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An Integrated AHP–Pugh Matrix Framework for Evaluating Green Supply Chain Development in the Food Industry

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ABSTRACT

This study proposes an integrated decision-making framework combinin Analytic Hierarchy Process (AHP) and the Pugh matrix to evaluate and su green supply chain development in the food industry. Despite the gro importance of sustainability, selecting appropriate strategies for green s chain implementation remains a complex multi-criteria problem involving qualitative and quantitative factors. To address this gap, the proposed app utilizes AHP to determine the relative importance of evaluation criteria an Pugh matrix to compare and rank alternative solutions systematically applicability of the framework is demonstrated through a case study i Vietnamese food industry, where multiple criteria related to environm economic, and operational performance are considered. The results identi most suitable strategy for enhancing green supply chain practices and prov structured basis for decision-making. Furthermore, comprehensive sensi analysis and an internal comparative analysis mathematically validat robustness of this selection, with Spearman's rank correlation testing reveali exceptionally high consistency (p= 0.9429) under varying weighting condi Additionally, an external comparative analysis utilizing AHP–WPM and WASPAS methods demonstrates a high convergence in strategic rankings, fu confirming the methodological validity and resilience of the final selection findings highlight the effectiveness of integrating AHP and the Pugh mat handling complex decision environments and offer practical implication managers and policymakers seeking to promote sustainable supply development. This study contributes to the existing literature by introduc hybrid multi-criteria decision-making framework and validating its usefuln a real-world context, thereby supporting more informed and transp decision-making in sustainable supply chain management.

1. Introduction

1.1 Background and Research Motivation

In the context of globalization and international economic integration, sustainable development has become an inevitable requirement across industries, particularly in the food sector, where

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supply chains are highly complex and strongly influenced by both market dynamics and environmental conditions [1, 2].

Rapid population growth, changing consumption patterns, and increasing environmental awareness have placed significant pressure on businesses to restructure their supply chains toward sustainability, commonly referred to as green supply chains [3].

Green supply chain management (GSCM) represents a modern approach that integrates economic objectives with environmental responsibility, aiming to achieve comprehensive sustainable development. A key characteristic of green supply chains is the minimization of negative environmental impacts through the use of clean energy, environmentally friendly materials, and cleaner production technologies [4]. In addition, GSCM emphasizes the optimization of logistics operations to reduce greenhouse gas emissions [5], as well as the adoption of eco-friendly packaging and circular economy practices such as reuse and recycling [6]. Firms implementing green supply chains often comply with international environmental standards such as ISO 14001, RoHS, and REACH, thereby enhancing transparency, corporate responsibility, and long-term competitiveness [7]. More broadly, GSCM involves the integration of environmental considerations throughout the entire supply chain, from product design and material selection to production, transportation, distribution, and end-of-life management [8]. This is particularly critical in the food industry, where strict requirements for safety, quality, and environmental compliance make green supply chain development both a challenge and a necessity for sustainable growth.

Despite its importance, the transition toward green supply chains remains challenging, especially when considering the environmental impacts of current food supply systems. Globally, the food system is responsible for approximately one-third of total greenhouse gas emissions, mainly originating from production, processing, and transportation activities [9]. In Vietnam, rapid urbanization and industrialization have led to a significant increase in packaging waste, food loss, and emissions from logistics activities, while many enterprises have yet to fully integrate sustainability into their operational strategies [10, 11]. Food waste has become a pressing issue, accounting for an estimated 50–60% of total solid waste in urban areas [12]. Furthermore, emissions from Vietnam's food system have continued to rise over the past decade, contributing more than one-quarter of total national emissions in 2020 [13]. In addition to environmental concerns, inefficiencies in the food supply chain also contribute to resource depletion, water pollution, and increased food safety risks [14]. These challenges highlight the urgent need for effective and sustainable supply chain solutions in the Vietnamese food industry.

In addition to environmental and operational challenges, decision-makers in the food industry often face difficulties in selecting appropriate green supply chain strategies due to the presence of multiple conflicting evaluation criteria and uncertainty in expert-based assessments. Therefore, there is a growing need for structured and transparent decision-support approaches capable of integrating both qualitative and quantitative considerations.

1.2 Research Gap and Study Objectives

In this context, identifying appropriate strategies for green supply chain development is essential. However, such decisions are inherently complex and involve multiple, often conflicting criteria, including cost efficiency, environmental performance, implementation feasibility, customer acceptance, and long-term economic benefits. Therefore, there is a need for robust decision-support tools that can systematically evaluate both qualitative and quantitative factors in a structured and transparent manner.

Multi-criteria decision-making methods have been widely applied to address such complex decision problems. Among them, the Analytic Hierarchy Process is one of the most commonly used techniques due to its ability to structure decision problems hierarchically and determine the relative importance of criteria through pairwise comparisons [15-17]. AHP is particularly advantageous in integrating both qualitative and quantitative information while ensuring consistency in the evaluation process [18]. Meanwhile, the Pugh matrix serves as an effective tool for comparing and selecting alternatives based on predefined criteria. Although previous studies have applied AHP or the Pugh matrix independently in sustainability-related decision-making contexts, limited research has explored their integration to enhance decision-making effectiveness in green supply chain development, particularly in the food industry. This gap provides a strong motivation for the present study. Although previous studies have applied AHP or the Pugh matrix independently in sustainability-related decision-making contexts, limited research has explored their integration to enhance decision-making effectiveness in green supply chain development, particularly in the food industry. In addition to this methodological gap, there remains a limited number of case-based studies focusing specifically on green supply chain strategy evaluation in the Vietnamese food industry. Existing studies often discuss sustainability challenges conceptually, but provide limited practical guidance for selecting and prioritizing green supply chain strategies under real-world operational conditions. Given the increasing environmental pressures, infrastructure limitations, and sustainability requirements within Vietnam's food sector, there is a growing need for a context-specific and structured decision-support framework.

From a practical perspective, this study aims to support managers and policymakers in identifying suitable green supply chain development strategies for the food industry. From a methodological perspective, the study proposes an integrated AHP–Pugh framework to improve the consistency, transparency, and effectiveness of strategic evaluation processes involving multiple decision criteria.

To address this research gap, this study proposes an integrated decision-making framework combining AHP and the Pugh matrix to evaluate and select optimal strategies for green supply chain development. The proposed approach leverages AHP to determine the weights of evaluation criteria and the Pugh matrix to systematically compare alternative solutions. The applicability of the framework is demonstrated through a case study in the Vietnamese food industry, providing practical insights into sustainable supply chain development.

1.3 Contributions of the Study

This study makes three main contributions. First, it develops a hybrid MCDM framework integrating AHP and the Pugh matrix for evaluating green supply chain development. Second, it applies the proposed framework to a real-world case study in Vietnam, demonstrating its practicality and effectiveness. Third, it provides managerial implications that support decision-makers in designing and implementing sustainable supply chain strategies. In addition, the study incorporates sensitivity analysis and comparative discussion to further examine the robustness and practical applicability of the proposed framework.

2. Literature Review

2.1 Green Supply Chain Management in the Food Industry

Green supply chain management (GSCM) has gained increasing attention as organizations seek to balance economic performance with environmental sustainability. For the food industry, the implementation of GSCM is especially vital because of the huge environmental footprint of this industry. Previous research has stressed the necessity of the integration of environmental aspects into all phases of the supply chain, starting from sourcing and production and ending with transportation and waste disposal [6, 8].

Some scholars have pointed out that the introduction of environmentally friendly practices like eco-packing, cleaner production technologies, and logistic practices can help decrease negative impacts on the environment and make operations more efficient at the same time [5, 7]. The implementation of environmental regulations and international standards as well as the principles of the circular economy are seen as a driving force in sustainable supply chains. Nevertheless, selecting effective strategies for the GSCM implementation proves to be quite a challenge, especially in developing countries.

2.2 Application of MCDM Methods in Green Supply Chain Decision-Making

Due to the multi-dimensional nature of sustainability issues, multi-criteria decision-making methods have been widely used to support decision-making in green supply chain management. These methods enable decision-makers to evaluate alternatives based on multiple criteria, including environmental, economic, and operational factors.

Among various MCDM approaches, the Analytic Hierarchy Process is one of the most widely applied methods for determining the relative importance of criteria through pairwise comparisons [19]. AHP is particularly useful in situations where both qualitative and quantitative factors must be considered simultaneously. In the context of green supply chain management, AHP has been applied to evaluate sustainability performance, prioritize environmental strategies, and support supplier selection [16, 20].

The Pugh matrix is a practical technique utilized to evaluate alternatives by comparing each of them to a certain standard (baseline). The technique is extensively applied in the areas of engineering design and strategic decision making because of the simplicity and effectiveness associated with evaluating several criteria at once.

2.3 Contemporary Methodological Advancements and Hybrid MCDM Models

Modern advances in decision science (2025-2026) show a clear paradigm shift in the utilization of more sophisticated Multi-Criteria Decision Analysis and hybrid models that can solve strategic problems. In relation to sustainable development and strategy making in general, researchers have made use of more structured decision-making approaches to analyze green economy options and tackle environmental issues [21, 22]. In particular, when looking at the context of biomass supply chains, modern literature highlights the need to take into account market externalities and the system of emission trading by analyzing network equilibrium solutions to understand the economic effects of green economy [23]. Moreover, in terms of structural choice and optimization within agro-food firms, the modern trend is to replace heuristics with more robust intuitionism techniques due to increased ambiguity of corporate settings [24].

As far as methodological approaches are concerned, the combination of AHP with supplementary methods for ranking decisions has become one of the prevailing tendencies around the world in different high-risk decision-making domains. Indeed, many authors show that models developed using AHP can be easily combined with other MCDM techniques such as TOPSIS, MABAC, CoCoSo, and Simple Additive Weighting (SAW), etc., in order to avoid subjectivity of experts and to manage operational risks. In particular, SWOT-AHP-TOPSIS hybrid systems can be effectively used in prioritizing macro-scale development initiatives [25], whereas Fuzzy AHP-MABAC [26] and Fuzzy AHP-EWAA-Fuzzy CoCoSo [27] models exhibit impressive accuracy in assessing the physical equipment and location selection of important facilities in fuzzy settings. In highly dynamic situations, e.g., in urban combat planning or risk assessment under uncertainties, it is extremely necessary to use hybrid multicriteria models such as Borda-AHP-SAW and extended multi-criteria analysis models [28, 29].

Furthermore, the current literature suggests the quick integration of modern MCDM models with the concept of Industry 5.0 technology, intelligent logistics, and prediction-based decisions. Contemporary MCDM models involve the application of Fermatean neutrosophic hypersoft sets in managing the circular supply chain process [30] and using unique versions of WASPAS models for personalizing recommender models in smart urban transportation systems [31]. All these current technological advances highlight the fact that although there is extensive research on hybrid models in various industries and defense applications, considerable effort still needs to be done to apply them to sustainable food logistics.

2.4 Research Gap and Contributions

Notwithstanding the valuable findings of previous studies and the increasing sophistication of hybrid decision models, there remain a number of limitations in extant literature. First, although sophisticated mathematical models (such as fuzzy and neutrosophic approaches) become increasingly advanced and widely used, these models frequently lack clarity of understanding and are highly computationally intensive, thus making their practical implementation challenging for supply chain managers. On the other hand, the simplistic models utilized by themselves tend to be insufficient in accounting for the complexity of sustainability-related issues, particularly in complicated contexts like food supply chains. There is a notable lack of systematic application of alternative and weighting methods in existing literature.

Second, extensive research conducted in previous studies has uncovered numerous green supply chain development-related criteria, ranging from economic factors and environmental efficiency to operational effectiveness and transparency. Nonetheless, previous literature tends to evaluate these criteria individually and within narrow contexts, implying that an integrated approach, taking into consideration numerous conflicting variables, should be adopted in the current study. Towards this, the present study attempts to highlight all the necessary criteria, ranging from economics, environment, and operations such as the cold chain ability, among others. This will be discussed further in Section 4.3.

As such, the objective of this study is to bridge these knowledge gaps through the development of a combined AHP–Pugh Matrix approach that will be used as a basis for measuring green supply chain performance in the food industry. In doing so, the use of the structure-based AHP for identifying the precise values of criterion weightings and the straightforward Pugh Matrix method for comparing alternative solutions will provide a reliable decision-making methodology that is both effective and user-friendly. To support this new approach with evidence and enhance its practicality for managerial application, this study will apply this novel technique to the Vietnamese food industry and validate it via statistical testing.

3. Methodology

3.1 Research Framework

The present research paper suggests a decision-making model that combines both AHP and Pugh matrix techniques to help choose effective strategies for building green supply chains. The process includes two key steps.

Firstly, AHP is used to find the weightings of different criteria based on comparisons between them. Secondly, the Pugh matrix technique is used to analyze alternatives and rate their performance according to the weightings identified during the previous step.

The overall structure of the proposed framework is illustrated in Figure 1.

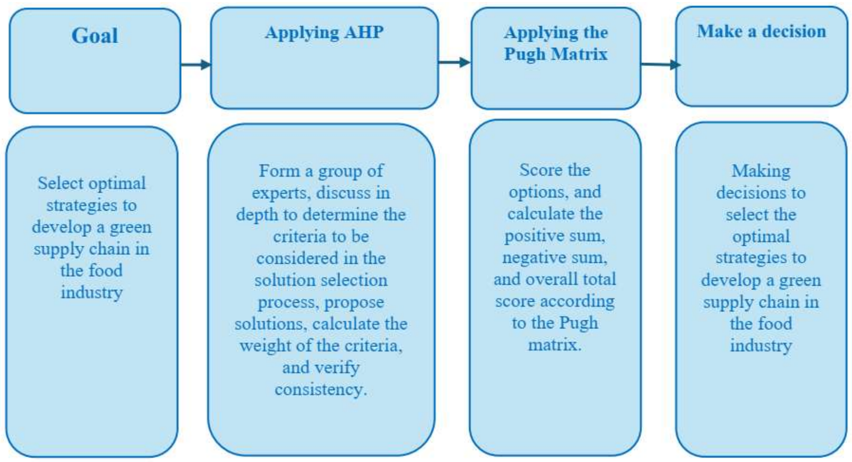

Fig. 1. Research framework

This framework provides a systematic and transparent approach to support decision-making in complex multi-criteria environments.

3.2 Analytic Hierarchy Process

The Analytic Hierarchy Process method is a multi-criteria decision-making method developed to assist managers and researchers in selecting the optimal solution in the presence of many complex factors, including both quantitative and qualitative factors [32]. AHP method can be seen as an efficient and systematic decision-making approach, which works well when many factors come into play [33]. This method has been based on the idea of system decomposition in which the issue being considered would be broken down into hierarchies consisting of the target, criteria, and alternatives [19]. By conducting the comparison between similar elements in each hierarchy, decision makers can assign the weight of each criterion with subjective judgment quantitatively [34]. This method is able to reflect conflicts between various factors and measure the extent of inconsistencies in the decision-making process via a pairwise comparison matrix [34]. Not only can it develop a transparent and understandable evaluation framework, but it also guarantees its logical reasonableness by means of consistency index [35].

High applicability and transparency in analysis make AHP an effective tool in policy decision-making as well as technical management. The AHP method has affirmed its important role in management research and practice, especially in areas such as supply chain management, sustainable development, technology selection, and public policy planning.

The implementation process of the AHP method consists of four main steps:

Step 1: Clearly define the objectives and build a hierarchical structure of the problem, including main criteria, sub-criteria, and alternative options/solutions.

Step 2: Compare the importance of each pair of criteria.

To develop the pairwise comparison matrices for the AHP model, expert opinions were gathered from fifteen specialists with extensive experience in the green food supply chain sector. For each required comparison in the AHP framework, the experts independently evaluated the relative importance of the criteria using the Saaty 1–9 scale. Given the multi-level structure of the AHP model and the large number of required comparisons, this process generated multiple pairwise comparison matrices for each decision context.

After collecting the expert evaluations, the individual judgments were synthesized and processed to construct the final pairwise comparison matrices. To combine the expert opinions into a unified decision matrix, a consensus-driven majority-voting method was employed during the group evaluation sessions. This approach is widely applied in group AHP decision-making when a panel interacts directly; it establishes the final entry for each pairwise comparison based on the standard integer value from the Saaty 1–9 scale that receives the agreement of the absolute majority of the 15 experts. This consensus-based procedure effectively integrates multiple expert insights into a unified evaluation framework while filtering out extreme individual outliers, ensuring that the aggregated matrices retain the structural integrity of the original Saaty scale as a reliable foundation for the subsequent AHP analysis.

Step 3: Calculate the relative weight of the criteria; check for consistency.

After finalizing the pairwise comparison matrices, the priority weights for each set of comparisons were determined through a stepwise calculation process applied to each matrix individually. Initially, the sum of each column was computed, and all elements were normalized by dividing each entry by its corresponding column total. The weight of each criterion (C1, C2, C3, …, Cn) was then obtained by calculating the average of the normalized values across its row, resulting in a priority vector of size n × 1.

Consistency analysis was done to measure the reliability of the evaluations. This was achieved by computing the largest eigenvalue and its corresponding normalized eigenvector, which forms the foundation upon which the relative significance of each criterion or sub-criterion is established. The normalized eigenvector's components are considered the final weights of each criterion. The process of normalization employed in this study is expressed in Equation (1).

$$Aw = W \times \lambda max \tag{1}$$

$$\lambda \text{ max}= \sum_{i=1}^{n} wi \times \sum_{j=1}^{n} aij. \tag{2}$$

$$CI= \frac{(\lambda \text{ max}-\text{n})}{\text{n}-1} \tag{3}$$

According to Saaty [34], a perfectly consistent matrix satisfies the condition λmax = n. Any deviation of λmax from n reflects a certain degree of inconsistency in the pairwise comparisons, as expressed in Equation (2). To measure this inconsistency, the Consistency Index (CI) is calculated, as shown in Equation (3). The Consistency Ratio (CR) is subsequently derived by comparing CI with the Random Index (RI), as presented in Equation (4).

$$CR= \frac{\text{CI}}{\text{RI}} \tag{4}$$

To facilitate accurate and efficient computation, Microsoft Excel was used as a supporting tool. A consistency ratio of CR ≤ 0.1 was adopted as the acceptable threshold. If this condition is not met, the pairwise comparisons must be re-evaluated and adjusted to improve consistency.

Step 4: Make a decision to select the optimal/priority option.

In this study, the AHP method is implemented to step 3. The final step of AHP is decision-making, which will be done through the Pugh matrix.

3.3 Pugh Matrix

The Pugh matrix, also known as standardized multiple-criteria comparison approach, is a popular decision-making technique used for choosing the best option from an array of alternative options using evaluation criteria. The central idea of the Pugh matrix approach is to draw up a comparative table between alternative options, using some reference option or base as the basis for comparison, after which each of the alternative options can be compared on the basis of being either better than, worse than, or comparable with the selected option [36]. With its simplicity, visual aspect, and highly transparent nature, the Pugh matrix not only enables organizations to make comparisons between options to select the better one [37], but also makes it possible to standardize the entire evaluation process through the forced comparison of alternative options using the reference standard [38]. The Pugh matrix has numerous merits, which have made it very popular in decision-making groups and design processes [39]. This approach is very handy in cases when there is need for choosing between different options that have almost the same weight; it does not require numerical data, but expert judgment instead.

According to Okuyucu & Tanık [40], the Pugh matrix implementation process includes the following basic technical steps

Step 1: Selection of Alternatives and Baseline

A set of alternative is identified. One alternative is selected as the baseline (reference) for comparison.

Step 2: Scoring of Alternatives

Each alternative is evaluated against the baseline for each criterion using a qualitative scoring system:

"+" indicates better performance than the baseline

"0" indicates equal performance

"−" indicates worse performance

Step 3: Weighted Evaluation

To enhance decision accuracy, the scores are combined with the criteria weights obtained from AHP. The overall score of each alternative is calculated by aggregating weighted evaluations across all criteria.

Step 4: Ranking of Alternatives

After completing the evaluation, the total score of each option will be calculated by adding all the corresponding positive and negative sum values. The option with the highest total score (Si) is usually considered optimal.

Total score (Si) is expressed in Equation (5):

$$S_i = \sum_{j=1}^{n} W_j . r_{ij} \tag{5}$$

In there: S_i: Total score of option i; W_j: Weight of criterion j; r_{ij}: Score of alternative i for criterion j compared to the baseline alternative.

4. Case Study: Green Supply Chain Development in the Vietnamese Food Industry

4.1 Overview of the Vietnamese Food Industry

The food industry in Vietnam plays a vital role in national economic development, contributing significantly to GDP, employment, and food security. In recent years, the sector has experienced rapid growth driven by urbanization, changing consumption patterns, and increasing integration into global markets. However, this growth has also led to significant environmental challenges, including increased greenhouse gas emissions, food waste, and resource depletion.

The structure of the food supply chain in Vietnam is characterized by fragmentation, with the participation of multiple stakeholders such as farmers, processors, distributors, and retailers. This complexity creates challenges in ensuring product quality, traceability, and environmental sustainability. In addition, many enterprises still face limitations in terms of technology, infrastructure, and financial resources, which hinder the adoption of green supply chain practices. This structural complexity makes the Vietnamese food supply chain a suitable context for applying multi-criteria decision-making approaches.

4.2 Case Study Design and Data Collection

This study adopts a case study approach to apply the proposed decision-making framework to the Vietnamese food industry. Data were collected through expert consultation to ensure the relevance and reliability of the evaluation process.

In order to ensure that the basis for conducting the AHP pairwise comparison and alternatives' evaluation would be strong and reliable, an expert group of 15 individuals was chosen using the method of purposive sampling. In order to be qualified as an expert, the following criteria were set up: having a higher educational degree and some research experience in sustainable operations or possessing no less than 10 years of experience in managing within the food supply chain field. The expert group consists of 5 professors/researchers, 6 food industry practitioners, and 4 supply chain managers from government or non-government regulating agencies.

These experts were actively involved in identifying the localized evaluation criteria, validating the proposed alternative strategies, and independently providing the pairwise comparison matrices required for the AHP analysis. Their diverse backgrounds and substantial collective experience ensure that both theoretical advancements and real-world operational constraints in Vietnam's food sector are effectively balanced within the decision-making model.

To improve the transparency and contextual depth of the expert evaluation process, representative qualitative opinions obtained from the participating experts are summarized in the manuscript. Several experts highlighted that cold chain deployment capability is particularly important in the Vietnamese food industry due to infrastructure limitations and the high risk of product deterioration during transportation and storage. Experts also noted that environmentally friendly practices and efficient resource utilization are increasingly important for improving sustainability performance and maintaining competitiveness in modern food supply chains. These qualitative insights supported the development of the pairwise comparison evaluations applied in the AHP framework.

4.3 Criteria and Alternative Strategies

As mentioned from the literature review and from the detailed expert consultation conducted above, an evaluation criterion is specifically formed to incorporate all the vital elements concerning the operation and sustainability of the food industry in Vietnam. As opposed to studying all the above elements separately, it becomes essential to analyze these elements within the context of the present case study. These are discussed below along with Table 1.

Table 1
Evaluation criteria for green supply chain development in the food industry

Criteria	Explanation	Source
Investment costs	These are the costs involved in making investments in a green supply chain initiative, comprising both fixed and variable costs, like the costs of acquiring and setting up technology infrastructure; costs of modifying production and logistics processes; costs of training staff and changing management processes; costs of consulting, certification, and meeting environmental requirements, etc.	Kenaria & Bahramimianroodb [41]
Transparency of origin	Traceability refers to the capacity to be able to follow the information all through the stages involved in the food chain starting from the harvesting of food stuffs right up to its consumption by the consumers. This ensures that foods can be traced, safe, and environmentally friendly.	Tran *et al.,* [42]
Cold chain deployment capabilities	The ability to implement cold chain technology ensures safe and high-quality goods with minimal environmental damage. It makes it easier for companies to optimize their performance in today's environment, which has consumers more conscious of their health and environmental issues. The implementation of cold chain technology is both an engineering issue and a competitive edge in today's business world.	Thi *et al.,* [43]
Environmentally friendly	Reflects the extent to which the solution contributes to reducing negative impacts on the environment compared to the current process. Includes typical indicators such as reducing greenhouse gas emissions, reducing solid and toxic waste, and increasing the use of recycled and renewable materials.	Jum *et al.,* [44]
Use resources efficiently	Waste Reduction: Assess the potential for reducing waste of resources during production, transportation, and distribution. Energy Efficiency: Prioritize the use of renewable energy sources and energy-saving solutions. Transportation Optimization: Select efficient transportation modes, minimize travel distances, and optimize vehicle utilization.	Gao *et al.,* [45]

As shown in Table 1, these criteria reflect the multi-dimensional nature of green supply chain development, encompassing economic, environmental, and operational considerations specific to the challenges faced by Vietnamese enterprises, such as infrastructure gaps in cold chains and rising demands for traceability. In addition, six alternative strategies for developing green supply chains in the food industry were identified and validated by the expert panel, as detailed in Table 2.

4.4 Application Procedure

The proposed framework is applied in two main stages. In the first stage, the AHP method is used to determine the relative importance of the evaluation criteria based on expert judgments. Pairwise comparison matrices are constructed and consistency is verified to ensure the reliability of the results.

In the second stage, the Pugh matrix is employed to evaluate and compare the alternative strategies. Each alternative is assessed against a baseline option across all criteria, and the results are aggregated using the criteria weights obtained from AHP.

This structured procedure enables a systematic and transparent evaluation process, providing a solid foundation for identifying the most suitable strategy for green supply chain development.

Table 2
Alternative strategies for green supply chain development

Alternative strategies	Explanation
Optimize shipping	Enhance logistics and distribution to cut down on fuel use and carbon dioxide emissions in the process of transportation. Ways include route optimization, fuel-efficient or electric cars, and cluster/chain deliveries. Effective warehouse management to shorten the distance involved in transport.
Effective waste management	Apply waste management and treatment methods in the supply chain according to the principle Reduce-Reuse-Recycle. For example: Separating waste at the source in the factory; Reusing by-products (fruit peels, coffee grounds...) as fertilizer, animal feed; Cooperating with third parties to collect and treat organic waste.
Use environmentally friendly packaging	Replace hard-to-decompose plastic packaging with recyclable, reusable, or biodegradable materials. Application examples: Packaging made from bagasse, kraft paper, or bioplastic; Packaging that can be reused many times; Minimalist design, reducing the amount of packaging material.
Propaganda-inspiration, awareness-raising training	Organize training programs for employees, suppliers, and stakeholders on green supply chain practices and their role in the system. Form: Periodic internal training on clean production and energy saving; Organize workshops and internal communication programs; Train suppliers on environmental standards.
Participate in the Carbon Credit Market	Participate in domestic carbon markets or regional markets (ASEAN, Korea, Japan) to sell or buy credits for activities in the food supply chain. Integrate Vietnam's food supply chain into the international market. Increase access to climate finance and increase green business and finance opportunities.
Selecting sustainable supply	Instead of just looking at the cost-efficiency of the suppliers, the problem of sustainable sourcing involves coming up with a set of evaluation criteria that can be used to assess the environmental, social, and governance aspect of the suppliers. The idea here is to assess, classify, and cooperate with the suppliers that are sustainable in nature for a prolonged period while excluding those that are unsuitable. Implementation of this strategy will not only make companies reduce their legal problems and improve their image, but will also result in environmental sustainability and social responsibility.

These alternatives serve as the decision options to be evaluated in the subsequent analysis using the integrated AHP–Pugh framework. The hierarchical model for decision-making is shown in Figure 2.

5. Results and Discussion

5.1 Results of AHP Analysis

The AHP method was employed to derive the relative importance of the evaluation criteria based on the synthesized expert judgments. To ensure conciseness, intermediate computational steps are omitted, focusing instead on the final aggregated weights that serve as the foundation for the subsequent strategic evaluation.

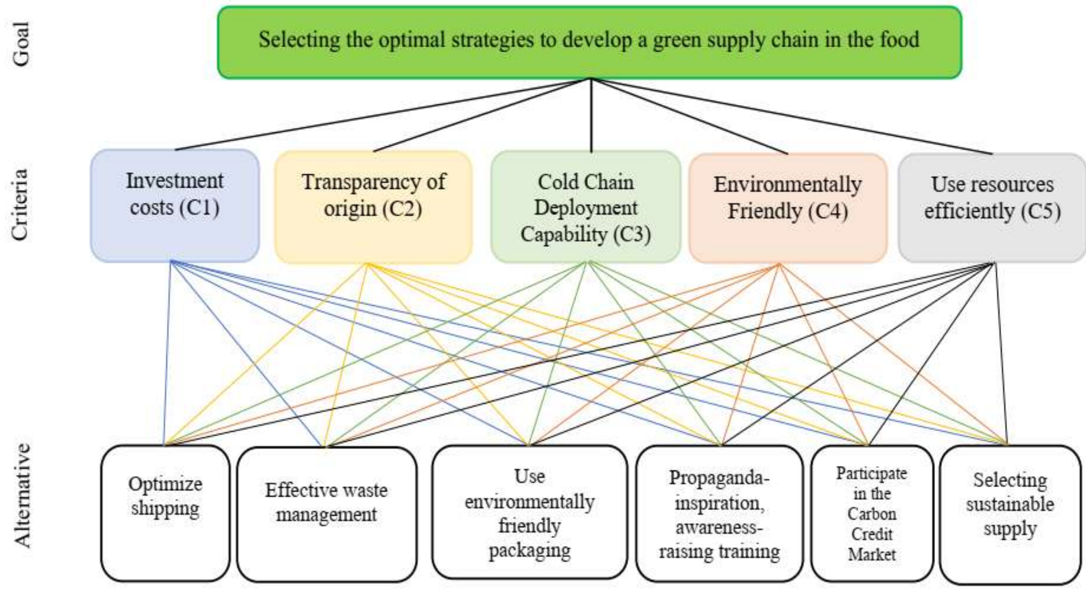

Fig. 2. Hierarchical model diagram for decision-making to select the optimal strategies for developing green supply chains in the Vietnamese food industry

To ensure the absolute transparency of the research and the full reproducibility of these results, the underlying distribution of individual expert judgments and the detailed step-by-step consolidation process for each pairwise cell are provided in Appendix A. This supplementary section demonstrates how the consensus integer values presented in the matrix (Table 3) were systematically derived from the 15 independent expert evaluations using the majority-voting framework.

Table 3
Priority vectors of criteria

	C1	C2	C3	C4	C5	Weight W_j
C1	1	1/3	1/7	1/5	1/2	0.0526
C2	3	1	1/3	1/2	2	0.1528
C3	7	3	1	2	5	0.4436
C4	5	2	1/2	1	3	0.2618
C5	2	1/2	1/5	1/3	1	0.0892

$n = 5$; $\lambda max = 5.0378$; $CI = \frac{\lambda max - n}{n-1} = \frac{5.0378-5}{5-1} = 0.009458$; $CR = \frac{CI}{RI} = \frac{0.009458}{1.12} = 0.00844$

Notes: (C1) Investment cost; (C2) Transparency of origin; (C3) Cold Chain Deployment Capability; (C4) Environmentally friendly; (C5) Use resources efficiently.

The findings show that sustainable decision criteria such as the Cold Chain Deployment Capability (C3) and Environmentally Friendly (C4) have the highest priority levels. This shows the change in the orientation of decisions from the cost-centric orientation towards the sustainability centric orientation. Although the investment cost criterion has been considered, its relatively lower weight shows that there is now a readiness among the decision makers to sacrifice cost for environmental reasons.

These results concur with the increasing trend among researchers on the increased awareness of environmental concerns in supply chains. Most importantly, these results show the capability of AHP in integrating expert knowledge into a consistent quantitative structure.

5.2 Results of Pugh Matrix Evaluation

Building upon the criteria weights derived from AHP, the Pugh matrix was applied to evaluate and rank the alternative strategies. Each alternative was assessed relative to a baseline across all criteria, and the weighted aggregation of scores was used to determine the overall performance.

The evaluation results are summarized in Table 4.

Table 4
Pugh matrix results

	W_j	S1	S2	S3	S4	S5	S6
Investment cost	0.0526	0	0	0	1	-1	1
Transparency of origin	0.1528	1	0	1	0	-1	1
Cold Chain Deployment Capability	0.4436	1	-1	0	0	-1	1
Environmentally friendly	0.2618	1	1	1	0	1	1
Use resources efficiently	0.0892	1	1	1	0	0	1
Total (+)		0.94739	0.35096	0.50377	0.05261	0.26180	1
Total (-)		0	-0.44362	0	0	-0.64904	0
Total score (S_i)		0.94739	-0.09265	0.50377	0.05261	-0.38723	1

Notes: (S1) Optimize shipping; (S2) Effective waste management; (S3) Use environmentally friendly packaging; (S4) Propaganda-inspiration, awareness-raising training; (S5) Participate in the Carbon Credit Market; (S6) Selecting sustainable supply.

The findings reveal that achieves the best overall performance and is hence considered the best alternative for promoting the green supply chain in the food industry. The reason why S6 outperforms other strategies is its capability to meet all high-priority criteria simultaneously instead of performing excellently on one criterion alone. This alternative performs effectively on more than one criterion, especially minimizing environmental impact and feasibility.

On the other hand, other strategies perform exceptionally well on some criteria but struggle to balance the same on other criteria. This brings about the weaknesses of making decisions based on one criterion only.

5.3 Sensitivity Analysis, Comparative Analysis, and Statistical Correlation Verification

To evaluate the robustness of the proposed decision-making framework, a sensitivity analysis was conducted by examining the impact of variations in criteria weights on the ranking of alternatives. Given their dominant influence in the AHP results, cold chain deployment capability (C3) and environmental friendliness (C4) were selected as key criteria for analysis.

Scenario 1: Reduction in the weight of C3

In this scenario, the weight of C3 was reduced from 0.4436 to 0.35, and the remaining weight was proportionally redistributed among the other criteria. This setting reflects situations where firms face financial or technological constraints that limit investments in cold chain infrastructure.

The results show that the ranking of the top alternatives remains unchanged. In particular, S6 retains the highest score, followed by S1 and S3. Although minor fluctuations are observed among lower-ranked alternatives, these changes do not significantly influence the overall decision outcome. This indicates that the dominance of S6 is not solely dependent on the weight of C3.

Scenario 2: Increase in the weight of C4

In this scenario, the weight of environmental friendliness (C4) was increased from 0.2618 to 0.35, reflecting stronger environmental priorities. The weights of the remaining criteria were adjusted proportionally to maintain normalization.

The results indicate that environmentally oriented strategies, particularly S3 (eco-friendly packaging), exhibit improved performance. However, S6 remains the top-ranked alternative, suggesting that it achieves a balanced performance across both environmental and operational dimensions.

Scenario 3: Equal weighting of criteria (Internal Comparative Analysis)

As such, to mitigate any possibility of bias from the expert's assessment and establish a neutral point of reference for comparing the alternatives, the weight of each criterion was kept constant at 0.20. In effect, the present example could be viewed as an example of a conventional Pugh matrix analysis. On this basis, S6 maintains its leading position, followed by S1 and S3.

To mathematically verify the statistical correlation and assess the exact structural alignment between the Proposed Weighted AHP-Pugh framework and the Standard Unweighted Pugh Matrix (Scenario 3), Spearman's rank correlation coefficient (ρ) was utilized. This standard tool evaluates the consistency between two sets of rankings using the following mathematical formulation (6):

$$\rho = \left[1 - \frac{n\sum_{1}^{n} d_i^2}{n(n^2-1)}\right] \tag{6}$$

Where d_i represents the difference between the ranks assigned to alternative i under the two different environments, and n signifies the total number of strategic alternatives evaluated (n = 6). Table 5 presents the comprehensive mathematical comparison and the resulting correlation metrics.

Table 5

Statistical correlation and rank verification between the weighted and unweighted frameworks

Strategic Alternatives	Proposed Weighted AHP-Pugh Rank (Base)	Standard Unweighted Pugh Rank (Scenario 3)	Rank Difference (d_i)	Squared Difference (d_i^2)
Strategy 1 (S1)	2	2	0	0
Strategy 2 (S2)	4	5	-1	1
Strategy 3 (S3)	3	3	0	0
Strategy 4 (S4)	5	4	1	1
Strategy 5 (S5)	6	6	0	0
Strategy 6 (S6)	1	1	0	0
Total ($\sum_{1}^{n} d_i^2$)	-	-	-	2
Spearman's Coefficient (ρ)	Base Framework	0.9429	-	-

As demonstrated in Table 5, the calculated Spearman correlation coefficient stands at 0.9429. According to international statistical conventions, a coefficient value between 0.90 and 1.00 indicates an almost perfect, extremely strong monotonic correlation. This mathematical validation proves that the core decision outcomes are highly reliable and resilient.

External Methodological Comparative Analysis

Beyond internal validation, an external comparative analysis was conducted to contrast the proposed AHP–Pugh Matrix framework with two prominent multi-criteria decision-making (MCDM) methods: the Weighted Product Method (AHP–WPM) and the Weighted Aggregated Sum Product

Assessment (AHP–WASPAS). This comparison utilized identical criteria weights and expert inputs to ensure a rigorous baseline. The comparative ranking outcomes illustrated in Figure 3.

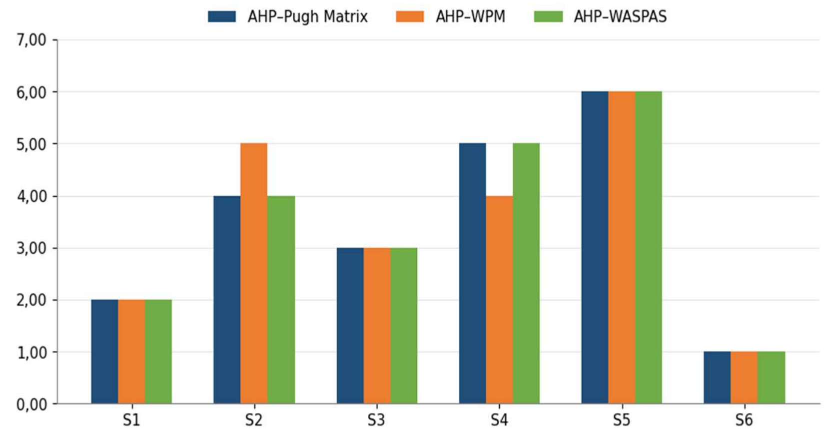

Fig. 3. Methodological comparison of alternative strategies under different MCDM frameworks

The results reveal a high degree of consensus among the three methodological approaches. Notably, S6 (Selecting sustainable supply) and S1 (Optimize shipping) consistently secure the first and second positions, respectively, across all models. This strong convergence confirms the mathematical reliability of the top-tier selections, demonstrating that the identification of the optimal green supply chain strategy is robust and independent of specific technical formulations.

Concurrently, minor ranking fluctuations were observed among the intermediate alternatives, specifically between S2 (Effective waste management) and S4 (Propaganda-inspiration, awareness-raising training). While the proposed framework and AHP–WASPAS rank S2 fourth and S4 fifth, this order is inverted in the AHP–WPM approach. These marginal discrepancies are logically attributed to the distinct mathematical structures of the techniques. While the Pugh matrix evaluates performance relative to a baseline utility and WASPAS integrates both additive and multiplicative dimensions, WPM relies strictly on multiplicative aggregation. Consequently, WPM heavily penalizes alternatives with lower scores in high-weight criteria. The fact that these varying structural logics still yield an identical top-ranking configuration strongly reinforces the validity and applicability of the proposed integrated framework.

Discussion of Sensitivity and Comparative Results

The sensitivity and comparative analysis demonstrates that the proposed AHP–Pugh framework produces stable and reliable outcomes under varying weighting conditions. The consistent ranking of S6 as the top-performing alternative across all scenarios indicates that the decision result is not sensitive to moderate changes in criteria importance.

This robustness is particularly important in real-world decision-making contexts, where uncertainty and variability in expert judgments are inevitable. The findings suggest that the integrated approach effectively mitigates the influence of such uncertainties by balancing multiple criteria within a structured evaluation framework.

Moreover, the observed stability reinforces the practical applicability of the model. Decision-makers can apply the proposed framework with confidence, knowing that the final outcome is resilient to reasonable variations in input assumptions.

The stability of the obtained rankings under different sensitivity scenarios and alternative methodological environments further confirms the reliability of the proposed evaluation framework. This high level of consistency aligns with the methodological findings in previous multi-criteria decision-making studies, such as Nedeljkovic *et al.,* [46], which emphasize that benchmarking proposed models against alternative techniques is essential to validate practical applicability in supporting complex strategic problems. The highly consistent ranking behavior observed across our multi-method analysis explicitly indicates that the proposed framework provides a stable, resilient, and reliable decision support tool for green supply chain strategy evaluation in the food industry.

Figure 4 illustrates the variation in the total scores of the six alternative strategies as the weight of criterion C3 changes within a specified range. The results show that S6 consistently achieves the highest score across all tested values, confirming the robustness of the decision-making framework. While minor variations are observed among intermediate alternatives, the overall ranking structure remains stable.

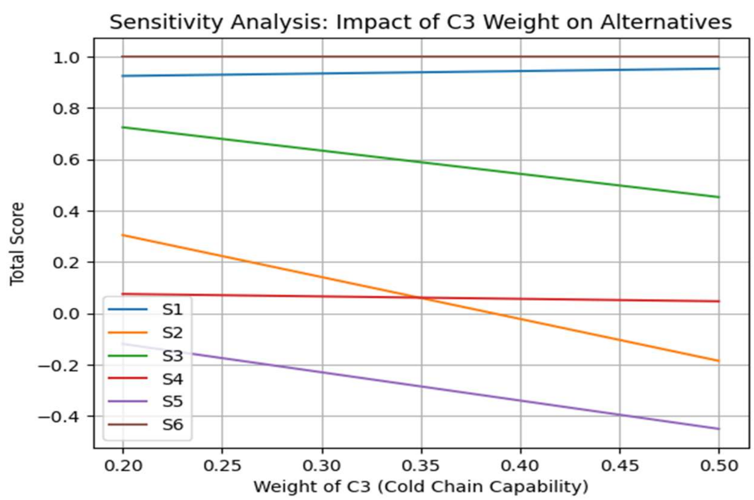

Fig. 4. Sensitivity analysis of alternative strategies under varying weights of cold chain deployment capability (C3)

5.4 In-depth Discussion

The findings of this study provide several important insights that contribute to both theory and practice.

The most vital insight from this verification is the absolute dominance of Strategy 6, which consistently secured the top rank across the baseline model, all weight fluctuations, the external cross-methodological comparisons (AHP–WPM and AHP–WASPAS) and even the unweighted neutral benchmark. This exceptional stability, mathematically reinforced by an almost perfect Spearman correlation coefficient of 0.9429, and the high convergence observed among alternative MCDM techniques, proves that S6 is a highly resilient and low-risk strategic choice that achieves a harmonized equilibrium across multiple dimensions simultaneously.

Firstly, the emphasis on environmental and operational criteria indicates the multi-dimensionality of sustainable decision-making. This implies that firms within the food industry have started to consider cost-effectiveness secondary, while their focus is becoming more comprehensive, taking into consideration their environmental obligations along with operational sustainability.

Secondly, the use of AHP along with the Pugh matrix method signifies an important methodological contribution to this research. On the one hand, AHP can provide an adequate procedure to evaluate criteria weights, while on the other hand, the Pugh matrix method can help compare alternatives. The application of these two methodologies ensures that the decision-making process becomes more consistent, objective, and comprehensible. This solution overcomes the limitations found in previous research, in which methodology is used in an isolated fashion. Furthermore, the incorporation of the external comparative analysis underscores that the proposed integrated framework is not technically isolated; rather, its structural logic produces equivalent outcomes to complex multiplicative algorithms like WPM and hybrid approaches like WASPAS, while maintaining the visual and intuitive advantages of the Pugh matrix. In addition, the application of the statistical correlation analysis shows through mathematical proof that the visual and intuitive framework of the Pugh matrix method is as effective as any complicated mathematical iteration.

Third, the empirical application in the Vietnamese food industry highlights the practical relevance of the proposed framework. The results demonstrate that the selected optimal strategy is not only environmentally beneficial but also operationally feasible within the constraints of a developing economy. This reinforces the adaptability of the proposed model to real-world contexts characterized by resource limitations and institutional challenges.

Moreover, the findings underline the importance of balance in decision-making. Strategies that perform moderately well across multiple criteria tend to be more sustainable in the long term than those that excel in a single dimension but perform poorly in others. This insight is particularly relevant for policymakers and managers seeking to design robust and resilient supply chain strategies.

6. Conclusion, Limitations and Future Research Directions

6.1 Conclusion

This study proposes an integrated decision-making framework that combines the Analytic Hierarchy Process and the Pugh matrix to evaluate and select optimal strategies for green supply chain development in the food industry. By applying the framework to a case study in Vietnam, the research demonstrates its effectiveness in addressing complex, multi-criteria decision-making problems characterized by both qualitative and quantitative factors.

The results indicate that sustainability-oriented criteria, particularly Cold Chain Deployment Capability (C3) and Environmentally friendly (C4), play a dominant role in shaping decision outcomes. Among the evaluated alternatives, the optimal strategy consistently demonstrates superior performance across multiple dimensions, highlighting the importance of balanced solutions that integrate environmental, operational, and economic considerations. The reliability of these empirical findings is robustly confirmed through comprehensive sensitivity analysis and internal comparative testing. Specifically, statistical validation using Spearman's rank correlation coefficient demonstrates an almost perfect monotonic consistency (ρ = 0.9429) across varying weighting conditions, mathematically proving that the final strategic ranking remains highly resilient to input uncertainties. Moreover, the robustness of the framework is successfully verified through an external comparative analysis against AHP–WPM and AHP–WASPAS models, which yields highly consistent ranking outputs for the top-tier strategies.

From a theoretical perspective, this study contributes to the literature by advancing a structured and integrated multi-criteria decision-making framework. Unlike prior studies that primarily rely on a single method, the proposed AHP–Pugh approach leverages the strengths of both techniques—AHP for determining criteria weights and the Pugh matrix for systematic alternative evaluation. This integration enhances the consistency, transparency, and practical relevance of the decision-making process, thereby addressing an important gap in sustainable supply chain research.

From a managerial standpoint, the findings provide actionable insights for practitioners in the food industry. The proposed framework serves as a practical decision-support tool that enables managers to evaluate alternative strategies in a structured and transparent manner. By incorporating sustainability criteria into the decision-making process, organizations can better align their operations with environmental objectives while maintaining operational feasibility and competitiveness. In particular, the results highlight the importance of adopting balanced strategies that perform well across multiple criteria rather than focusing on a single dimension.In addition, the study offers important implications for policymakers. The promotion of green supply chain practices requires not only firm-level initiatives but also supportive institutional frameworks. Policies that encourage sustainable investments, improve infrastructure (such as cold chain systems), and enhance environmental awareness can significantly facilitate the transition toward greener supply chains in the food sector.

The comparative discussion with previous MCDM studies also reinforced the reliability and applicability of the proposed approach for supporting strategic decision-making in green food supply chain management. Ultimately, the proposed framework offers a practical pathway toward more sustainable and resilient supply chain systems.

6.2 Limitations and Future Research Directions

Despite the usefulness of the presented hybrid approach of combining AHP with the Pugh matrix, several drawbacks should be considered in future research endeavors. First, the approach highly depends on subjective assessments of 15 experts, which may distort results due to biased opinion or exhaustion from lengthy evaluations. However, majority vote and consistency checks can mitigate this problem. Second, the approach was used only for assessing the Vietnamese food industry, which means that the obtained weights have been calculated in relation to the developing economy and might not be used in developed countries. Third, the approach is static and considers only one baseline scenario, while the reality is usually dynamic.

Possible areas for further improvement include testing the approach for other industries or countries, implementing fuzzy approaches like Fuzzy AHP, and incorporating performance indicators in addition to expert assessments.

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Conflicts of Interest
The authors declares no conflicts of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process
During the preparation of this work, the authors used AI-assisted tools ChatGPT-4 to enhance readability and improve language structure]. These tools were not used to generate scientific content, analyses, or conclusions. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final manuscript. No generative AI tools were used to create or modify the study figures or artwork.

Appendix A

Initial Elements and Expert Judgment Consolidation

In order to provide transparency in the decision-making procedure and make the calculations reproducible, the following appendix describes the organizational framework of the first level elements needed for AHP calculation.

During the consensus-driven workshop, the 15 experts evaluated the relative importance of the 5 main criteria using the standard Saaty 1–9 scale. While individual perspectives varied slightly during initial independent trials, the final matrix was constructed by adopting the absolute majority vote for each pairwise cell. Table A1 illustrates the detailed breakdown of individual votes and the derived group choice for each evaluation pair.

Table A1
Distribution of expert judgments and the finalized majority-voting results for each pairwise comparison

Pairwise Comparison (Criterion vs. Criterion)	Predominant Expert Judgment Pattern / Distribution (N = 15)	Adopted Integer (Majority Vote)	Resulting Matrix Entry (a_{ij})
C2 vs. C1	11 experts voted 3 (Moderately more important); 4 experts voted 2.	3	$a_{21} = 3$
C3 vs. C1	13 experts voted 7 (Very strongly more important); 2 experts voted 5.	7	$a_{31} = 7$
C4 vs. C1	10 experts voted 5 (Strongly more important); 5 experts voted 6.	5	$a_{41} = 5$
C5 vs. C1	12 experts voted 2 (Weakly more important); 3 experts voted 1.	2	$a_{51} = 2$
C3 vs. C2	9 experts voted 3 (Moderately more important); 6 experts voted 4.	3	$a_{32} = 3$
C4 vs. C2	11 experts voted 2 (Weakly more important); 4 experts voted 3.	2	$a_{42} = 2$
C2 vs. C5	12 experts voted 2 (Weakly more important); 3 experts voted 1.	2	$a_{25} = 2$
C3 vs. C4	14 experts voted 2 (Weakly more important); 1 expert voted 3.	2	$a_{34} = 2$
C3 vs. C5	10 experts voted 5 (Strongly more important); 5 experts voted 4.	5	$a_{35} = 5$
C4 vs. C5	13 experts voted 3 (Moderately more important); 2 experts voted 2.	3	$a_{43} = 3$

Note: Reciprocal values ($a_{ji} = 1/a_{ij}$) were automatically assigned to the opposite comparisons in the matrix layout, ensuring a mathematically coherent hierarchy prior to calculating the final consistency ratio (CR = 0.0084 <0.1).

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