevate the cargo's overall temperature, thereby increasing the risk of mold growth and biochemical degradation. Additionally, heated compartments adjacent to cargo holds, often located near engine rooms, may transfer excess heat if insufficiently insulated. Effective ventilation, consistent temperature monitoring, and adequate compartment insulation are critical measures for mitigating heat damage and preserving grain quality.

Wet Damage (Lirn et al. 2018; Ziegler et al. 2021) in maritime grain transport arises mainly from *sweat (condensation), hatch cover leakage*, and *leaks from pipes and tanks*. Cargo sweat occurs when temperature fluctuations cause moisture to condense on the grain, increasing its moisture content and promoting mold growth. Hatch cover leakage, often due to insufficient sealing, can allow seawater to enter during rough seas or heavy weather, directly compromising grain quality. Additionally, leaks from pipes and tanks within or near the cargo hold introduce further risks of moisture exposure.

Contamination of grain cargo (Ziegler et al. 2021; Baidhe et al. 2024) is influenced by multiple risk factors, including inherent vice, hold cleaning practices, environmental residues within storage areas, pest infestations, and cargo mixing. Grain inherently possesses qualities, such as moisture and organic material, that make it susceptible to attracting contaminants. This 'inherent vice' requires proactive measures during transport, as the grain's natural characteristics can lead to spoilage or contamination without proper precautions. On the other hand, thorough cleaning of the storage area and cargo holds is essential to maintain the cleanliness of grain cargo. Any *dust, stain, or rust* remaining in the hold can mix with the grain, potentially degrading its quality and marketability. Proper cleaning protocols must ensure that surfaces are free from such residues to maintain cargo purity. The *storage area* itself must meet high cleanliness standards, as unclean or poorly maintained spaces can harbor contaminants. Residual particles, dirt, or stains on hold walls can easily mix with grain, underscoring the need for dedicated grain-only storage or rigorous cleaning between different cargo types. *Dust, stains, and rust* within the cargo hold are key contamination risks. Dust and rust particles can settle into the grain during

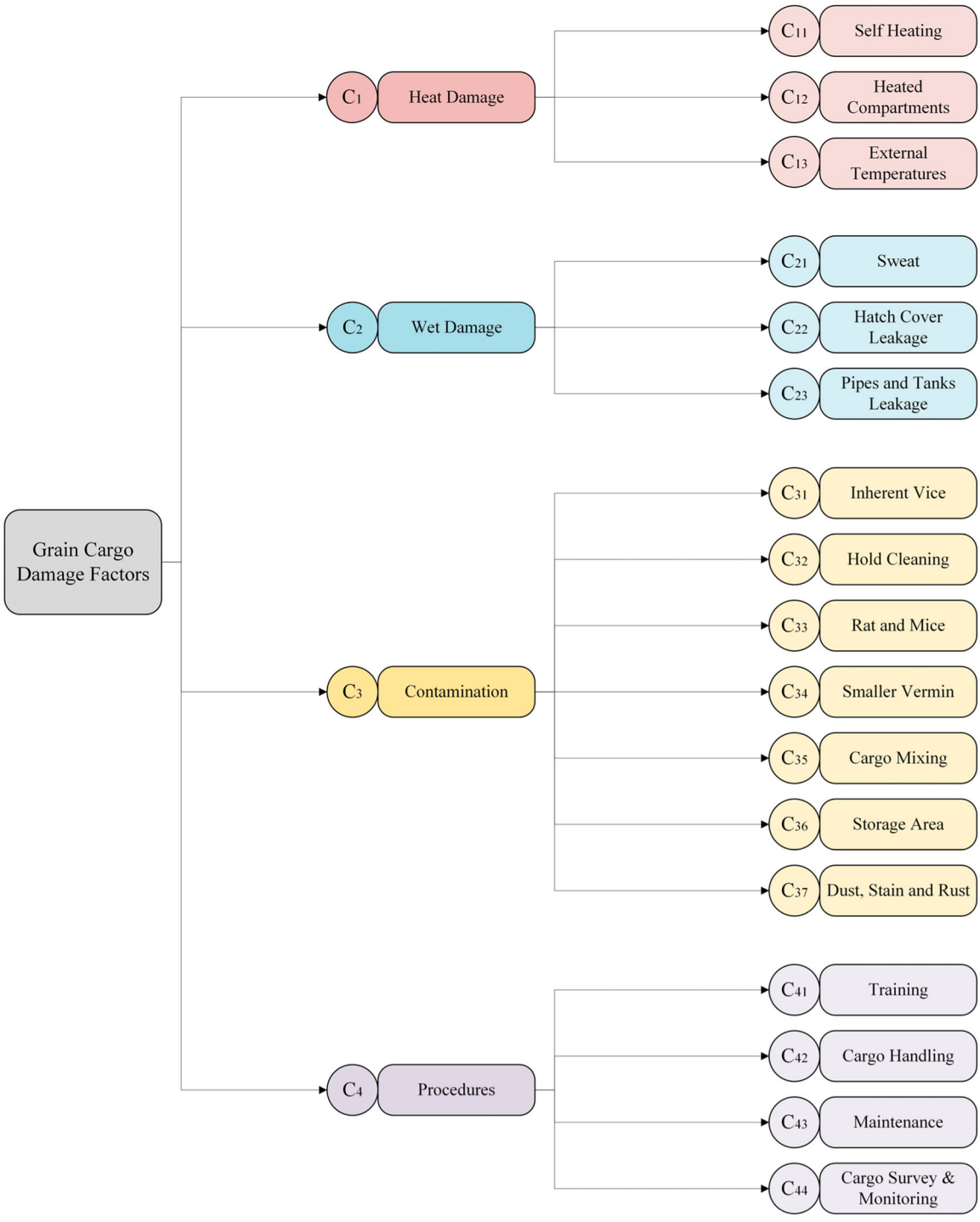


Figure 2. Hierarchical structure of grain cargo damage factors. '(This figure is available in color online.)

loading or transport, altering its purity and quality. Stains, especially from previous organic or chemical cargoes, can introduce foreign odors or toxins to the grain. Another damage factor for grain cargo is the presence of live organisms, such as rodents and smaller vermin. *Rodents*, including rats and mice, are a major concern for grain cargo contamination, as they can introduce physical impurities and pathogenic bacteria. Rodents often find their way into cargo holds, especially during loading and unloading in ports, highlighting the need for strict pest control measures. In addition to larger rodents, *smaller vermin* such as insects can infiltrate the grain cargo, damaging kernels and spreading contaminants. These pests are often harder to detect but can significantly affect grain quality and require regular fumigation and inspection. Lastly, *cargo mixing*, or the

unintentional blending of different cargo types, poses contamination risks when grain is stored in holds that previously contained other materials. Even trace residues from prior loads can compromise grain quality, making it vital to designate clean, well-prepared storage spaces for each shipment.

Procedures (Hill 1994) for the effective management of grain cargo during maritime transport rely on well-defined practices that encompass *training, cargo handling, maintenance, and cargo survey and monitoring*. Comprehensive training programs are essential for equipping personnel with the knowledge and skills to implement best practices and safety protocols. Proper cargo handling techniques are critical to preventing damage and contamination, emphasizing the importance of secure loading and unloading processes. Additionally, regular maintenance of equipment and facilities ensures that all machinery operates efficiently and that the cargo hold remains free from contaminants and leakages. Continuous cargo survey and monitoring facilitate the early detection of potential issues, enabling timely interventions to maintain grain quality. Collectively, these procedural elements are vital for mitigating risks and ensuring the integrity of grain during maritime transport.

The above criteria represent the key factors contributing to grain cargo damage in maritime transportation, and their structure is presented in Figure 2. To analyze these criteria and evaluate their significance, a multi-criteria decision-making method was selected and applied.

2.2. Method

Multi-criteria decision-making (MCDM) can be defined as a structured approach that facilitates the evaluation of alternative options based on multiple, and often conflicting, criteria. In this process, the decision-maker systematically identifies relevant evaluation factors, assigns relative weights to reflect their importance, and subsequently analyses the available alternatives in accordance with these prioritized criteria.

The present study aims to establish a comprehensive evaluation framework by incorporating the perspectives of three domain experts, with the intent of assessing a wide range of criteria through comparative judgment. In addressing such multi-criteria problems, the Analytic Hierarchy Process (AHP) has been widely recognized and utilized within the relevant literature (Doğru and Bucak 2025; Hazar et al. 2025). However, various studies, including the work of Slamaa et al. (2021), have indicated that the Neutrosophic-AHP (N-AHP) methodology offers enhanced accuracy and reliability in comparison to conventional AHP and Fuzzy AHP (FAHP) models. Accordingly, the N-AHP technique was selected as the methodological foundation for this research. N-AHP is a decision-making tool designed for complex multi-criteria evaluations, incorporating neutrosophic logic to express indeterminacy, ambiguity, and incomplete information. The approach is predicated on the assignment of neutrosophic weights and scores based on decision-makers' predefined criteria. This enables a more refined and realistic assessment process, particularly in environments characterized by uncertainty and vagueness (Slamaa et al. 2021).

2.2.1. Neutrosophic set theory

This section provides a comprehensive overview of the fundamental concepts associated with Neutrosophic Set (NS) theory (Vafadarnikjoo et al. 2023).

Definition 2.1: Let U denote a finite universal set, where x represents an arbitrary element within U. A NS A defined over U is described by three distinct membership functions: the truth-membership function $T_A(x)$, the in-determinacy-membership function $I_A(x)$, and a falsity-membership function $F_A(x).T_A(x), I_A(x)$. Each of these functions' maps to the non-standard interval $(0^-, 1^+)$. The structure of the set A can be formally represented as follows (Smarandache 1999):

$$lA = \{\langle x, (T_A(x), I_A(x), F_A(x))\rangle : x\ U,\ T_A\ (x),\ I_A\ (x),\ F_A \in 0^-\ ,\ 1^+[\ \}, \tag{1}$$

Note that $0^- \leq T_A(x) + I_A(x) + F_A(x) \leq 3^+$.

Definition 2.2: Let U denote a finite universal set, and let x represent an arbitrary element within U. A single-valued neutrosophic set (SVNS), denoted by A, is characterized by three distinct membership functions defined on U: the truth-membership function $T_A(x)$, the indeterminacy-membership function $I_A(x)$, and the falsity-membership function $F_A(x)$. $T_A(x), I_A(x)$, Each of these functions maps elements of U to values in the closed interval $[0, 1]$. The structure of an SVNS can thus be formally expressed as follows (Wang et al. 2010):

$$A = \{< x, (T_A(x), I_A(x), F_A(x)) > : x \epsilon U,\ T_A\ (x),\ I_A\ (x),\ F_A(x) \in [0\ ,\ 1]\}, \tag{2}$$

It should be noted that the following condition holds for any SVNS:

$$0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3$$

For the purpose of simplicity, an SVNS is denoted as $A = \{< x, (T_A(x), I_A(x), F_A(x)) > : x \in U\}$ is often represented in its simplified form as $A = \{\langle T_A(x), I_A(x), F_A(x)\rangle : x \in U\}$.

Definition 2.3: A single-valued trapezoidal neutrosophic number (SVTNN), denoted by $\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \rangle$, where $a_1, b_1, c_1, d_1 \in R$, $a_1 \le b_1 \le c_1 \le d_1$ with membership degrees $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \in [0, 1]$ is a specific form of SVNN. In this context, the corresponding truth-membership $T_{\tilde{a}}(x)$, indeterminacy-membership $I_{\tilde{a}}(x)$, and falsity-membership $F_{\tilde{a}}(x)$ functions are defined through the following equations (Deli and Subas 2014):

$$T_{\tilde{a}}(x) = \begin{cases} \dfrac{(x - a_1)w_{\tilde{a}}}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ w_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{(d_1 - x)w_{\tilde{a}}}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 0, & \\ 0, & \end{cases} \tag{3}$$

$$I_{\tilde{a}}(x) = \begin{cases} \dfrac{(b_1 - x + u_{\tilde{a}}(x - a_1))}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ u_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{(x - c_1 + u_{\tilde{a}}(d_1 - x))}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 1, & \text{otherwise}, \end{cases} \tag{4}$$

$$F_{\tilde{a}}(x) = \begin{cases} \dfrac{\left(b_1 - x + y_{\tilde{a}}(x - a_1)\right)}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ y_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{\left(x - c_1 + y_{\tilde{a}}(d_1 - x)\right)}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 1, & \text{otherwise}. \end{cases} \tag{5}$$

Definition 2.4 (Ye 2017a)**:**
Given $\tilde{a} =< (a_1, b_1, c_1, d_1)w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}};$ and $\tilde{b} = (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} >,$ and $\lambda > 0$, $w_{\tilde{a}}, w_{\tilde{a}}, y_{\mathfrak{a}}, w_{\mathfrak{b}}, u_{\tilde{b}}, y_{\tilde{b}} \in [0, 1]$, $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 \in \mathbb{R}$, $a_1 \le b_1 \le c_1 \le d_1$, and $a_2 \le b_2 \le c_2 \le d_2$, and then Equations (6) and (7) are true:

$$\tilde{a} + \tilde{b} = \left\langle (a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2); w_{\tilde{a}} + w_{\tilde{b}} - w_{\tilde{a}}w_{\tilde{b}}, u_{\tilde{a}}u_{\tilde{b}}, y_{\tilde{a}}y_{\tilde{b}} \right\rangle, \tag{6}$$

$$\lambda\,\tilde{a} = \left\langle (\lambda a_1, \lambda b_1, \lambda c_1, \lambda d_1); 1 - (1 - w_{\tilde{a}})^{\lambda}, u_{\tilde{a}}^{\lambda}, y_{\tilde{a}}^{\lambda} \right\rangle \tag{7}$$

When $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 > 0$, then Equations (8) and (9) are true:

$$\tilde{a}\,\tilde{b} = \left\langle (a_1a_2, b_1b_2, c_1c_2, d_1d_2); w_{\tilde{a}}w_{\tilde{b}}, u_{\tilde{a}} + u_{\tilde{b}} - u_{\tilde{a}}\tau_{\tilde{b}}, y_{\tilde{a}} + y_{\tilde{b}} - y_{\tilde{a}}y_{\tilde{b}} \right\rangle \tag{8}$$

$$\tilde{a}^{\lambda} = \left\langle (a_1^{\lambda}, b_1^{\lambda}, c_1^{\lambda}, d_1^{\lambda}); w_{\tilde{a}}^{\lambda}, 1 - (1 - u_{\tilde{a}})^{\lambda}, 1 - \left(1 - y_{\tilde{a}}\right)^{\lambda} \right\rangle. \tag{9}$$

Definition 2.5 (Ye 2017a)**:**
Given $\tilde{a} =< (a, \mathrm{b}, \mathrm{c}, d); w_a^{\sim}, u_a^{\sim}, y_a^{\sim}$ and $a, b, c, d > 0$. Then, the score function of $\tilde{a}$ can be calculated in accordance with the following equation:

$$S(\tilde{a}) = \frac{1}{12}(a + b + c + d)\left(2 + w_{\tilde{a}} - w_{\tilde{a}} - y_{\tilde{a}}\right), \; S(\tilde{a}) \in [0, 1]. \tag{10}$$

Definition 2.6 (Ye 2017a)**:** Consider two single-valued trapezoidal neutrosophic numbers (SVTNNs), denoted as

$$\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \rangle, \text{ and } \tilde{b} = \langle (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \rangle$$

with the condition that $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 > 0$.

According to Equation (10), the score functions $S(\tilde{a})$ and $S(\tilde{b})$ are calculated. The comparison is then made as follows:

if $S(\tilde{a}) > S(\tilde{b})$, then $\tilde{a} > \tilde{b}$;
if $S(\tilde{a}) = S(\tilde{b})$, then $\tilde{a} = \tilde{b}$.

Definition 2.7: Let $\tilde{a}_j = \left\langle (a_j, b_j, c_j, d_j); w_{\tilde{a}_i}, u_{\tilde{a}_j}, y_{\tilde{a}_j} \right\rangle$ be a collection of SVTNNs for $j = 1, 2, \ldots, n$. The Trapezoidal Neutrosophic Weighted Arithmetic Averaging (TNWAA) operator is defined based on the formulation presented by (Ye 2017a).

$$\mathrm{TNWAA}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \sum_{j=1}^{n} p_j\tilde{a}_j = \left\langle \left(\sum_{j=1}^{n} p_jb_j, \sum_{j=1}^{n} p_jc_j, \sum_{j=1}^{n} p_ja_j, \sum_{j=1}^{n} p_jd_j \right); 1 - \prod_{j=1}^{n} (1 - w_{a_j})^{p_j}, \prod_{j=1}^{n} u_{a_j}^{p_j}, \prod_{j=1}^{n} y_{\tilde{a}_j}^{p_j} \right\rangle \tag{11}$$

where p_j is the weight of $\tilde{a}_j (j = 1, 2, \ldots, n)$ while $p_j > 0$, and $\sum_{j=1}^{n} p_j = 1$.

In this study, expert evaluations were represented using SVTNNs to capture uncertainty and vagueness

in human judgment. To aggregate these assessments effectively, the TNWAA method was employed. This approach has been recognized in the literature as a reliable technique for synthesizing multiple expert opinions within neutrosophic environments (Vafadarnikjoo and Scherz 2021; Vafadarnikjoo et al. 2023).

2.2.2. Subtraction, division, and inversion of SVTNNs

The concepts of subtraction and division for simplified single-valued neutrosophic numbers (SVNNs) and single-valued neutrosophic sets (SVNSs) were initially introduced by (Smarandache and Pramanik 2016) and by (Ye 2017b). Furthermore, Rani and Garg (2019) explored these operations within the framework of interval neutrosophic sets. Building upon these foundational works, this section presents the definitions of subtraction, division, and inversion for single-valued triangular neutrosophic numbers (SVTNNs) in their general, non-simplified form, as discussed by (Rani and Garg 2019).

2.2.3. Subtraction of SVTNNs (Vafadarnikjoo and Scherz 2021)

Let $\tilde{a} =< (a_1, b_1, c_1, d_1); w_{\tilde{a}}, w_{\tilde{a}}, y_{\tilde{a}},$ and $\tilde{b} = (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}$ be two SVTNNs, and $w_a, w_{\tilde{a}}, y_{\tilde{a}}, w_{-}, \psi_{\tilde{b}}, y_{\tilde{b}} \in [0, 1]$ with the restrictions that $w_{-} \neq 1$, $v_b \neq 0$, $y_b \neq 0$, and $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 \in \mathbb{R}$, $a_1^b \leq b_1 \leq c_1 \leq d_1$, and $a_2 \leq b_2 \leq c_2 \leq d_2$, then the subtraction of the two SVTNNs is shown in

$$\tilde{a} - \tilde{b} = \left\langle (a_1 - d_2, b_1 - c_2, c_1 - b_2, d_1 - a_2); \frac{w_{\tilde{a}} - w_{\tilde{b}}}{1 - w_{\tilde{b}}}, \frac{w_{\tilde{a}}}{w_{\tilde{b}}^*}, \frac{y_{\tilde{a}}}{y_{\tilde{b}}^{\sim}} \right\rangle \tag{12}$$

Note: Negative outcomes should be replaced with zero, while values exceeding one should be adjusted to one.

Proof: *Consider Equation (13).*

$$\begin{aligned} &\tilde{a} = (a_1, b_1, c_1, d_1); w_{\tilde{a}}, w_{\tilde{a}}, y_{\tilde{a}}\ ; \\ &\tilde{b} = (a_2, b_2, c_2, d_2); w_{\tilde{b}}, w_{\tilde{b}}, y_{\tilde{b}}\ ; \\ &\tilde{c} = (x, r, z, s); w_{\tilde{c}}, w_{\tilde{c}}, y_{\tilde{c}} \\ &\tilde{a} - \tilde{b} = \tilde{c}. \end{aligned} \tag{13}$$

By performing neutrosophic addition with the term $\tilde{b}$ on both sides of Equations (13) through (16), we derive the following expression:

$$\begin{aligned} \tilde{a} &= \tilde{c} + \tilde{b} \\ &= \left\langle (x + a_2, r + b_2, z + c_2, s + d_2); w_{\tilde{c}} + w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}}, u_\tau u_{\tilde{b}}, y_{\tilde{c}} y_{\tilde{b}} \right\rangle. \end{aligned} \tag{14}$$

Then,

$$\begin{aligned} \tilde{a} &= (a_1, b_1, c_1, d_1); w_a, u_{\tilde{a}}, y_{\tilde{a}} \\ &= < (x + a_2, r + b_2, z + c_2, s + d_2); w_{\tilde{c}} \\ &\quad + w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}}, u_c \tau_{-}, y_{\tilde{c}} y_{\tilde{b}} \end{aligned} \tag{15}$$

and

$$\begin{cases} w_{\tilde{a}} = w_{\tilde{c}} + w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}} \Rightarrow w_{\tilde{a}} - w_{\tilde{b}} = w_{\tilde{c}}(1 - w_{\tilde{b}}) \Rightarrow w_{\tilde{c}} = \dfrac{w_{\tilde{a}} - w_{\tilde{b}}}{1 - w_{\tilde{b}}}, \\ u_{\tilde{a}} = u_c \tilde{u}_b \Rightarrow u_c = \dfrac{u_{\tilde{a}}}{u_{\tilde{b}}}, \\ y_{\tilde{a}} = y_c y_b \Rightarrow y_c = \dfrac{y_{\tilde{a}}}{y_{\tilde{b}}} \end{cases} \tag{16}$$

It is concluded that $-\tilde{b} =< (-d_2, -c_2, --a_2); (w_b/w_b - 1), (1/u_b), (1/y_b^{-}) >$, noting the remark above.

2.2.4. Division of SVTNNs

Let us define two single-valued trapezoidal neutrosophic numbers as follows:

$$\begin{aligned} \tilde{a} &=< (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \text{ and } \tilde{b} \\ &= (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \end{aligned}$$

where all components $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2$ are strictly positive real numbers, and the order relations, $a_1 \leq b_1 \leq c_1 \leq d_1$ and $a_2 \leq b_2 \leq c_2 \leq d_2$, hold. Moreover, the membership degrees $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}, w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}$ [0, 1] are all within the interval [0, 1], under the constraints $w_b \neq 1$, $v_b \neq 0$, and $y_b \neq 0$. Under these conditions, the division operation for the two SVTNNs can be formally expressed as follows:

$$\tilde{a} \div \tilde{b} =< \left(\frac{a_1}{d_2}, \frac{b_1}{c_2}, \frac{c_1}{b_2}, \frac{d_1}{a_2}\right); \frac{w_{\tilde{a}}}{w_{\tilde{b}}}, \frac{u_{\tilde{a}} - \psi_{\tilde{b}}}{1 - u_{\tilde{b}}}, \frac{y_{\tilde{a}} - y_{\tilde{b}}}{1 - y_{\tilde{b}}} \tag{17}$$

Note: Any value less than zero is to be substituted with zero, while any value exceeding one should be replaced by one.

Proof: *Consider Equation (18), where the neutrosophic values are defined as follows:*

$$\begin{aligned} &\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \rangle; \\ &\tilde{b} = \langle (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \rangle \\ &\tilde{c} = \langle (x, r, z, s); w_{\tilde{c}}, w_{\tilde{c}}, y_{\tilde{c}} \rangle \\ &\tilde{a} \div \tilde{b} = \tilde{c}. \end{aligned} \tag{18}$$

By applying neutrosophic multiplication of to $\tilde{b}$ both sides of Equation (18), the following relation is derived:

$$\tilde{a}=\tilde{c}\times\tilde{b}$$
$$=\langle(xa_2,rb_2,zc_2,sd_2);w_{\tilde{c}}w_{\tilde{b}},u_{\tilde{c}}+u_{\tilde{b}}-u_{\tilde{c}}u_{\tilde{b}},y_{\tilde{c}}+y_{\tilde{b}}-y_cy_{\tilde{b}}\rangle \quad (19)$$

Then,

$$\tilde{a}=\langle(a_1,b_1,c_1,d_1);w_{\tilde{a}},u_{\tilde{a}},y_{\tilde{a}}\rangle$$
$$=\langle(xa_2,rb_2,zc_2,sd_2);w_{\tilde{c}}w_{\tilde{b}},u_{\tilde{c}}+u_{\tilde{b}}-u_{\tilde{c}}u_{\tilde{b}},y_{\tilde{c}}+y_{\tilde{b}}-y_cy_{\tilde{b}}\rangle \quad (20)$$

and

$$\begin{cases} w_{\tilde{a}}=w_{\tilde{c}}w_{\tilde{b}}\Rightarrow w_{\tilde{c}}=\dfrac{w_{\tilde{a}}}{w_{\tilde{b}}}, \\ u_{\tilde{a}}=u_{\tilde{c}}+u_{\tilde{b}}-u_{\tilde{c}}u_{\tilde{b}}\Rightarrow u_{\tilde{a}}-u_{\tilde{b}}=u_{\tilde{c}}(1-u_{\tilde{b}})\Rightarrow u_{\tilde{c}}=\dfrac{u_{\tilde{a}}-u_{\tilde{b}}}{1-u_{\tilde{b}}}, \\ y_{\tilde{a}}=y_{\tilde{c}}+y_{\tilde{b}}-y_{\tilde{c}}y_{\tilde{b}}\Rightarrow y_{\tilde{a}}-y_{\tilde{b}}=y_{\tilde{c}}(1-y_{\tilde{b}})\Rightarrow y_{\tilde{c}}=\dfrac{y_{\tilde{a}}-y_{\tilde{b}}}{1-y_{\tilde{b}}}. \end{cases} \quad (21)$$

2.2.5. Inverse of an SVTNN

Let $\tilde{a}=\langle(a_1,b_1,c_1,d_1);w_{\tilde{a}},w_{\tilde{a}},y_{\tilde{a}}\rangle$ be an SVTNN where $a_1,b_1,c_1,d_1>0$ and $a_1\le b_1\le c_1\le d_1$ Also let $w_{\tilde{a}},u_{\tilde{a}},y_{\tilde{a}},\in[0,1]$. The inverse of $\tilde{a}$, denoted as $\tilde{a}-1$, is formally defined as:

$$\tilde{a}-1=\frac{1}{\tilde{a}}$$
$$=\left(\frac{1}{d_1},\frac{1}{c_1},\frac{1}{b_1},\frac{1}{a_1}\right);\frac{1}{w_{\tilde{a}}},\frac{u_{\tilde{a}}}{u_{\tilde{a}}-1},\frac{y_{\tilde{a}}}{y_a-1} \quad (22)$$

Note: If any resulting component yields a negative value, it should be replaced by zero. Similarly, if a component exceeds one, it must be adjusted to one to remain within the neutrosophic domain.

Proof: *Let us consider the original SVTNN* $\tilde{a}=\langle(a_1,b_1,c_1,d_1);w_{\tilde{a}},u_{\tilde{a}},y_{\tilde{a}}\rangle$, *and suppose its inverse is denoted as* $\tilde{a}-1=\langle(x,r,z,s);w_\tau,u_\tau,y_c\rangle$. *Then, the inverse can be expressed as the division of the neutrosophic identity element* $\langle(1,1,1,1);1,0,0\rangle$ *by the original SVTNN:*

$$\tilde{a}-1=\frac{1}{\tilde{a}}=\frac{\langle(1,1,1,1);1,0,0\rangle}{\langle(a_1,b_1,c_1,d_1);w_{\tilde{a}},w_{\tilde{a}},y_{\tilde{a}}\rangle}. \quad (23)$$

Applying the division operation defined for SVTNNs (as per Equation 17), the result follows directly.

2.2.6. Neutrosophic-analytical hierarchy process (N-AHP)

The concept of neutrosophic sets, originally proposed by Smarandache in 1999, represents an advancement beyond traditional fuzzy and intuitionistic fuzzy set theories. By integrating degrees of truth, indeterminacy, and falsity, Neutrosophic sets provide a more comprehensive mathematical structure for handling complex, imprecise, and conflicting information (Broumi et al. 2018; Karadayi-Usta 2022). Due to this flexible structure, the neutrosophic approach has been widely adopted in various real-world decision-making contexts that require managing uncertainty and partial knowledge. A distinctive strength of Neutrosophic logic lies in its ability to better represent uncertainty and contradictions, which are often present in expert evaluations. Unlike classical fuzzy logic systems, which are limited in handling indeterminate information, neutrosophic logic introduces a more extensive analytical mechanism. This enhancement is particularly useful when dealing with multifaceted or ambiguous problems, where conventional models are inadequate. Consequently, it offers significant advantages in the analysis of data sets that are inherently uncertain or inconsistent.

The use of Neutrosophic clusters allows experts to convey their judgments with a higher degree of nuance by explicitly incorporating uncertainty as a measurable component. Here, the degree of indeterminacy reflects the level of disagreement or lack of consensus among experts involved in the decision-making process. The proposed N-AHP framework addresses inconsistencies in expert judgments by synthesizing multiple viewpoints into a cohesive evaluation. This aggregation process contributes to improved decision reliability and reduces subjective bias.

Moreover, within Neutrosophic clusters, individual elements or resources are treated as independent entities that do not influence each other's behavior, regardless of their respective evaluations or outcomes (Smarandache and Pramanik 2016; Smarandache 2021). This independence assumption further reinforces the model's ability to accommodate diverse expert opinions without introducing interaction-based distortions.

Traditional AHP methods rely on crisp and definitive judgments provided by decision-makers, which may not adequately reflect the inherent uncertainty and imprecision present in complex decision-making environments. To address this limitation, the present study integrates neutrosophic sets into the AHP framework, thereby

introducing a greater degree of flexibility and adaptability in representing expert opinions. Neutrosophic sets are particularly effective in capturing the ambiguity and partial truth inherent in human judgment, offering a robust mathematical tool for expressing indeterminacy. Within the proposed approach, a pairwise comparison matrix is developed for each decision criterion, reflecting their relative importance. The comparison between two elements determines the dominance of one over the other, as perceived by the decision-makers. To quantify this comparative evaluation under uncertainty, the Neutrosophic AHP utilizes neutrosophic numbers, which consist of truth-membership, indeterminacy-membership, and falsity-membership degrees. This allows for a more comprehensive and realistic modeling of uncertainty in decision scenarios (Saaty 1987). The reliability of the results depends on the quality and consistency of expert judgments. In this study, obtaining consistent assessments from the expert panel was a key step. To address potential inconsistencies or bias, variability and conformity measures were used to evaluate the level of agreement among experts. The choice of conformity measure depends on the scale used to quantify expert responses, ensuring that extreme deviations or outlier judgments are properly accounted for (Ishizaka and Nemery 2013; Wójciak 2015). The judgments are based on Saaty's fundamental 9-point scale, which facilitates consistency and structure in preference expression. Table 1 shows the linguistic terms commonly employed by decision-makers during pairwise comparisons and the corresponding weights assigned using neutrosophic evaluation techniques, as suggested by (Radwan et al. 2016). This integration not only enhances the analytical rigor of the AHP methodology but also improves its applicability to real-world problems characterized by ambiguity and incomplete information.

The N-AHP method was implemented through a structured series of procedural steps, as outlined by (Vafadarnikjoo et al. 2023):

2.2.6.1. Step 1: development of the pairwise comparison matrix. In this step, the relative importance of each component is evaluated by the decision-makers using Saaty's fundamental rating scale (see Table 1). Components are classified as either criteria or alternatives. Participants in the expert survey select linguistic terms that best express the comparative importance of one element over another. These qualitative judgments are then converted into quantitative values for subsequent analysis.

To illustrate, suppose we are comparing a set of criteria $C_1, C_2, \ldots, C_n$. The decision-maker k^{th} (where $k = 1, 2, \ldots, p$) provides an evaluation for the relative importance of criterion C_i versus C_j, resulting in an entry a_{ijk} within the pairwise comparison matrix. This procedure yields a reciprocal matrix, as shown in Equation (1) (Hayaty et al. 2014), where each matrix element represents a directed comparison between two components based on the judgment of the respective expert. In practice, a pairwise comparison matrix is constructed separately for both primary and secondary criteria. This matrix is derived from the selected linguistic terms and subsequently converted into their corresponding neutrosophic representations. When multiple experts are involved in the decision-making process, their individual comparison matrices are integrated to form a single aggregated matrix. This aggregation is typically carried out using the geometric mean method or other well-established approaches found in the multi-criteria decision-making (MCDM) literature. The aim of this integration is to ensure a consistent and representative synthesis of expert opinions, enhancing the

Table 1. N-AHP SVTNNs rating scale (Vafadarnikjoo et al. 2023).

Numerical scale	Verbal scale	SVTNNs	Score function
1/9	Extremely less important	< (0.11,0.11,0.11,0.11); 1,0,0 >	0.11
1/8	Very very strongly less important	< (0.11,0.11,0.13,0.14); 1,0,0 >	0.12
1/7	Very strongly plus less important	< (0.11,0.13,0.14,0.17); 1,0,0 >	0.14
1/6	Strongly plus less important	< (0.13,0.14,0.17,0.2); 1,0,0 >	0.16
1/5	Strongly less important	< (0.14,0.17,0.2,0.25); 1,0,0 >	0.19
1/4	Moderately plus less important	< (0.17,0.20,0.25,0.33); 1,0,0 >	0.24
1/3	Moderately less important	< (0.14,0.17,0.33,0.50); 1,0,0 >	0.29
1/2	Weakly less important	< (0.20,0.25,0.5,1); 1,0,0 >	0.49
1	Equally important	< (1,1,1,1); 0.5,0.5,0.5 >	0.5
2	Weakly more important	< (1,2,4,5); 0.4,0.65,0.6 >	1.15
3	Moderately more important	< (2,3,6,7); 0.3,0.75,0.7 >	1.28
4	Moderately plus more important	< (3,4,5,6); 0.6,0.35,0.4 >	2.78
5	Strongly more important	< (4,5,6,7); 0.8,0.15,0.2 >	4.49
6	Strongly plus more important	< (5,6,7,8); 0.7,0.25,0.3 >	4.66
7	Very strongly plus more important	< (6,7,8,9); 0.9,0.1,0.1 >	6.75
8	Very very strongly more important	< (7,8,9,9); 0.85,0.1,0.15 >	7.15
9	Extremely more important	< (9,9,9,9); 1,0,0 >	9

robustness and validity of the comparative analysis.

$$A_k = [a_{ijk}] = \begin{bmatrix} 1 & a_{12k} & \cdots & a_{1nk} \\ 1/a_{12k} & 1 & \ldots & a_{2nk} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1nk} & 1/a_{2nk} & \cdots & 1 \end{bmatrix} \quad (24)$$

2.2.6.2. Step 2: evaluation of consistency ratio (CR). In alignment with the methodological framework established by Saaty (Liberatore 1982), conducting a consistency assessment is essential to distinguish logically coherent judgments from inconsistent ones within the decision-making process. This evaluation ensures the reliability of pairwise comparisons by verifying whether the comparative judgments are transitive and logically sound. The procedure for computing the consistency ratio is provided in Equation (25) and illustrated in Table 2. According to the threshold criterion proposed by (Leung and Cao 2000), if the calculated CR value equals or exceeds 0.1, the decision makers must re-evaluate and adjust their initial judgments to enhance consistency.

$$CR = \frac{((\lambda_{\max} - n)/(n-1))}{RI} \quad (25)$$

2.2.6.3. Step 3: transformation of linguistic terms into single-valued trapezoidal neutrosophic numbers. In this step, qualitative assessments expressed through linguistic terms are systematically converted into corresponding single-valued trapezoidal neutrosophic numbers. This conversion is carried out by utilizing the predefined scale outlined in Table 1, ensuring that subjective opinions are quantified in a manner suitable for computational analysis under uncertainty.

2.2.6.4. Step 4: aggregation of individual judgments using neutrosophic arithmetic operators. To consolidate the opinions of multiple decision makers into a unified evaluation, the single-valued trapezoidal neutrosophic weighted arithmetic mean operator is applied. This operator, as formulated by Ye (2017a), facilitates the integration of diverse perspectives by assigning appropriate weights to each expert's input, resulting in a collective neutrosophic representation, as demonstrated in Equation (26). This aggregation process is fundamental in group decision-making environments where consensus must reflect varying levels of expertise and confidence (Ye 2017a).

Table 2. Random index values (*RI*) used for consistency assessment (Golden et al. 2012).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$TNWAA\ (\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \sum_{j=1}^{n} p_j \tilde{a}_j = \left\langle \left(\sum_{j=1}^{n} p_j a_j, \sum_{j=1}^{n} p_j b_j, \sum_{j=1}^{n} p_j c_j, \sum_{j=1}^{n} p_j d_j \right); 1 - \prod_{j=1}^{n} (1 - w_{\tilde{a}_j})^{p_j}, \prod_{j=1}^{n} (u_{\tilde{a}_j})^{p_j}, \prod_{j=1}^{n} (y_{\tilde{a}_j})^{p_j} \right\rangle, \quad (26)$$

2.2.6.5. Step 5: neutrosophic synthetic values. To compute the neutrosophic synthetic value corresponding to each element (S_i), Equation (27) is utilized. In this formulation, the parameter n signifies the total number of elements under consideration, while n_{ij} refers to the entry located at the (i, j) position within the aggregated pairwise comparison matrix. This computational step is crucial for integrating the pairwise judgments into a unified neutrosophic framework, ensuring that uncertainty, indeterminacy, and inconsistency in expert evaluations are adequately captured.

$$S_i = \sum_{j=1}^{n} n_{ij} \times \left[\sum_{i=1}^{n} \sum_{j=1}^{n} n_{ij} \right]^{-1}, \quad i = 1, \ldots, n, \quad (27)$$

2.2.6.6. Step 6: derivation of final significance weights. In this phase, the final significance weights associated with each criterion or element are determined by employing Equation (28). The results are expressed in the form of single-valued trapezoidal neutrosophic numbers (SVTNNs), denoted as W_i. These weights reflect the relative importance of the elements within the decision-making context, incorporating the inherent uncertainty of the evaluations. Subsequently, Equation (29) is applied to facilitate the comparison and ranking of these weights. This methodological approach is aligned with the procedures outlined by (Ye 2017a), enabling a structured and rigorous assessment of alternatives within a neutrosophic environment.

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i}, \quad i = 1, \ldots, n, \quad (28)$$

$$S(\tilde{a}) = \frac{1}{12}(a + b + c + d)(2 + w_{\tilde{a}} + u_{\tilde{a}} + y_{\tilde{a}}), \quad S(\tilde{a}) \in [0, 1] \quad (29)$$

3. Results

The objective of this research is to investigate and evaluate the main causes of grain spoilage and loss during sea transport. By analyzing the extent to which each contributing factor contributes to these issues, the study proposes strategic measures to effectively mitigate these risks and protect the quality of the cargo. In order to ensure an accurate assessment, this study employs the N–AHP, an advanced method that is highly regarded for its capacity to address uncertainty and complexity in multi-criteria decision-making. This approach enables a systematic evaluation of the key parameters affecting cargo safety and provided a robust framework for identifying and prioritizing risk factors. The AHP is a widely used method for decision-making analysis, known for its simplicity, effectiveness, and credibility (Chul Park and Lee 2018). The neutrosophic scale can be integrated into the AHP to enhance its functionality and facilitate the prioritization of identified factors, enabling a more comprehensive evaluation of critical parameters. To ensure an objective and comprehensive identification of the critical factors contributing to grain cargo damage, a structured and iterative consultation process was carried out with a group of six experts. Each expert was selected based on extensive professional experience of more than ten years in operating vessels engaged in grain cargo transportation and demonstrated expertise in bulk cargo handling. This composition ensured that both technical and operational perspectives were adequately represented, leading to balanced and unbiased insights. Details of the experts are provided in Table 3, which includes industry professionals with extensive experience in bulk carrier operations.

As illustrated in Figure 1, the expert consultation process consisted of two stages. In the first stage, Expert Group A participated in an online meeting designed to present the study's conceptual framework, methodological approach, and practical objectives. During this session, the preliminary list of criteria – derived from a comprehensive literature review and analyses of P&I Club claim reports – was reviewed, discussed, and refined through interactive dialogue. This collaborative exchange enabled the validation of the most relevant factors and the elimination of overlapping or less significant ones. As a result of the first stage, a total of 17 critical criteria were confirmed and categorized into four main groups: heat damage (3 criteria), wet damage (3 criteria), contamination (7 criteria), and procedural issues (4 criteria).

In the second stage, individual online meetings were conducted with each member of Expert Group B to introduce the N-AHP method, explain the evaluation procedure, and obtain their independent assessments of the finalized criteria. Following these meetings, the N-AHP approach, originally proposed by Radwan et al. (2016), was employed to perform a comprehensive evaluation and prioritization of 17 critical criteria contributing to grain deterioration. For this purpose, the experts were asked to assess the relative importance of each criterion using neutrosophic linguistic measurement values within a neutrosophic fuzzy environment. The linguistic terms and their corresponding neutrosophic values are defined in Table 1. A structured questionnaire, prepared according to the predefined evaluation framework presented in Table 2, was distributed to collect the experts' assessments. The responses were then aggregated to form the neutrosophic decision matrix shown in Table 4, which served as the basis for the subsequent analytical phase.

Expert assessments were used to determine the relative importance of the identified criteria. It is therefore crucial to establish a fair and accurate weighting of these criteria in order to ensure a reliable assessment. However, the selected operator must effectively minimize the subjectivity of expert judgments to ensure that the results remain objective and reliable. In this study, to aggregate the expert opinions effectively, we employed the TNWAA operator, as outlined in Equation (14). The opinions of three experts were aggregated using the TNWAA operator in order to establish a collective decision-making matrix, as outlined in Table 5. Gray-shaded values denote the truth (T), indeterminacy (I), and falsity (F) membership degrees of the SVTNNs. The neutrosophic synthetic values corresponding to each identified causal factor were derived by utilizing the aggregated pairwise comparison matrix, as outlined in Equation (4). This methodological framework facilitates the incorporation of expert evaluations under conditions of ambiguity and incomplete information, circumstances commonly encountered when analyzing intricate and interdependent causal relationships. The computed neutrosophic

Table 3. Experts' information.

Expert Group	Experts	Qualification	Current Position	Serves on ships
A	Expert #1	Unlimited Chief Officer	Chief Officer	10 Years
A	Expert #2	Unlimited Chief Officer	Chief Officer	11 Years
A	Expert #3	Unlimited Master	Master	13 Years
B (DM1)	Expert #4	Unlimited Master	Cargo Surveyor	22 Years
B (DM2)	Expert #5	Unlimited Master	Ship Broker	18 Years
B (DM3)	Expert #6	Unlimited Chief Officer	Marine Superintendent	15 Years

Table 4. Neutrosophic decision matrix of criteria comparisons (per expert).

DM 1

				C1	C2	C3	C4									
		C1		1,00	5,00	1,00	3,00				**C1**		1,00	6,00	4,00	3,00
		C2		0,20	1,00	0,25	0,50				**C2**		0,17	1,00	0,25	0,33
		C3		1,00	4,00	1,00	2,00				**C3**		0,25	4,00	1,00	2,00
		C4		0,33	2,00	0,50	1,00				**C4**		0,33	3,00	0,50	1,00
					C11	**C12**	**C13**							**C11**	**C12**	**C13**
	C11				1,00	1,00	0,33			**C11**				1,00	1,00	0,25
	C12				1,00	1,00	0,33			**C12**				1,00	1,00	0,33
	C13				3,00	3,00	1,00			**C13**				4,00	3,00	1,00
					C21	**C22**	**C23**							**C21**	**C22**	**C23**
	C21				1,00	1,00	0,33			**C21**				1,00	3,00	0,25
	C22				1,00	1,00	0,33			**C22**				0,33	1,00	0,33
	C23				3,00	3,00	1,00			**C23**				4,00	3,00	1,00
	C31	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**			**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**
C31	1,00	3,00	0,50	3,00	1,00	2,00	3,00		**C31**	1,00	3,00	0,33	2,00	0,50	4,00	4,00
C32	0,33	1,00	0,50	7,00	0,50	1,00	1,00		**C32**	0,33	1,00	0,50	2,00	0,50	1,00	1,00
C33	2,00	2,00	1,00	5,00	2,00	2,00	2,00		**C33**	3,00	2,00	1,00	5,00	3,00	4,00	2,00
C34	0,33	0,14	0,20	1,00	0,50	1,00	1,00		**C34**	0,50	0,50	0,20	1,00	0,33	0,50	1,00
C35	1,00	2,00	0,50	2,00	1,00	1,00	2,00		**C35**	2,00	2,00	0,33	3,00	1,00	3,00	4,00
C36	0,50	1,00	0,50	1,00	1,00	1,00	1,00		**C36**	0,25	1,00	0,25	2,00	0,33	1,00	1,00
C37	0,33	1,00	0,50	1,00	0,50	1,00	1,00		**C37**	0,25	1,00	0,50	1,00	0,25	1,00	1,00
			C41	**C42**	**C43**	**C44**						**C41**	**C42**	**C43**	**C44**	
	C41		1,00	1,00	1,00	0,50				**C41**		1,00	0,33	0,33	0,50	
	C42		1,00	1,00	1,00	0,50				**C42**		3,00	1,00	0,33	0,33	
	C43		1,00	1,00	1,00	1,00				**C43**		3,00	3,00	1,00	0,50	
	C44		2,00	2,00	1,00	1,00				**C44**		2,00	3,00	2,00	1,00	

DM 3

			C1	C2	C3	C4	
	C1		1,00	7,00	5,00	2,00	
	C2		0,14	1,00	0,20	0,25	
	C3		0,20	5,00	1,00	1,00	
	C4		0,50	4,00	1,00	1,00	
				C11	**C12**	**C13**	
	C11			1,00	0,33	0,50	
	C12			3,00	1,00	0,50	
	C13			2,00	2,00	1,00	
				C21	**C22**	**C23**	
	C21			1,00	4,00	0,50	
	C22			0,25	1,00	0,33	
	C23			2,00	3,00	1,00	
	C31	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**
C31	1,00	1,00	1,00	1,00	2,00	2,00	2,00
C32	1,00	1,00	0,33	4,00	1,00	1,00	4,00
C33	1,00	3,00	1,00	3,00	2,00	3,00	3,00
C34	1,00	0,25	0,33	1,00	0,50	1,00	0,50
C35	0,50	1,00	0,50	2,00	1,00	4,00	3,00
C36	0,50	1,00	0,33	1,00	0,25	1,00	2,00
C37	0,50	0,25	0,33	2,00	0,33	0,50	1,00
			C41	**C42**	**C43**	**C44**	
	C41		1,00	0,50	0,50	1,00	
	C42		2,00	1,00	1,00	0,33	
	C43		2,00	1,00	1,00	1,00	
	C44		1,00	3,00	1,00	1,00	

values, which reflect the relative significance of each cause within the decision-making context, are systematically summarized in Table 6.

In the final stage of the neutrosophic AHP analysis, the ultimate weights for each criterion were determined, where the sum of all normalized crisp values equaled 1, providing a comprehensive prioritization across all criteria. Based on these crisp values, alternatives are ranked according to their score functions. The ranking of the main criteria is presented in Table 7 and illustrated in Figure 3. The results of the proposed model reveal that the highest values of the score functions correspond to the risk factors C_2 and C_4, which are ranked as follows: $C_2 > C_4 > C_3 > C_1$.

The analysis demonstrated that C_2 holds the greatest weight, indicating its dominant influence relative to the other evaluated criteria. A considerable difference in weight between C_2 and the second-highest-ranked criterion, C_4, further highlights the distinct significance of C_2 within the decision-making framework. Likewise, the ranking reveals a clear differentiation between C_3 and C_1, underscoring the roles of C_2 and C_4 as the

Table 5. Combined matrix of decision makers' opinions with the TNWAA operator.

	C1	C2	C3	C4
C1	1,00	4,93	2,29	1,59
	1,00	5,94	2,71	2,62
	1,00	6,95	3,11	5,24
	1,00	7,96	3,48	6,26
	0,50	0,80	0,62	0,33
	0,50	0,16	0,30	0,72
	0,50	0,18	0,34	0,66
C2	0,13	1,00	0,16	0,17
	0,15	1,00	0,19	0,20
	0,20	1,00	0,23	0,35
	0,26	1,00	0,30	0,55
	1,00	0,50	1,00	1,00
	0,00	0,50	0,00	0,00
	0,00	0,50	0,00	0,00

	C1	C2	C3	C4
C3	0,29	3,30	1,00	1,00
	0,32	4,31	1,00	1,59
	0,37	5,31	1,00	2,52
	0,44	6,32	1,00	2,92
	0,74	0,66	0,50	0,43
	0,00	0,26	0,50	0,60
	0,00	0,32	0,50	0,56
C4	0,16	1,82	0,34	1,00
	0,19	2,88	0,40	1,00
	0,38	4,93	0,63	1,00
	0,63	5,94	1,00	1,00
	1,00	0,42	0,79	0,50
	0,00	0,55	0,00	0,50
	0,00	0,55	0,00	0,50

	C11	C12	C13
C11	1,00	0,52	0,17
	1,00	0,55	0,20
	1,00	0,59	0,25
	1,00	0,69	0,35
	1,00	0,79	0,55
	0,50	0,63	1,00
	0,50	0,00	0,00
C12	1,26	1,00	0,16
	1,44	1,00	0,19
	1,82	1,00	0,38
	1,91	1,00	0,63
	0,42	0,50	1,00
	0,57	0,50	0,00
	0,56	0,50	0,00
C13	1,82	1,59	1,00
	2,88	2,62	1,00
	4,93	5,24	1,00
	5,94	6,26	1,00
	0,42	0,33	0,50
	0,55	0,72	0,50
	0,55	0,66	0,50

	C21	C22	C23
C21	1,00	1,82	0,17
	1,00	2,29	0,20
	1,00	3,11	0,35
	1,00	3,48	0,55
	0,50	0,45	1,00
	0,50	0,51	0,00
	0,50	0,52	0,00
	0,29	1,00	0,14
	0,32	1,00	0,17
	0,44	1,00	0,33
	0,55	1,00	0,50
C22	0,79	0,50	1,00
	0,00	0,50	0,00
	0,00	0,50	0,00
C23	1,82	2,00	1,00
	2,88	3,00	1,00
	4,93	6,00	1,00
	5,94	7,00	1,00
	0,42	0,30	0,50
	0,55	0,75	0,50
	0,55	0,70	0,50

	C31	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**
C1	1,00	1,59	0,30	1,26	0,58	1,44	1,82
	1,00	2,08	0,35	1,82	0,79	2,52	2,88
	1,00	3,30	0,55	2,88	1,26	4,31	4,93
	1,00	3,66	0,79	3,27	1,71	5,31	5,94
	0,50	0,36	0,79	0,39	0,58	0,46	0,42
	0,50	0,66	0,00	0,62	0,00	0,53	0,55
	0,50	0,63	0,00	0,59	0,00	0,52	0,55
C2	0,27	1,00	0,18	2,62	0,34	1,00	1,44
	0,30	1,00	0,22	3,83	0,40	1,00	1,59
	0,40	1,00	0,44	5,43	0,63	1,00	1,71
	0,50	1,00	0,79	6,46	1,00	1,00	1,82
	0,79	0,50	1,00	0,60	0,79	0,50	0,53
	0,00	0,50	0,00	0,28	0,00	0,50	0,44
	0,00	0,50	0,00	0,29	0,00	0,50	0,46
C3	1,26	1,26	1,00	3,17	1,26	1,82	1,26
	1,82	2,29	1,00	4,22	2,29	2,88	2,29
	2,88	4,58	1,00	6,00	4,58	4,93	4,58
	3,27	5,59	1,00	7,00	5,59	5,94	5,59
	0,39	0,36	0,50	0,58	0,36	0,42	0,36

	C31	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**
C5	0,58	1,00	0,18	1,26	1,00	1,82	1,82
	0,79	1,59	0,22	2,29	1,00	2,29	2,88
	1,26	2,52	0,44	4,58	1,00	3,11	4,93
	1,71	2,92	0,79	5,59	1,00	3,48	5,94
	0,58	0,43	1,00	0,36	0,50	0,45	0,42
	0,00	0,60	0,00	0,68	0,50	0,51	0,55
	0,00	0,56	0,00	0,63	0,50	0,52	0,55
C36	0,19	1,00	0,17	1,00	0,29	1,00	1,00
	0,23	1,00	0,20	1,26	0,32	1,00	1,26
	0,40	1,00	0,35	1,59	0,44	1,00	1,59
	0,69	1,00	0,55	1,71	0,55	1,00	1,71
	1,00	0,50	1,00	0,46	0,79	0,50	0,46
	0,00	0,50	0,00	0,55	0,00	0,50	0,55
	0,00	0,50	0,00	0,53	0,00	0,50	0,53
C37	0,17	0,55	0,18	1,00	0,17	0,58	1,00
	0,20	0,58	0,22	1,26	0,20	0,63	1,00
	0,29	0,63	0,44	1,59	0,35	0,79	1,00
	0,44	0,69	0,79	1,71	0,55	1,00	1,00
	1,00	0,63	1,00	0,46	1,00	0,63	0,50

(*Continued*)

Table 5. Continued.

	C1	C2	C3	C4		C1	C2	C3	C4		C11	C12	C13		
	0,62	0,68	0,50	0,26	0,68	0,55	0,68		0,00	0,00	0,00	0,55	0,00	0,00	0,50
	0,59	0,63	0,50	0,30	0,63	0,55	0,63		0,00	0,00	0,00	0,53	0,00	0,00	0,50
C4	0,31	0,16	0,14	1,00	0,18	0,58	0,58								
	0,35	0,19	0,17	1,00	0,22	0,63	0,63								
	0,46	0,26	0,28	1,00	0,44	0,79	0,79								
	0,63	0,38	0,40	1,00	0,79	1,00	1,00								
	0,79	1,00	1,00	0,50	1,00	0,63	0,63								
	0,00	0,00	0,00	0,50	0,00	0,00	0,00								
	0,00	0,00	0,00	0,50	0,00	0,00	0,00								
	C41	**C42**	**C43**	**C44**		**C41**	**C42**	**C43**	**C44**						
C41	1,00	0,30	0,30	0,34	**C43**	1,26	1,26	1,00	0,58						
	1,00	0,35	0,35	0,40		1,82	1,44	1,00	0,63						
	1,00	0,55	0,55	0,63		2,88	1,82	1,00	0,79						
	1,00	0,79	0,79	1,00		3,27	1,91	1,00	1,00						
	0,50	0,79	0,79	0,79		0,39	0,42	0,50	0,63						
	0,50	0,00	0,00	0,00		0,62	0,57	0,50	0,00						
	0,50	0,00	0,00	0,00		0,59	0,56	0,50	0,00						
C42	1,26	1,00	0,52	0,16	**C44**	1,00	1,59	1,00	1,00						
	1,82	1,00	0,55	0,19		1,59	2,62	1,26	1,00						
	2,88	1,00	0,69	0,38		2,52	5,24	1,59	1,00						
	3,27	1,00	0,79	0,63		2,92	6,26	1,71	1,00						
	0,39	0,50	0,63	1,00		0,43	0,33	0,46	0,50						
	0,62	0,50	0,00	0,00		0,60	0,72	0,55	0,50						
	0,59	0,50	0,00	0,00		0,56	0,66	0,53	0,50						

primary drivers of grain cargo deterioration risk. These weights are based on expert judgments and may vary across different expert panels; however, the neutrosophic framework accounts for uncertainty and partial inconsistency in human evaluations.

The logical consistency of expert judgments was verified using the CR test for each pairwise comparison matrix. The obtained CR values were 0.0533 for the main criteria, 0.0707 for C1, 0.0647 for C2, 0.0668 for C3, and 0.0752 for C4. All these values are below the conventional threshold of 0.1, indicating satisfactory internal consistency among the expert assessments. This confirms that the pairwise comparison matrices are coherent and that the derived weights reliably represent expert priorities.

4. Discussion

In this study, the main criteria and corresponding subcriteria were prioritized by their respective weights to evaluate their significance in the context of grain cargo damage in maritime transportation. The analysis revealed that Wet Damage (C_2) represents the most critical factor, emphasizing the high risk of moisture exposure to cargo, with aspects like Hatch Cover Leakage being particularly impactful. The second most critical criterion, Procedures (C_4), underscores the importance of standardized operational practices, such as Cargo Handling and Training, in safeguarding cargo integrity. Contamination (C_3) ranked third, pointing to the need for preventive measures against environmental pollutants, with attention to sub-factors like Vermin and Dust. Finally, Heat Damage (C_1), while carrying the lowest weight, remains relevant, especially for temperature-sensitive cargo, where factors such as Self-Heating are of concern. Each of these main criteria and their associated sub-criteria is discussed in detail, providing a comprehensive evaluation of their impact on cargo damage.

Wet damage is frequently cited as a significant source of cargo damage in the literature. Wet damage is frequently cited in the literature as a major source of cargo loss. Consistent with previous studies, the present analysis identified wet damage as the most influential risk factor, with a weight of 0.5291. This finding is particularly important because grain cargo is highly sensitive to moisture exposure. Although Kuo et al. (2022) reported that wet damage had the highest likelihood among the identified maritime transport risks, their study focused on general seaborne cargo and found its consequences to be relatively less severe than those of other risk categories. In contrast, the present study suggests that wet damage has more serious implications for grain cargo, given the rapid deterioration that occurs when grain comes into contact with water (Kuo et al. 2022). Cargo sweat (C_{21}) emerged as the second most influential sub-factor within the wet-damage category. This result is consistent with the known role of condensation in maritime grain transport, where moisture accumulation inside the hold can reduce cargo quality and market value. Previous studies have likewise shown that sweating in ship holds contributes to

Table 6. Neutrosophic synthetic values (S_i) for criteria.

S1	0.04	0.05	0.08	0.12	1.00	0.00	0.00
S2	0.28	0.41	0.71	1.05	0.98	0.01	0.02
S3	0.09	0.13	0.19	0.29	1.00	0.00	0.00
S4	0.09	0.16	0.36	0.53	1.00	0.00	0.00
Total	0.50	0.75	1.34	1.99	1.00	0.00	0.00
S11	0.21	0.32	0.71	1.04	0.83	0.16	0.15
S12	0.16	0.25	0.64	0.95	0.88	0.00	0.00
S13	0.07	0.09	0.16	0.26	1.00	0.00	0.00
Total	0.45	0.66	1.51	2.24	1.00	0.00	0.00
S21	0.15	0.23	0.54	0.81	0.94	0.00	0.00
S22	0.23	0.35	0.85	1.24	0.81	0.19	0.18
S23	0.06	0.08	0.14	0.22	1.00	0.00	0.00
Total	0.44	0.65	1.53	2.28	1.00	0.00	0.00
S31	0.03	0.05	0.11	0.18	1.00	0.00	0.00
S32	0.06	0.10	0.22	0.34	1.00	0.00	0.00
S33	0.02	0.03	0.06	0.11	1.00	0.00	0.00
S34	0.10	0.17	0.38	0.60	0.99	0.00	0.00
S35	0.04	0.06	0.14	0.25	1.00	0.00	0.00
S36	0.08	0.12	0.26	0.42	0.99	0.00	0.00
S37	0.08	0.14	0.32	0.51	0.99	0.00	0.00
Total	0.41	0.66	1.51	2.42	1.00	0.00	0.00
S41	0.159	0.254	0.546	0.771	0.895	0.116	0.100
S42	0.146	0.221	0.506	0.734	0.960	0.00	0.00
S43	0.100	0.129	0.225	0.316	0.980	0.00	0.00
S44	0.074	0.091	0.165	0.267	1.00	0.00	0.00
Total	0.479	0.694	1.441	2.088	1.00	0.00	0.00

export-quality deterioration and highlights the need for effective moisture control during transport. The study conducted by Huang et al. indicates that the process of cargo and ship sweating can result in a deterioration of export quality by 15–20% (Huang MC et al. 2023). Similarly, Buxton et al. (1978) discuss the formation of sweat in a ship's hold, emphasizing the necessity of controlling moisture content to prevent such issues (Buxton et al. 1978). Leaking hatch covers (C_{22}) are a primary cause of wet damage in grain cargoes during maritime transport. The Swedish Club (2018) reported that leaking hatch covers are the most common cause of wet damage claims on bulk carriers, often occurring in conjunction with heavy weather (The Swedish Club 2018). Grain cargoes are particularly prone to wet damage due to their hygroscopic nature. The ingress of water through leaking hatch covers can lead to mold growth, mycotoxin contamination, and spontaneous heating, which can compromise the quality and safety of the cargo. Therefore, ensuring the integrity of hatch covers is paramount in preventing wet damage to grain cargoes. In addition to external water ingress, internal moisture migration within the cargo, such as condensation or cargo sweat, also contributes significantly to wet damage. Wang and Zhou investigated the condensation of grain cargo that occurred in bulk carriers. Their findings indicate that the risk of condensation on the shipside of a cargo hold is perpetually present if the inner surface of the shipside is in direct contact with the cargo. Moreover, they emphasize that an extended journey exacerbates the movement of moisture from the core of the bulk grain to the ship's side, hence increasing the risk of condensation. According to the present findings, sweat (C_{21}) is the second most influential sub-factor within the wet-damage category, with a normalized crisp value of 0.3902. This result is consistent with the findings of (Wang and Zhou

Table 7. Final ranks and normalized weights of criteria.

Codes	Criteria	Criteria SVTNN weights							Crisp	Normalized Crisp	Rank
C_1	Heat Damage	0.02	0.04	0.10	0.23	1.00	0.00	0.00	0.0968	0.0596	4
C_2	Wet Damage	0.14	0.31	0.96	2.09	0.98	0.01	0.02	0.8593	0.5291	1
C_3	Contamination	0.05	0.09	0.26	0.57	1.00	0.00	0.00	0.2428	0.1495	3
C_4	Procedures	0.05	0.12	0.48	1.06	1.00	0.00	0.00	0.4250	0.2617	2
C_{11}	Self-Heating	0.10	0.22	1.07	2.33	0.83	0.16	0.15	0.7797	0.4330	2
C_{12}	Heated Compartment	0.07	0.17	0.96	2.12	0.88	0.00	0.00	0.7960	0.4420	1
C_{13}	External Temperatures	0.03	0.06	0.24	0.57	1.00	0.00	0.00	0.2250	0.1249	3
C_{21}	Sweat	0.06	0.15	0.82	1.85	0.94	0.00	0.00	0.7067	0.3902	2
C_{22}	Hatch Cover Leakage	0.10	0.23	1.30	2.83	0.81	0.19	0.18	0.9048	0.4996	1
C_{23}	Pipes & Tanks Leakage	0.03	0.05	0.22	0.51	1.00	0.00	0.00	0.1995	0.1102	3
C_{31}	Inherent Vice	0.01	0.03	0.17	0.44	1.00	0.00	0.00	0.1653	0.0760	6
C_{32}	Hold Cleaning	0.03	0.06	0.33	0.82	1.00	0.00	0.00	0.3112	0.1430	4
C_{33}	Rat and Mice	0.01	0.02	0.09	0.28	1.00	0.00	0.00	0.0973	0.0447	7
C_{34}	Smaller Vermin	0.04	0.11	0.58	1.44	0.99	0.00	0.00	0.5415	0.2488	1
C_{35}	Cargo Mixing	0.01	0.04	0.22	0.60	1.00	0.00	0.00	0.2187	0.1005	5
C_{36}	Storage Area	0.03	0.08	0.40	1.01	0.99	0.00	0.00	0.3797	0.1745	3
C_{37}	Dust, Stain and Rust	0.03	0.09	0.49	1.24	0.99	0.00	0.00	0.4627	0.2126	2
C_{41}	Training	0.08	0.18	0.79	1.61	0.89	0.12	0.10	0.5716	0.3465	2
C_{42}	Cargo Handling	0.07	0.15	0.73	1.53	0.96	0.00	0.00	0.4306	0.3592	1
C_{43}	Maintenance	0.05	0.09	0.32	0.66	0.98	0.00	0.00	0.2712	0.1633	3
C_{44}	Cargo Survey & Monitoring	0.04	0.06	0.24	0.56	1.00	0.00	0.00	0.2272	0.1309	4

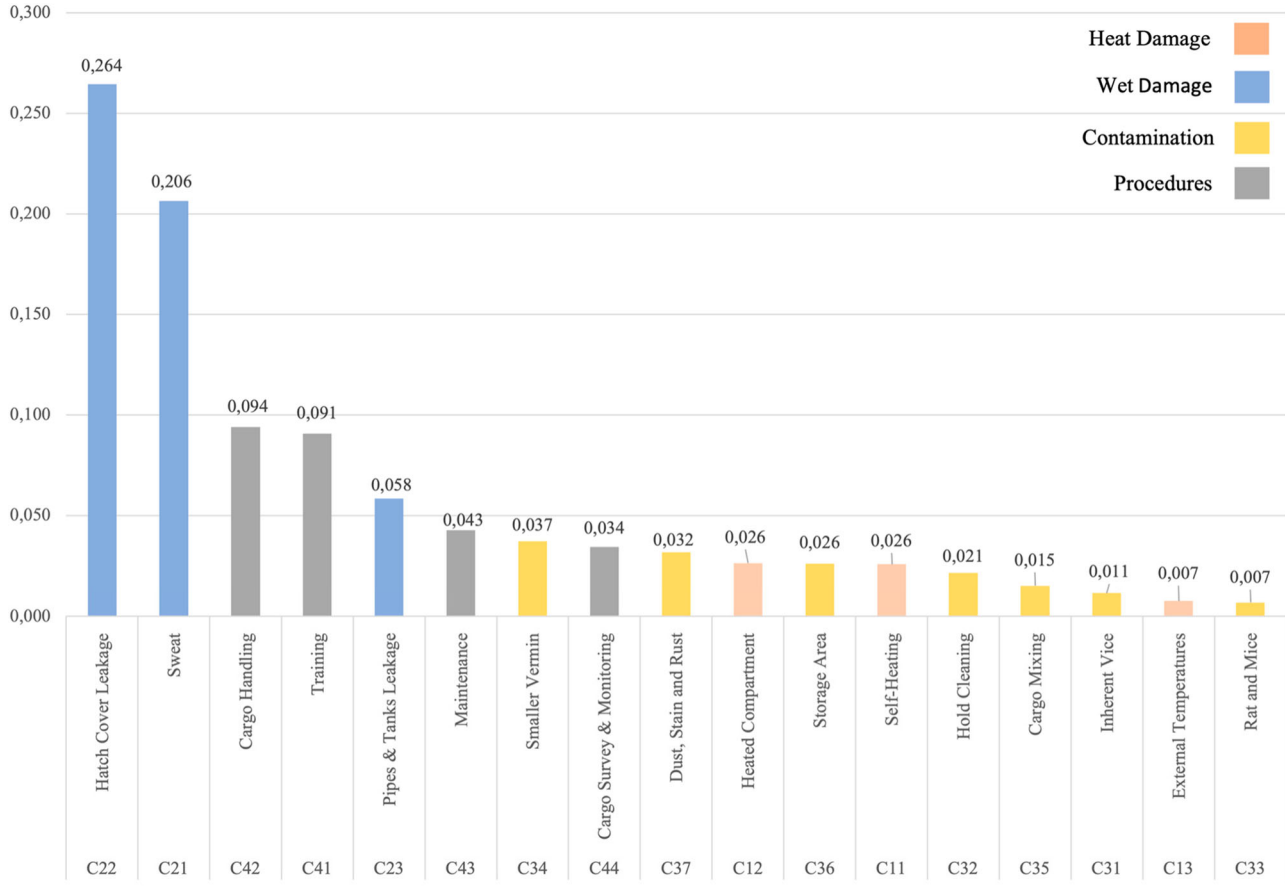


Figure 3. Weights of sub-criteria. '(This figure is available in color online.)

2023). Extending the discussion from bulk cargoes in ships to other transportation modes, Lirn and Wong (2013) conducted a study to identify the elements influencing grain cargo transportation modes for shippers. According to their results, the cargo damage ratio is the most important aspect in cargo and quality control. Their research also shows that, due to ventilation issues in containers, grain cargo is more likely to be damaged when transported in containers than in bulk carriers. They state that because grain is a perishable product, it is typically ordered in big quantities and can be instantly damaged by numerous molds and fungi in a humid and poorly ventilated atmosphere which is similar to our findings (Lirn and Wong 2013). Building on these observations, our study further highlights the relative importance of specific sources of wet damage during maritime transport of bulk grain. Within the wet-damage category, hatch-cover leakage was identified as the most influential sub-factor (0.4996), followed by sweat (0.3902) and leaks from pipes and tanks (0.1102). As stated in a technical report published by the North of England P&I Club, the presence of leakage from bilges or tanks into the holds has the potential to result in wet damage to grain cargo (NorthStandard 2024). The findings of this study demonstrate that this is the least expected source of wet damage. Nevertheless, given the potentially large volume of water that could enter the hold, special attention should still be paid to this issue.

Procedure-related issues were evaluated through four sub-criteria: training (C_{41}), cargo handling (C_{42}), maintenance (C_{43}), and cargo survey and monitoring (C_{44}). Although all four contribute to cargo preservation, their relative influence differs. Cargo Handling (C_{42}), with the highest weight (0.3592), is paramount, as effective handling minimizes the risk of physical damage, contamination, and losses – a critical need given grain's sensitivity to crushing and exposure. Effective handling of grain cargo is essential for minimizing losses and has been widely addressed in the literature. Florani (2017) emphasized efficiency, dust control, and stability in the cargo handling process. The author highlighted the critical importance of allowing time for proper settlement of the grain and ensuring that all corners of the ship's holds are adequately filled during loading to prevent cargo shifting during sea voyages. Additionally, Florani identified dust generation as a significant challenge in loading and unloading operations, stressing

the importance of dust suppression units and vacuum unloading systems in addressing this issue. While vacuum systems consume more energy compared to mechanical systems, they offer advantages such as dust-free operations and reduced reliance on auxiliary equipment. In this context, Florani advocated for considering both operational efficiency and environmental impacts in cargo handling processes (Florani 2017). These observations are consistent with the present findings, which highlight the importance of both planning and implementation during cargo-handling operations. According to Tadesse (2020), post-harvest processes such as packaging, storage, and transportation often lead to significant damage, making them a major cause of grain losses. To address this issue, adopting efficient cargo handling techniques, along with ensuring the use of proper packaging, adequate storage conditions, and reliable transportation methods, is crucial. Similar to Cargo Handling (C_{42}), Training (C_{41}) holds significant weight with a value of 0.3465, emphasizing the critical role of skilled personnel in effectively implementing grain-specific procedures, such as ventilation management and stowage stability, to minimize the risk of spoilage. In the literature, there is limited research on training aimed at preventing grain cargo damage; however, there are prominent guidelines available within the maritime industry (Tadesse 2020). Although that study does not explicitly focus on training, the problems it identifies are closely associated with inadequate personnel knowledge and practice. In this respect, its conclusions indirectly support the present findings. 'A Guide to Good Practice' published by the North of England P&I Association emphasized that effective training of shipboard crew is essential for minimizing grain cargo damage by ensuring proper handling, stowage, and management practices are implemented throughout the voyage. Such training provides the necessary skills for uniform cargo distribution, the prevention of shifting, and the maintenance of vessel stability. Moreover, training for practical implementation of international standards such as SOLAS, the IMSBC Code, the International Grain Code, the ISM Code, and the BLU Code promotes safe operations and contributes to minimizing grain cargo damage (Bliault and Jonas 2015). These findings support the influence of training on the safe carriage of grain cargoes as demonstrated by our study.

Contrary to Cargo Handling (C_{42}) and Training (C_{41}) criteria, Maintenance (C43), with a lower weight of 0.1633, remains essential but plays a more supportive role by ensuring that cargo holds and equipment are kept in optimal condition, reducing wet damage and contamination risk. According to the guide published by The North of England P&I Association, maintenance plays a vital role in preventing grain cargo damage by ensuring the safe and efficient transportation of bulk grain. Regular upkeep of the holds, including checking for waterproofing and structural integrity, prevents water ingress, thus safeguarding the grain from spoilage. Furthermore, the proper maintenance of ventilation systems is essential for moisture control, reducing the risks of mold or fermentation. Ensuring the smooth operation of loading and unloading equipment, along with the upkeep of dust control systems, minimizes the likelihood of damage or contamination during handling. The maintenance of cargo securing systems, such as shifting boards and tarps, ensures cargo stability during transit. Routine inspections, compliance with regulations, and effective cleaning practices help maintain the cargo's quality (NorthStandard 2024). Although maintenance received a relatively lower weight than cargo handling and training, it remains an important supporting factor in preventing wet damage and contamination. On the other hand, Cargo Survey & Monitoring (C_{44}) is another low-weighted (0.1309) criterion; however, it provides real-time feedback for adjusting environmental conditions, allowing for timely intervention if issues like moisture buildup arise. Moreover, it is highly recommended by P&I Clubs (North of England, Standard) to appoint a cargo surveyor before loading and discharging. Together, these sub-criteria form a comprehensive framework that, by integrating proactive handling, training, upkeep, and monitoring, significantly enhances grain cargo safety during maritime transport, which is in line with our results.

Contamination (C3) ranked as the third most influential main factor and remains a significant source of grain loss during maritime transport. Grain cargo contamination can arise from several sources, including polluted air or water, infestation by insects, birds, and rodents, and adverse environmental conditions. Furthermore, unhygienic handling practices, inadequate processing equipment, and inappropriate storage conditions exacerbate the risk of contamination (Sirohi et al. 2021). It is widely agreed that contamination, whether by microorganisms, pests, or other foreign substances, is a significant factor in the deterioration of cargo quality and market value. In particular, the role of rodents in the contamination of grains has been revealed as a significant contributing factor to the deterioration of stored products. Rodent activity not only causes direct physical damage through feeding but also contributes indirectly by introducing moisture through urine. This increase in water activity can promote the proliferation of molds, creating a favorable environment for fungal growth (Hodges et al. 2014;

Edoh Ognakossan et al. 2018). The growth of fungi, including Aspergillus, Fusarium, and Penicillium, can result in the production of mycotoxins, which are toxic secondary metabolites that can have adverse effects on both humans and animals (Mannaa and Kim 2017). These findings underscore the need for proactive risk assessment by shipping companies, port authorities, and insurers. While our study meets all these criteria, the comparatively small impact of the contamination element represents the principal distinction between our results and those of other research.

Heat damage (C1), which can result in significant economic and nutritional losses, was identified as the least influential of the four main criteria in the present study. Nevertheless, its role in grain deterioration should not be underestimated. Heat damage arises from temperature fluctuations during storage and transportation and can adversely affect grain composition, quality, and market value. Furthermore, external heat sources present a substantial risk to cargo integrity. Direct exposure of cargo holds to heat sources, including overheated fuel tanks, hot fuel-oil pipelines, and engine-room bulkheads, is a major contributor to thermal damage. A case study involving the carriage of soybean meal from Brazil to Thailand reported severe cargo discoloration, overheating, and caking in the aftermost cargo hold due to heat transfer from adjacent fuel oil tanks, demonstrating the potentially destructive consequences of localized heating (Arora and Vandenborn 2021). In addition to external heat sources, self-heating (C11) constitutes a major concern in grain transportation. This process occurs when biological activity within the cargo, including grain respiration, microbial activity, and fungal growth, generates heat that accumulates within the cargo mass. The risk is further amplified by elevated moisture levels, which accelerate microbial proliferation and oil hydrolysis, thereby promoting oxidation reactions and increasing the probability of spontaneous heating and combustion (Arora and Vandenborn 2021; TMS Grup 2022). Similar observations have been reported in grain storage studies, where increasing grain temperature and moisture content accelerate respiration rates, generating both heat and water that subsequently promote fungal growth, insect infestation, and quality deterioration (Atungulu et al. 2019). Likewise, research on rice has demonstrated that elevated temperatures can negatively affect grain development, quality, and physiological performance, particularly when combined with unfavorable humidity conditions and water stress (Jagadish et al. 2015). Furthermore, studies conducted on highly perishable agricultural commodities such as sweet corn identified temperature as the primary determinant of post-harvest quality because elevated temperatures accelerate respiration, dehydration, sugar degradation, fungal growth, and overall quality losses (Becerra-Sanchez and Taylor 2021). Although these studies emphasize the dominant role of heat, the present findings suggest that the relative importance of heat damage is highly context-dependent. A key explanation for this discrepancy lies in differences in research objects, transportation environments, and transportation modes. Many studies emphasizing temperature effects focus on grain storage systems, silos, warehouses, or highly perishable agricultural commodities, where temperature accumulation represents the primary deterioration mechanism. In contrast, the present study specifically evaluates grain cargoes transported in bulk carriers under commercial maritime conditions. Unlike storage facilities, maritime transportation exposes grain cargoes to a broader range of operational and environmental hazards, including hatch-cover leakage, cargo sweat, seawater ingress, cargo handling deficiencies, and maintenance-related failures. Moreover, transportation mode can substantially influence the relative importance of deterioration factors. Previous studies have shown that grain transported in containers is more susceptible to temperature accumulation and ventilation-related problems because of the confined nature of the transport unit, whereas bulk carriers generally benefit from larger cargo spaces and voyage ventilation procedures that can partially mitigate heat accumulation (Lirn and Wong 2013). Consequently, moisture-related incidents and operational failures may occur more frequently and produce more immediate cargo claims than direct thermal degradation in bulk maritime transport. Methodological differences should also be considered. While many previous studies rely on experimental observations, physiological measurements, or storage trials that quantify the direct impact of temperature on grain quality, the present study employs a TNWAA-based Neutrosophic AHP framework that captures expert perceptions regarding the practical significance and frequency of damage factors encountered in real maritime operations. Therefore, the lower ranking of heat damage should not be interpreted as evidence that temperature is unimportant. Rather, it suggests that under commercial maritime grain transportation conditions, heat often acts as a secondary or amplifying mechanism that intensifies moisture migration, microbial activity, fungal growth, and insect development, whereas wet damage and procedural deficiencies are perceived as the primary triggers of cargo deterioration. This interpretation reconciles the

present findings with previous studies and highlights the context-dependent nature of grain deterioration risks across different commodities, transportation modes, and operational environments.

Although the effects of each analyzed parameter have been discussed in detail above, there are certain methodological limitations that should be acknowledged in the evaluation of this study. In practical maritime operations, some primary factors may trigger multi-dimensional and compound effects; for example, hatch-cover leakage can lead to moisture ingress, mold proliferation, mycotoxin contamination, and increased microbial activity, resulting in spontaneous heating. Despite these potential interactions, in the present study each risk factor was treated as an independent element within the N-AHP hierarchy. This independence assumption, while a simplification, was deliberately adopted to enable clear prioritization of the principal risk drivers, which is the primary objective. By focusing on the main drivers, the study provides decision-makers with actionable insights to target interventions effectively. Future research could extend this framework by explicitly modeling interdependencies and performing scenario-based sensitivity analyses to assess how interaction pathways influence overall risk rankings.

5. Conclusions

This study presents a comprehensive assessment of the factors contributing to grain cargo damage during maritime transportation through the development and application of a TNWAA-based Neutrosophic Analytical Hierarchy Process framework. By integrating neutrosophic sets with the AHP methodology, the proposed approach effectively addresses the uncertainty and subjectivity inherent in expert judgments, providing a more robust and realistic evaluation of grain deterioration risks than conventional decision-making methods. The results revealed that wet damage, procedural issues, contamination, and heat damage are the principal factors affecting grain cargo integrity, ranked in descending order of importance. The findings demonstrate that grain deterioration is a multidimensional problem in which physical, environmental, biological, and operational factors interact throughout the transportation process. Beyond causing quantitative losses, these factors can significantly affect grain quality through changes in taste, odor, appearance, nutritional value, germination potential, and marketability, while also increasing the risk of microbial growth, mycotoxin formation, and pest infestation. The study therefore provides valuable insights into the mechanisms that contribute to post-harvest grain losses and offers a structured framework for prioritizing risk mitigation efforts.

From a practical perspective, the prioritization results provide a roadmap for maritime stakeholders to allocate resources more effectively. Since wet damage was identified as the most critical factor, preventive measures should primarily focus on moisture management through rigorous hatch-cover maintenance, leakage prevention, cargo hold waterproofing, effective bilge management, and optimized ventilation practices to minimize condensation and cargo sweat. Given the high ranking of procedural issues, shipping companies should strengthen crew training programs, standardize cargo handling procedures, implement preventive maintenance systems, and conduct regular cargo surveys and monitoring throughout the voyage.

Contamination risks can be reduced through strict hold-cleaning protocols, pest-control programs, fumigation procedures, and enhanced cargo hold hygiene standards. Although heat damage received the lowest ranking among the main criteria, continuous temperature monitoring, adequate insulation of heat-generating spaces, ventilation management, and early detection of self-heating should remain integral components of cargo preservation strategies because heat can amplify moisture migration, microbial activity, and overall cargo deterioration. The findings also highlight the importance of adopting advanced monitoring technologies capable of providing real-time information on cargo temperature, moisture conditions, and environmental parameters throughout the voyage. The integration of digital monitoring systems, predictive maintenance practices, and risk-based inspection programs could significantly improve the early detection of cargo deterioration and support more proactive decision-making. In addition, closer cooperation among shipping companies, port authorities, cargo owners, surveyors, insurers, and regulatory bodies is essential to establish best practices and improve the overall resilience of maritime grain transportation systems.

In conclusion, this study contributes to both the academic literature and maritime industry practice by providing a systematic framework for identifying, evaluating, and prioritizing grain cargo damage factors. The proposed TNWAA-based Neutrosophic AHP approach offers a practical decision-support tool for maritime stakeholders seeking to reduce grain losses, improve cargo quality preservation, enhance food security, and promote the sustainability of global grain transportation. Future research may extend the present framework by investigating the interdependencies among risk factors, incorporating larger expert panels

from different geographical regions, and evaluating the effectiveness of emerging monitoring and control technologies under real operational conditions.

Author contributions

CRediT: **Seyid Mahmud Esad Demirci:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing; **Hüseyin Elçiçek:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing; **Gökhan Özkaya:** Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Refik Canimoğlu:** Data curation, Validation, Writing – original draft, Writing – review & editing.

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No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.20679252.

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