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A Fuzzy DEMATEL-ANP-TOPSIS Model for Cross-Border E-Commerce Driven Agricultural Value Chain Upgrading in Henan

Huawei Li[1,*]

1 Phd, Lecturer, School of Finance and Economics Zhengzhou University of Economics and Business, Zhengzhou, China, 451191.

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ABSTRACT

Globalisation and digital transformation are fundamentally changing agricultural supply chains, with the digital economy emerging as a catalyst for more connected, intelligent, and sustainable agricultural systems. Within this evolving landscape, cross-border e-commerce (CBEC) has become a strategic mechanism for enhancing agricultural value chains by improving efficiency, increasing value creation, and strengthening international market integration. As one of China's principal agricultural regions and a major grain-producing province, Henan is experiencing an important transition from conventional agricultural practices to a digitally enabled agricultural economy. Achieving this transformation requires strategic decision-making under multiple, often conflicting, criteria while operating within constraints associated with limited resources and a complex policy environment. Consequently, selecting the most suitable agricultural value chain upgrading strategy represents a challenging multi-criteria decision-making (MCDM) problem. To address this challenge, the present study develops an integrated hybrid decision-support framework grounded in decision science. The proposed framework combines fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL), fuzzy Analytic Network Process (Fuzzy ANP), and fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). By integrating these complementary approaches, the framework effectively captures uncertainty in expert judgements while simultaneously accounting for the interdependent relationships among evaluation criteria. An evaluation index system was established through a comprehensive review of the literature together with the Delphi method, resulting in five principal dimensions: digital infrastructure, cross-border logistics and cold chain, quality control and traceability, policy support and financial empowerment, and human capital and innovation. These dimensions were operationalised using fifteen critical evaluation criteria. The empirical findings identify cross-border logistics and cold chain efficiency, together with digital infrastructure capability, as the principal causal drivers facilitating agricultural value chain upgrading. Among the four strategic alternatives evaluated, optimisation of the cross-border cold chain logistics network and airport transport channels achieved the highest closeness coefficient (0.714), indicating that it represents the most effective implementation strategy under current conditions. The stability and reliability of the proposed framework were further confirmed through sensitivity analysis and comparative evaluation using fuzzy MARCOS and fuzzy COPRAS methods, both of which produced consistent ranking outcomes. Overall, this research extends the application of MCDM techniques within digitally driven agricultural

* *Corresponding author.*
E-mail address: 15937193073@163.com
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supply chains while offering practical guidance for policymakers seeking to formulate targeted digital agriculture strategies and promote sustainable rural revitalisation in Henan Province as well as other developing agricultural economies.

1. Introduction

The continued acceleration of global economic integration has intensified structural transformations within agricultural supply chains, exposing the inherent limitations of conventional value chain models. Across many developing economies, agricultural value chains have historically been hindered by persistent structural inefficiencies, including asymmetric information, prolonged distribution channels, substantial logistics losses, and limited opportunities for value addition. Consequently, farmers and primary agricultural processing enterprises have remained concentrated at the lower end of the "smile curve," preventing them from capturing a fair share of the value generated throughout the supply chain [1]. Meanwhile, the rapid expansion of the digital economy has fundamentally reshaped agricultural production and distribution through the widespread application of advanced technologies, including the Internet of Things (IoT), big data analytics, blockchain, and artificial intelligence. The increasing integration of these technologies throughout agricultural activities signifies the global transition towards Agriculture 4.0 and the emerging Agriculture 5.0 paradigm [2;18;19]. Within this evolving digital landscape, CBEC has emerged as an innovative business model that effectively connects digital technologies with international commerce. By eliminating many geographical and physical constraints associated with conventional international trade, CBEC reduces transaction search, matching, and execution costs while simultaneously creating direct export opportunities for specialised, geographically indicated, and high-value agricultural products [3; 20; 21].

Situated in central inland China, Henan Province serves not only as a strategic pillar of the country's food security system but also as an important production base for distinctive agricultural commodities. Recognising the transformative potential of digitalisation, the provincial government has identified the digital economy as a primary driver of high-quality regional development and established strategic objectives aimed at substantially increasing both the contribution of manufacturing to provincial GDP and the scale and penetration of core digital economy industries by 2025 [4]. Considerable progress has also been achieved in the development of CBEC through the Zhengzhou Air Port Economic Comprehensive Experimental Zone, the continuous expansion of the Air Silk Road initiative, and the adoption of innovative logistics solutions, including TIR (International Road Transport). Collectively, these initiatives have contributed to remarkable growth in both CBEC transaction volumes and settlement values across the province [5]. Available evidence further demonstrates that the digital economy has become an important catalyst for regional industrial integration, particularly in accelerating agricultural modernization [6]. Despite these achievements, agricultural products—especially fresh and processed commodities—continue to face challenges that differ considerably from those encountered by standardised industrial and 3C electronic products. Persistent shortcomings include inadequate cold chain infrastructure coverage, insufficient alignment with international sanitary and phytosanitary (SPS) requirements, limited brand premium capability, and a shortage of professionals possessing integrated expertise in agriculture and digital trade. These obstacles illustrate that digital transformation does not automatically generate immediate developmental benefits for agriculture. Without comprehensive strategic planning supported by scientifically grounded decision-making mechanisms, regional agricultural development remains vulnerable to the widening effects of the digital divide.

Agricultural value chain upgrading represents a complex socio-economic process characterised by dynamic interactions among technological, institutional, logistical, financial, and human resource factors. Because available resources are inherently limited, policymakers, industry organisations, and enterprise managers must evaluate numerous strategic alternatives while balancing multiple and often competing decision criteria. Such circumstances clearly represent a typical MCDM problem. Furthermore, the complexity of agricultural ecosystems and the subjective nature of expert evaluations introduce considerable uncertainty into the decision-making process. Consequently, integrating fuzzy set theory with MCDM techniques has become an increasingly accepted approach within operations research, management science, and decision engineering for addressing ambiguity and improving the reliability of complex strategic decision [22],[23].

Although previous research has generated substantial knowledge regarding the application of the digital economy in agriculture and the operational development of CBEC, comparatively few studies have integrated these research domains within a unified decision-support framework for agricultural value chain upgrading. Moreover, limited attention has been devoted to constructing hybrid decision-support models specifically tailored to regional contexts such as Henan Province, where both theoretical understanding and practical policy guidance are simultaneously required. To bridge this research gap, the present study develops a hybrid decision analysis framework that integrates Fuzzy DEMATEL, Fuzzy ANP, and Fuzzy TOPSIS [7], enabling the quantitative optimisation of agricultural value chain upgrading strategies [8]. The study makes three principal contributions. First, it establishes a comprehensive multidimensional evaluation index system that reflects the combined influence of the digital economy and CBEC on agricultural value chain upgrading. Second, Fuzzy DEMATEL is employed to identify the causal relationships and interdependencies among the critical driving factors within the system, while Fuzzy ANP is utilised to determine global priority weights by overcoming the conventional assumption of criterion independence. Finally, Fuzzy TOPSIS is applied to prioritise the alternative strategies, and the robustness of the resulting rankings is further verified through comprehensive sensitivity analysis together with comparative evaluations using Fuzzy MARCOS and Fuzzy COPRAS [9]. The findings provide both a solid theoretical foundation and a practical policy framework for supporting the sustainable and high-quality upgrading of agricultural supply chains in Henan Province and other regions facing similar developmental challenges.

2. LITERATURE REVIEW

2.1 Theoretical Logic of Digital Economy and Agricultural Value Chain Upgrade

The digital economy has fundamentally transformed the operating principles of the global economic landscape, and its integration with agriculture extends well beyond the concepts of precision and smart farming. Rather than influencing production activities alone, digitalisation is reshaping the processes through which value is created, transferred, and distributed across the entire agricultural ecosystem [10],[24]. Existing studies have extensively examined the contribution of digital platform capabilities to agricultural industrial development, consistently demonstrating that digital technologies improve supply chain efficiency, enhance resilience against operational disruptions, and facilitate the commercialisation and diffusion of innovation throughout the agricultural sector [2],[25]. Nevertheless, the relationship between the digital economy and agricultural value enhancement is considerably more complex than a straightforward positive association. Contemporary research argues that digitalisation does not generate uniformly increasing benefits for green agricultural development or value chain upgrading. Instead, empirical evidence derived from large-scale panel datasets reveals pronounced nonlinear threshold effects together with U-shaped or inverted U-shaped spatial spillover patterns during the process of agricultural transformation [11].

During the initial phase of digital transformation, agricultural systems often experience considerable financial and operational pressures arising from substantial sunk investments, including broadband infrastructure deployment, sensor installation, and cloud platform development. These challenges are further intensified by the relatively limited digital competencies of farming communities, which may temporarily reduce profitability as implementation costs increase. However, once digital technologies achieve sufficient penetration and become fully integrated across the agricultural value chain, the cumulative advantages generated by network externalities and expanding data-driven economies of scale begin to emerge. At this stage, digital transformation becomes a powerful driver of higher value creation, productivity enhancement, and intensive agricultural development. Furthermore, empirical investigations suggest that government intervention does not exert a consistently positive influence throughout this transition. Instead, its regulatory role generally follows an inverted U-shaped pattern, indicating that excessive or insufficient intervention may both constrain development outcomes [6]. Consequently, within the Chinese context—and particularly in strategically important grain-producing provinces such as Henan—the successful application of the digital economy depends on achieving an appropriate balance between preserving national food security and maximising long-term economic value.

2.2 The Strategic Role of Cross-Border E-Commerce in Shaping the Agricultural Supply Chain

As a fundamental component of digital international trade, CBEC has substantially transformed the movement of agricultural products from production regions to overseas consumer markets. By streamlining traditional trading structures, CBEC platforms minimise information acquisition costs, reduce profit losses associated with multiple intermediaries, and lower the transaction and contractual costs that have historically characterised cross-border agricultural trade. These improvements enable producers to establish more direct access to international markets while responding more efficiently to overseas consumer demand. Consequently, agricultural producers are increasingly encouraged to improve product quality and adopt standardised production practices that satisfy global market requirements [12],[26],[27]. Furthermore, the expansion of digital commerce has reshaped agricultural production patterns by encouraging the allocation of resources towards products with greater market profitability, thereby motivating farmers to shift from conventional production towards higher value-added agricultural commodities [12]. More recently, the rapid development of live-streaming commerce and multi-channel network (MCN) business models has created innovative opportunities for promoting Chinese agricultural products in international markets. Through real-time interaction and visual product presentation, live-streaming platforms strengthen brand storytelling, expand overseas market exposure, and reinforce consumer confidence in geographical indication products by enhancing both traceability and perceived authenticity [13].

Despite these advantages, the international expansion of agricultural products through CBEC continues to encounter several industry-specific challenges. The inherent characteristics of agricultural commodities—including product heterogeneity, high perishability, and compliance with stringent sanitary and phytosanitary (SPS) regulations imposed by importing countries—make efficient cross-border operations considerably more demanding. Under these conditions, the effectiveness of cold chain logistics, the reliability of digital traceability systems, and the efficiency of bilateral customs clearance procedures become decisive factors influencing whether agricultural products can successfully compete in global markets [14]. In response to these constraints, the Chinese government has introduced the "Digital Commerce Empowering Agriculture" initiative, which prioritises the enhancement of county-level and rural postal and express logistics infrastructure while promoting innovative logistics models through comprehensive CBEC pilot zones. These policy measures are intended to remove logistical barriers affecting the upstream distribution and international export of agricultural products. Simultaneously, increasing attention has been directed towards developing the Digital Green Supply System (DGSS), which aims to ensure the seamless integration of information flows, physical logistics, and sustainability objectives throughout the agricultural value chain. This integrated approach has gained broad recognition among both researchers and industry practitioners as a critical pathway for supporting sustainable agricultural development [15],[28].

2.3 Application of Multi-Criteria Decision-Making (MCDM) Methods in Complex Supply Chain Evaluation

MCDM has become one of the most effective analytical approaches for addressing complex decision environments involving supply chain management, regional development planning, supplier evaluation, and technology assessment [29], [30]. Its ability to accommodate multiple, often conflicting, evaluation criteria enables decision-makers to generate systematic, transparent, and scientifically grounded solutions for complex strategic problems [1; 8]. Among the diverse range of MCDM techniques, DEMATEL is particularly effective for exploring the structural relationships within complex systems by analysing direct influence matrices. This approach distinguishes between driving (cause) factors and dependent (effect) factors through the evaluation of influence intensity and reciprocal interactions among system elements. In contrast, ANP extends the capabilities of AHP by eliminating the restrictive assumption that decision criteria are mutually independent. Instead, it accommodates both feedback mechanisms across hierarchical levels and interdependencies among evaluation criteria, thereby providing a more realistic representation of complex decision structures. Integrating the total influence matrix generated by DEMATEL into the unweighted supermatrix of ANP, commonly referred to as the DANP model, represents a well-established strategy for reducing subjective weighting bias while deriving objective global weights that reflect network-based relationships among evaluation criteria [7]. For prioritising competing strategic alternatives, TOPSIS remains one of the most widely adopted techniques because of its intuitive geometric foundation, flexibility across different data structures, and straightforward interpretation of ranking outcomes.

Recognising that expert assessments inevitably involve subjective judgement and linguistic uncertainty, recent studies have increasingly incorporated fuzzy set theory into conventional MCDM techniques. The adoption of TFNs in place of precise numerical values enables decision models to accommodate ambiguity and minimise the influence of individual cognitive bias, thereby improving analytical robustness when addressing complex decision environments characterised by incomplete or uncertain information [31], [32]. Building upon the insights derived from the existing literature, the present study develops an integrated analytical framework for agricultural value chain upgrading by incorporating key dimensions related to the digital economy, cross-border logistics, quality traceability, policy and financial support, and human capital. Based on this conceptual foundation, a Fuzzy DEMATEL-ANP-TOPSIS decision model is developed and implemented to address the existing gap in quantitative evaluation approaches within this research domain.

3. MATERIALS AND METHODS

3.1 Construction of the Evaluation Index System

Developing a scientifically rigorous, systematic, and region-specific evaluation index system constitutes the foundation of effective MCDM. To achieve this objective, the present study first conducted a comprehensive review of the relevant literature and incorporated the distinctive geographical, economic, and policy characteristics of Henan Province, particularly its strategic roles as a national CBEC pilot zone, a key Air Silk Road hub, and one of China's major agricultural provinces. On this basis, a preliminary evaluation index system was formulated. To refine and validate the proposed indicators, a Delphi consultation panel comprising 12 senior specialists from the fields of agricultural economics, CBEC platform operations, digital agriculture policy planning, and logistics and supply chain management was established [33], [34]. Following three rounds of anonymous consultation, expert feedback, and iterative indicator refinement, the final "Evaluation Index System for CBEC Driving the Upgrading of Agricultural Value Chain in the Digital Economy" was developed. The completed framework comprises five primary criterion dimensions (C1–C5) and fifteen corresponding sub-criteria. Detailed descriptions of each evaluation indicator together with their supporting literature sources are presented in Table 1.

Table 1
Evaluation Index System for Key Driving Factors of Agricultural Value Chain Upgrading

Main Criterion Dimension	Sub-Criterion Indicators	Description of Assessment Content & Basis of Academic Literature
C1. Digital infrastructure capabilities	C11. Rural broadband and 5G network coverage	Measuring the completeness of the underlying communication facilities in agricultural production areas is a prerequisite physical condition for farmers to access e-commerce
	C12. Integration degree of agricultural big data cloud platforms	The degree of data convergence and collaboration among upstream and downstream of the industrial chain and the breaking of information silos [2]
	C13. Penetration rate of smart agricultural equipment	The actual application level of IoT sensors, agricultural drones, etc., in the front-end production stages
C2. Cross-border Logistics and Cold Chain Efficiency	C21. Cross-border Air and Land Transport Hub Degree	The comprehensive capability of relying on Zhengzhou Airport Port and the China-Europe Railway Express to radiate the global logistics network [5]
	C22. Forward Warehouse and Cold Chain Construction Level at Origin	The core hardware that determines the turnover efficiency of fresh agricultural products, reduces post-harvest losses, and ensures export quality
	C23. Bilateral Customs Clearance and Return Convenience	The application of cross-border return modes, the construction of green channels, and the smoothness of cross-border inspection and quarantine procedures [3]
C3. Quality Control and Traceability System	C31. Compliance Rate of International Standards for Agricultural Products	Qualification assurance for breaking through technical trade barriers and integrating into the high-end market access system of target countries
	C32. Full Life Cycle Traceability Rate of Blockchain	Technical certification for anti-counterfeiting and traceability using distributed ledger technology to enhance trust among overseas consumers
	C33. Added Value Level of Agricultural Product Deep Processing	Measuring the ability of agriculture to escape the low-price competition of primary raw materials and ascend to the high-end of the value chain
C4. Policy Support and Financial Empowerment	C41. Policy Intensity for "Digital Commerce Empowering Agriculture" and Industrial Integration	The strength of the government’s macro guidance in areas such as tax exemptions and special subsidies
	C42. Penetration Rate of Green Agricultural Supply Chain Finance	Credit and risk control support provided by commercial banks and insurance institutions for low-carbon agriculture and cross-border trading enterprises
	C43. Cross-border Payment Clearing and Foreign Exchange Convenience	Speed of international trade fund circulation, popularity of digital payment tools, and ability to prevent exchange rate risks
C5. Human Capital and Innovation Network	C51. Composite Cross-border Digital E-commerce Talent Reserve	Equipped with both modern agricultural knowledge and practical cross-border e-commerce skills; the labor supply [16]
	C52. Regional Collaborative Innovation Incubation Intensity	The efficiency of technology transfer and knowledge spillover between universities, agricultural research institutes, and e-commerce enterprises
	C53. Digital Literacy and Participation Will of Rural Households	The subjective initiative of agricultural producers to accept new business models and actively integrate into the e-commerce ecosystem [12]

3.2 Mathematical Preliminary Knowledge of Fuzzy Set Theory

In complex evaluation environments, expert assessments are frequently expressed through linguistic terms that inherently contain uncertainty, such as "very important" or "weak influence." To convert these imprecise qualitative judgements into a quantitative form suitable for analysis, this study adopts TFNs. Let a TFN be denoted as Ã = (l, m, u), where l, m, and u are real numbers satisfying the condition l ≤ m ≤ u. These three parameters represent the lower bound, the most probable value, and the upper bound of a fuzzy judgement, corresponding respectively to the most pessimistic estimate, the most plausible assessment, and the most optimistic estimate. Considering two independent TFNs, $\tilde{A}_1 = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2)$, their fundamental algebraic operations are expressed as follows.

- Addition Operation: $\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$
- Subtraction Operation: $\tilde{A}_1 \ominus \tilde{A}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2)$
- Multiplication Operation (Approximated When Both are Positive): $\tilde{A}_1 \otimes \tilde{A}_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2)$
- Scalar Multiplication Operation ($k > 0$): $k \otimes \tilde{A}_1 = (kl_1, km_1, ku_1)$

To ensure compatibility with the conventional matrix-based algorithms employed in the subsequent stages of analysis, fuzzy values are transformed into corresponding crisp values through a defuzzification process. In this study, the Centre of Area (COA) method is adopted because of its wide acceptance and effectiveness in converting fuzzy representations into single representative numerical values. The defuzzification procedure is expressed in Equation (1).

$$Crisp(\tilde{A}) = \frac{l+4m+u}{6} \tag{1}$$

The Euclidean distance between two TFNs, $\tilde{A}_1$ and $\tilde{A}_2$, is determined using the following expression, as presented in Equation (2).

$$d(\tilde{A}_1, \tilde{A}_2) = \sqrt{\frac{1}{3}[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2]} \tag{2}$$

3.3 Fuzzy DEMATEL-ANP-TOPSIS Comprehensive Decision Support Framework

The hybrid decision support model developed in this study follows the following mathematical steps:

Phase 1: Constructing a Criterion-Related Causal Network using Fuzzy DEMATEL

Step 1.1: Establish the Fuzzy Direct Influence Matrix

Using a five-level fuzzy linguistic scale (no influence, weak influence, moderate influence, strong influence, and extremely strong influence), K experts were invited to assess the direct influence of criterion *i* on criterion *j*. Aggregate the experts' opinions using the arithmetic mean method to generate the comprehensive fuzzy direct influence matrix $\tilde{Z} = [\tilde{z}_{ij}]_{n\times n}$.

Step 1.2: Defuzzification and Matrix Normalization

Apply the centroid method formula to defuzzify $\tilde{Z}$ into a crisp matrix $Z = [z_{ij}]_{n\times n}$. Then, sum the values column-wise and take the maximum to standardize the matrix, resulting in the standardized direct influence matrix $X = [x_{ij}]_{n\times n}$ (3):

$$x_{ij} = \frac{z_{ij}}{\max\limits_{1\le i\le n} \sum_{j=1}^{n} z_{ij}} \tag{3}$$

Step 1.3: Calculate the Comprehensive Total Impact Matrix T

The total influence matrix captures the complete network of both direct and indirect causal relationships within the system, as expressed in Equation (4).

$$T = X(I - X)^{-1} \tag{4}$$

In the formula, I represents the $n \times n$ identity matrix.

Step 1.4: Calculate Centrality and Causality

The row sum (D_i) and column sum (R_i) of the total influence matrix (T) are calculated for each criterion. The centrality (Prominence), expressed as $D_i + R_i$, represents the overall significance of a criterion within the system by reflecting its total level of interaction with other criteria. The causality (Relation), calculated as $D_i - R_i$, indicates the direction of influence. A positive value signifies that the criterion predominantly influences other factors and is therefore classified as a "cause factor," whereas a negative value indicates that the criterion is primarily influenced by other factors and is classified as an "effect factor."

Phase 2: Determine the Global Composite Objective Weights using Fuzzy ANP

To overcome the limitations associated with the assumption of independent criterion weighting, this stage constructs the network-based weight structure using the total influence matrix generated by DEMATEL [7].

Step 2.1: Construct the Unweighted Supermatrix W

The submatrices within the total influence matrix (T) corresponding to the same main criterion dimension are normalised by both rows and columns to generate the normalised total influence matrix (T^{α}). The transpose of this normalised matrix is then obtained to construct the unweighted supermatrix (W).

Step 2.2: Construct the Weighted Supermatrix W^{α}

Similarly, the dimension normalisation matrix is established using the total influence matrix of the main criterion dimensions (C1–C5). The weighted supermatrix (W^{α}) is then generated by multiplying the corresponding blocks of the unweighted supermatrix (W) by the respective dimension normalisation weights.

Step 2.3: Calculate the Limit Supermatrix W^{*}

Successive power iterations are applied to the weighted supermatrix (W^{α}) until the values in each column converge to a stable and uniform state. After convergence, any column vector of the resulting limit supermatrix represents the global composite priority weights of the sub-criteria within the network system.

Phase 3: Utilizing Fuzzy TOPSIS for the Evaluation and Optimization of Strategic Alternatives

Step 3.1: Establish the Fuzzy Evaluation Decision Matrix

For the performance evaluation of the *m* alternative strategic plans across *n* criteria, experts assign ratings using a predefined linguistic scale. These individual assessments are then aggregated to construct the fuzzy decision matrix.

Step 3.2: Matrix Normalization and Weighting

To eliminate dimensional inconsistencies among the evaluation criteria, the decision matrix is transformed through linear fuzzy normalisation. The global weights obtained in Phase 2 are then incorporated to generate the weighted standardised fuzzy decision matrix ($\tilde{P}$).

Step 3.3: Determine the Fuzzy Positive Ideal Solution and Negative Ideal Solution

The upper and lower boundary values for each evaluation criterion are extracted from the standardised decision matrix to establish the fuzzy positive ideal solution and the fuzzy negative ideal solution.

Step 3.4: Calculate the Distance Measures

Calculate the distance (d_i^+) of each alternative strategy (*i*) from the fuzzy positive ideal solution and the distance (d_i^-) from the fuzzy negative ideal solution, as expressed in Equation (5).

$$d_i^+ = \sum_{j=1}^{n} d\,(\tilde{p}_{ij}, \tilde{v}_j^+) \quad ; \quad d_i^- = \sum_{j=1}^{n} d\,(\tilde{p}_{ij}, \tilde{v}_j^-) \tag{5}$$

Step 3.5: Calculate the Relative Proximity Coefficient (CC_i) and Finalize the Ranking (6)

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{6}$$

The closer the relative closeness coefficient (CC_i) is to 1, the nearer the corresponding strategic alternative is to the positive ideal solution and the farther it is from the negative ideal solution. Accordingly, the strategy with the highest CC_i value is identified as the most suitable implementation pathway for upgrading the agricultural value chain.

4. Results and Analysis

To comprehensively evaluate the applicability of the proposed decision support model and generate quantitative policy recommendations for the Henan Provincial Government and enterprises operating within the agricultural value chain, this study performed an empirical assessment of the following four macro-level strategic alternatives. These strategies were formulated by considering the geographical characteristics of Henan Province together with the development priorities outlined in the "14th Five-Year Plan".

- A1: Deepening the Integration of the Digital Ecosystem Cloud Platform and the "Digital Commerce Empowering Agriculture" initiative
  This strategy places primary emphasis on strengthening digital infrastructure through the establishment of a province-wide cloud-based agricultural trading and big data analytics platform. It further advocates the promotion of emerging digital marketing formats, including "village livestreaming," to reconstruct the integrated flow of information and capital from agricultural production areas directly to international purchasers.
- A2: Cross-Border Cold Chain Logistics Forward Warehouse Network and Optimization of Airport Channels
  This alternative concentrates on improving large-scale logistics infrastructure. Building upon Zhengzhou's strategic role as an Air Silk Road freight hub, investment is directed towards developing an extensive network of modern forward warehouses across major agricultural production regions. Simultaneously, the strategy seeks to enhance the integration between TIR international road transportation and advanced air cold chain logistics, thereby reducing supply chain disruptions, minimising product losses, and addressing cold chain interruptions during the export of fresh agricultural
- A3: Internationalization of Agricultural Product Brands, Anti-Counterfeiting Traceability, and Upgrading of High-End Processing
  This strategy focuses on enhancing the core value of agricultural products through the integration of blockchain and IoT technologies. These technologies will provide internationally recognised digital anti-counterfeiting and traceability identities for distinctive agricultural products, including Xinyang Maojian tea, Yuanyang rice, and premium processed ready-to-eat products. Particular attention is directed towards expanding access to high-net-worth overseas market segments while increasing international brand recognition and premium value [13].
- A4: Green Agriculture-Specific Supply Chain Finance and the Construction of a Cross-Border Talent Ecosystem
  This strategy emphasises the development of supporting institutional mechanisms. In partnership with financial institutions, it proposes the introduction of low-interest green financing schemes for

cross-border agricultural supply chains together with cargo return insurance for international trade. At the same time, cooperation with leading domestic and international agricultural universities is encouraged to establish industry–education integration bases within Henan Province, thereby addressing the shortage of multidisciplinary professionals possessing expertise in both agriculture and digital trade.

4.1 Decomposition of Indicator Causal Relationship Based on Fuzzy DEMATEL

Using the evaluation questionnaires completed by the 12 experts, the total influence matrix was computed to determine the centrality and cause degree of each evaluation criterion. The corresponding results are presented in Table 2.

Table 2
The Calculation Results of Centrality and Causality in Fuzzy DEMATEL and the Classification of Indicator Attributes

Main Criteria	Sub Indicators	Impact (D)	Influence (R)	Centrality ($D+R$)	Cause Degree ($D-R$)	Attribute Classification
C1	C11	3.425	1.810	5.235	1.615	Cause Factor
	C12	3.210	2.540	5.750	0.670	Cause Factor
	C13	2.890	2.960	5.850	-0.070	Effect Factor
C2	C21	3.515	2.010	5.525	1.505	Cause Factor
	C22	3.480	2.650	6.130	0.830	Cause Factor
	C23	2.760	2.110	4.870	0.650	Cause Factor
C3	C31	2.150	3.520	5.670	-1.370	Effect Factor
	C32	2.640	3.240	5.880	-0.600	Effect Factor
	C33	1.950	4.120	6.070	-2.170	Effect Factor
C4	C41	3.650	1.450	5.100	2.200	Cause Factor
	C42	2.850	2.200	5.050	0.650	Cause Factor
	C43	2.450	2.580	5.030	-0.130	Effect Factor
C5	C51	3.120	2.850	5.970	0.270	Cause Factor
	C52	3.010	2.450	5.460	0.560	Cause Factor
	C53	2.310	3.450	5.760	-1.140	Effect Factor

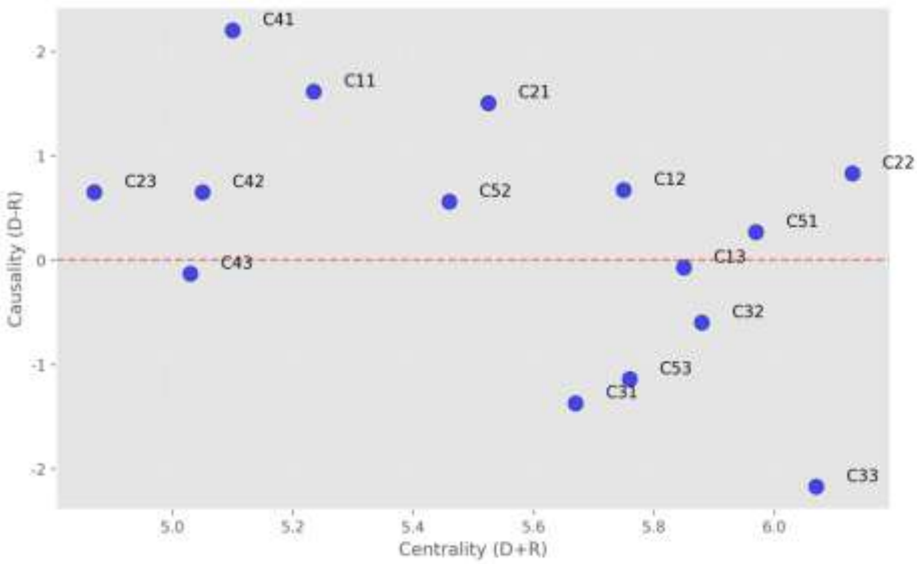

Fig.1: The Causal Relationship Diagram of DEMATEL Evaluation Indicators (Centralization vs. Cause Degree)

The results presented in Table 2 and Figure 1 reveal several important dynamic characteristics of the proposed system.

4.1.1 Macroscopic Source Driving Force

The policy dimension represented by the intensity of the "Digital Commerce Empowering Agriculture" initiative and industrial integration policies (C41) records the highest positive cause degree (2.200), followed by rural broadband infrastructure (C11) and cross-border air and land transportation hubs (C21). These findings quantitatively demonstrate that proactive government policies, robust digital communication infrastructure, and strategically located transportation hubs constitute the principal driving forces underpinning the digital transformation of the regional agricultural economy [35].

4.1.2 Importance of Core Nodes

Based on the centrality values, which reflect the overall significance of each criterion within the system, the origin-based forward warehouse and cold chain construction level (C22) achieves the highest score (6.130) while also exhibiting a substantial positive cause degree. This finding suggests that cold chain infrastructure occupies the most influential position within the evaluation framework and serves as a critical driver that facilitates the development of downstream activities, including anti-counterfeiting traceability and international certification.

4.1.3 Result-oriented Evolution of Terminal Value

The value-added level of deep agricultural product processing (C33) demonstrates relatively high centrality while simultaneously exhibiting a pronounced negative cause degree (-2.170), identifying it as a representative terminal effect factor within the system. This indicates that the achievement of high value-added agricultural outcomes does not depend on an individual driving factor. Instead, it emerges as the cumulative result of coordinated interactions among digital platforms, cross-border cold chain logistics, and supportive policy and financial mechanisms.

4.2 Global Composite Weight Calculation Based on Fuzzy ANP

Following the transformation of the directed causal relationship network generated by DEMATEL into a limit supermatrix, the model calculated the global relative weights while accounting for the interdependencies among the evaluation criteria. The resulting global priority weights, free from the bias associated with the assumption of criterion independence, are presented in Table 3.

Table 3

The Fuzzy ANP Global and Local Composite Weight Distribution of Evaluation Criteria

Main Dimension	Dimension Weight	Sub-Indicator	Local Weight	Global Weight	Global Ranking
C1	0.231	C11	0.268	0.062	9
		C12	0.554	0.128	2
		C13	0.178	0.041	14
C2	0.283	C21	0.406	0.115	3
		C22	0.512	0.145	1
		C23	0.082	0.023	15
C3	0.187	C31	0.256	0.048	12
		C32	0.524	0.098	4
		C33	0.220	0.041	13
C4	0.134	C41	0.358	0.048	11
		C42	0.380	0.051	10
		C43	0.262	0.035	16
C5	0.165	C51	0.558	0.092	5
		C52	0.400	0.066	8
		C53	0.042	0.007	17

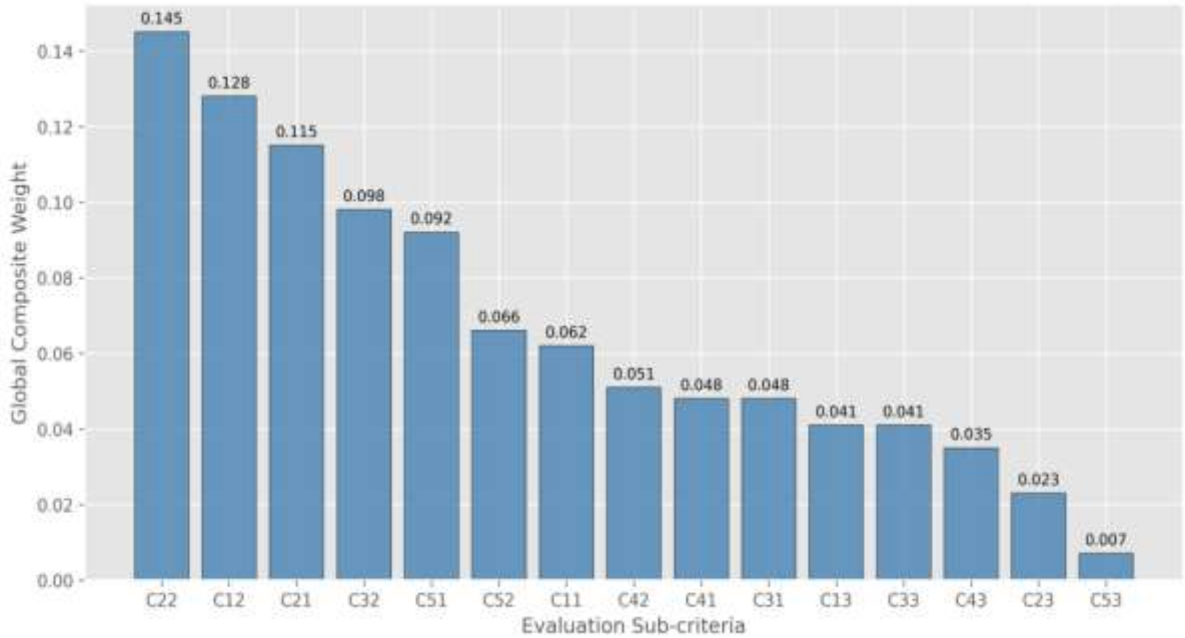

Fig.2: Bar Chart Showing the Global Composite Weight Distribution of the Evaluation Criterion in Fuzzy ANP

As illustrated in Table 3 and Figure 2, the global weight distribution provides a rigorous quantitative basis for prioritising resource allocation. Among all evaluation criteria, the origin-based forward warehouse and cold chain (C22) achieves the highest global weight (0.145), followed by the agricultural big data cloud platform (C12) with a weight of 0.128 and the cross-border hub degree (C21) with a weight of 0.115. Notably, these three highest-ranked criteria are entirely associated with C1 (digital infrastructure) and C2 (cross-border logistics). These findings objectively demonstrate that, within the context of CBEC-enabled agricultural exports, the integration of physical logistics infrastructure and digital information platforms forms the dual-core foundation driving agricultural value chain upgrading [36].

4.3 Optimization of Strategic Alternatives Based on Fuzzy TOPSIS

Following the integration of the global weights obtained from ANP, the model implemented the Fuzzy TOPSIS geometric distance procedure to determine the closeness coefficient (CC_i) of each of the four macro-level strategic alternatives relative to the ideal solution. The final evaluation and ranking results are reported in Table 4.

Table 4
Fuzzy TOPSIS Evaluation and Ranking of Alternative Agricultural Value Chain Upgrading Strategies

Strategic Plan	Distance from Positive Ideal Solution (d_i^+)	Distance from Negative Ideal Solution (d_i^-)	Proximity Coefficient (CC_i)	Priority Ranking
A1 (Digital Ecological Cloud Platform Integration)	0.3241	0.6582	0.6700	2
A2 (Cold Chain Forward Network and Airline Channel)	0.2853	0.7126	0.7141	1
A3 (Brand-based Traceability and Deep Processing)	0.4157	0.5268	0.5589	3
A4 (Special Finance and Cross-border Talents)	0.5124	0.4355	0.4594	4

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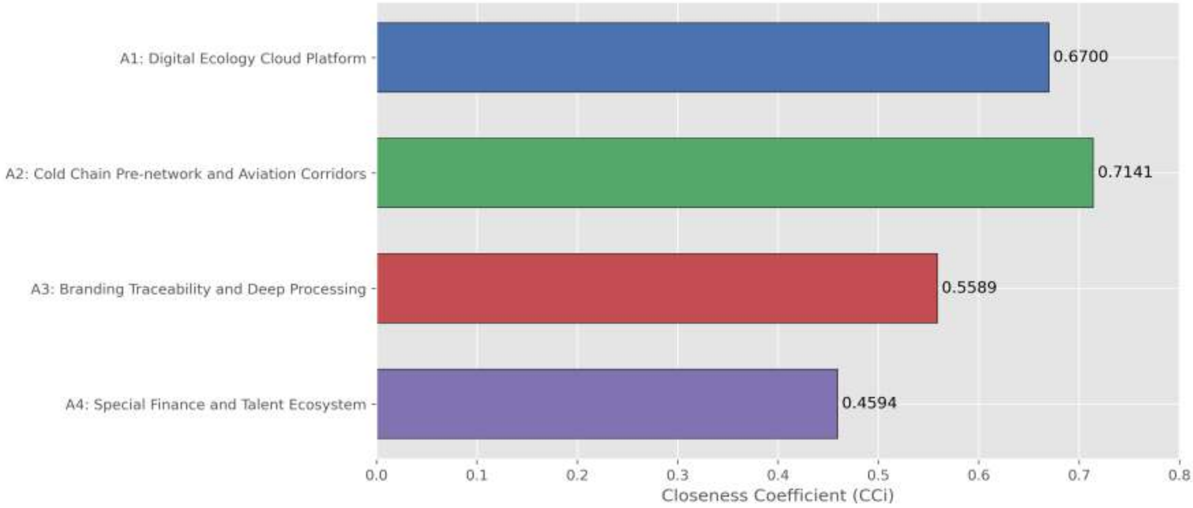

Fig.3: Comparison Chart of the Proximity Coefficient (CCi) of Each Alternative Strategic Plan

According to the TOPSIS evaluation principle, a higher closeness coefficient indicates that a strategic alternative is positioned nearer to the ideal solution after considering the relative importance of all evaluation criteria. As illustrated in Figure 3, the overall ranking of the four strategic alternatives is A2 > A1 > A3 > A4. Among these alternatives, A2 (Cross-border Cold Chain Forward Network and Optimization of Airport Channel) achieves the highest closeness coefficient (0.7141), identifying it as the most appropriate strategy for accelerating the transformation and upgrading of the agricultural value chain in Henan Province under current conditions. The A1 strategy also exhibits considerable strategic strength, with a closeness coefficient of 0.6700, indicating its role as a complementary strategic priority that can effectively support the implementation of the leading alternative.

4.4 Model Robustness Verification: Sensitivity Analysis and Multi-Method Comparison

To further verify the scientific validity and reliability of the proposed decision-making model, this study incorporates both sensitivity analysis and comparative evaluation using alternative decision-making algorithms [17].

Sensitivity Analysis: Within the interval of [-30%, +30%], the weight assigned to the highest-ranked criterion, C22 (Cold Chain Construction Level), was systematically varied in 5% increments. To preserve the total weight at 1, the weights of all remaining criteria were proportionally adjusted during each experimental scenario.

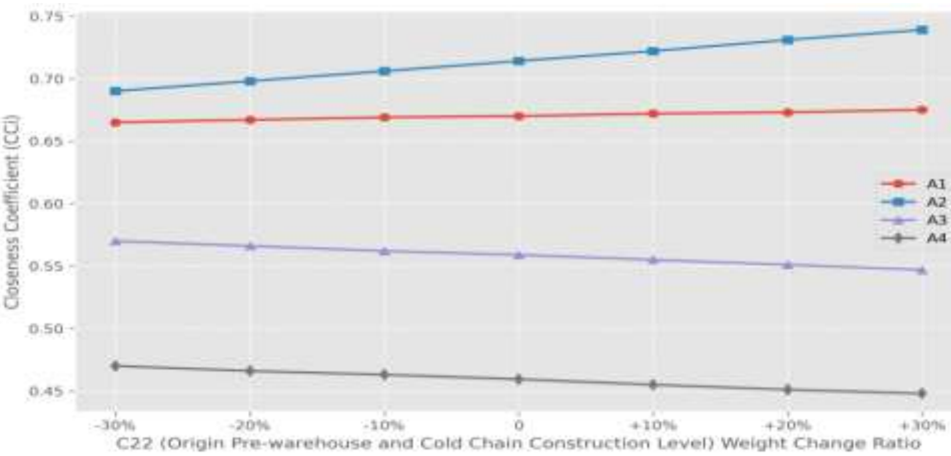

Fig.4: Sensitivity Analysis Diagram Under the Fluctuation of C22 Criterion Weights

As illustrated in Figure 4, the sensitivity analysis demonstrates that although the closeness coefficients of certain strategic alternatives exhibit minor variations under substantial changes in criterion weights, the overall ranking pattern remains unchanged, with A2 consistently retaining the highest position and A4 remaining the lowest-ranked alternative. This stability indicates that the final decision is robust and is not excessively influenced by the subjective assignment of a single criterion weight.

Multi-Method Horizontal Comparison Analysis: To further examine the consistency and convergence of the ranking results, this study conducted a parallel comparative analysis using the same input dataset and criterion weights. In addition to the proposed model, the Fuzzy MARCOS model, which is based on compromise solution ranking, and the Fuzzy COPRAS model [9] were implemented to evaluate the same set of strategic alternatives under identical conditions.

Table 5

Cross-Validation Comparison Results of Different Fuzzy MCDM Evaluation Models

Strategic Plan	Fuzzy TOPSIS (CC_i)	Rank	Fuzzy MARCOS (K_i)	Rank	Fuzzy COPRAS (Q_i)	Rank
A1	0.6700	2	0.8124	2	0.2854	2
A2	0.7141	1	0.8956	1	0.3312	1
A3	0.5589	3	0.6512	3	0.2201	3
A4	0.4594	4	0.5233	4	0.1633	4

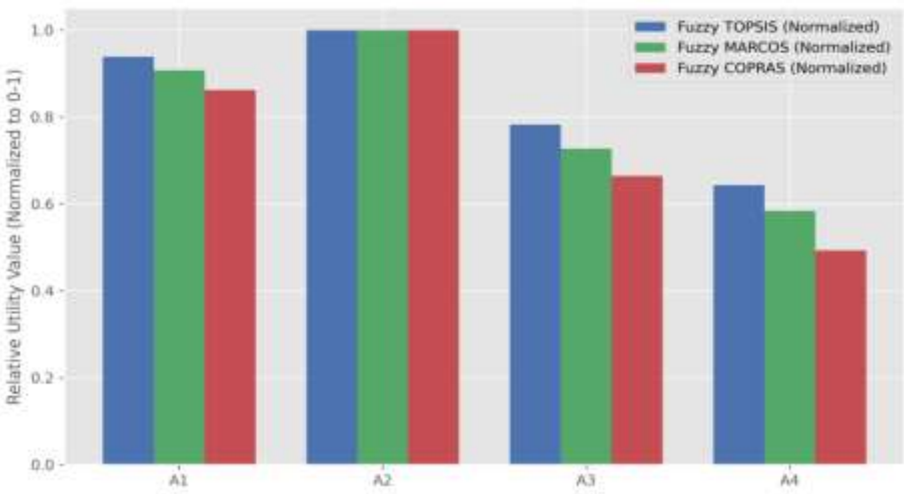

Fig.5: Comparison and Verification of Different Fuzzy MCDM Evaluation Models

The comparative results presented in Table 5 and Figure 5 clearly indicate that, although the utility values generated by the different algorithms vary in magnitude because of differences in their underlying aggregation mechanisms and mathematical formulations, the resulting strategic priority rankings remain identical across all methods (A2 > A1 > A3 > A4). This consistency across multiple decision-making algorithms further demonstrates the robustness and cross-algorithm reliability of the decision outcomes produced by the proposed framework.

5. DISCUSSION

The integrated evaluation framework developed in this study, combining causal relationship analysis, network-based weight optimisation, and ideal solution ranking, offers a robust quantitative approach for investigating the developmental dynamics of regional agriculture. The analytical results generated by the model reveal several underlying structural relationships and policy implications, providing valuable insights into the mechanisms shaping agricultural value chain development.

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5.1 The Core Positioning Logic of Logistics Cold Chain and Digital Infrastructure

As illustrated by the radar chart in Figure 6, the quantitative evaluation framework identifies "Cross-border Cold Chain Forward Network and Optimization of Air Routes (A2)" as the highest-priority strategic alternative. Consistent with this finding, the DEMATEL causal analysis also recognises cold chain infrastructure and air transportation hubs as the principal driving factors within the evaluation system. These results underscore the critical constraints limiting the integration of inland agricultural products into international markets. The successful export of high-quality agricultural commodities, particularly fresh produce and processed products, depends heavily on efficient transportation networks and appropriate storage conditions. In the absence of an origin-based forward cold storage network and streamlined cross-border green customs clearance channels, agricultural exports are likely to experience substantial product losses during international distribution [3]. Although Henan Province lacks the maritime advantages enjoyed by China's eastern coastal regions, it has substantially strengthened its international logistics capacity through the Zhengzhou–Luxembourg Air Silk Road and TIR international road transport network, thereby improving the efficiency of cross-border freight operations [5]. Consequently, the strategic value of A2 lies in overcoming geographical limitations by leveraging high-efficiency multimodal logistics to offset the disadvantages associated with inland location. The strong performance of A1 (Digital Ecological Cloud Platform Integration), which ranks second among the evaluated alternatives, further emphasises the transformative role of data resources in restructuring agricultural trading mechanisms. The establishment of an integrated cloud-based big data platform covering the entire agricultural value chain, together with the incorporation of DGSS and the application of e-commerce algorithms to directly connect producers with overseas consumer demand, can significantly reduce the dependence on traditional intermediary channels. Such an integrated digital ecosystem creates opportunities for dispersed agricultural cooperatives to expand their participation across multiple stages of the value chain, thereby enhancing both market access and value creation [15], [37],[38].

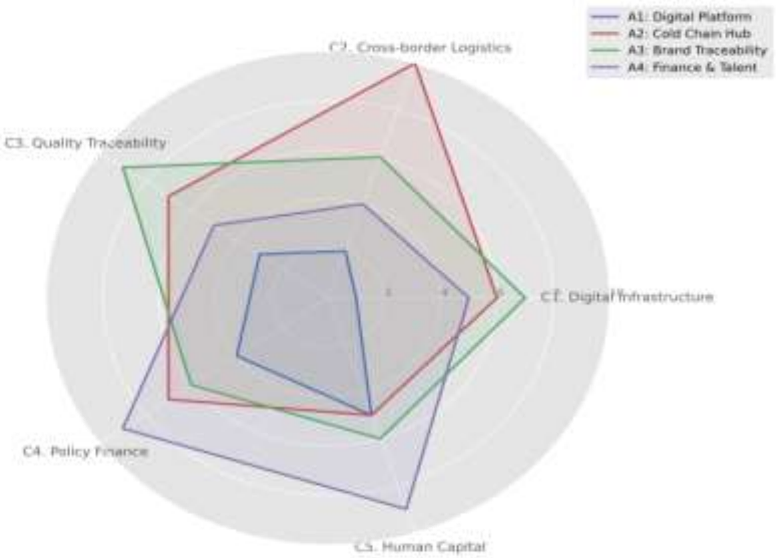

Fig.6: The Radar Chart Showing the Advantages of the Four Major Macro Strategies in Each Dimension

5.2 The Non-Linear Threshold of Digital Dividends and the U-Shaped Effect of Value Evolution

The DEMATEL results indicate that both the level of added value from deep processing (C33) and the compliance rate of international standard certifications (C31) possess negative cause degrees, identifying them as downstream effect factors that are primarily influenced by other components within the system. This pattern suggests that agricultural value chain upgrading is not achieved

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through isolated interventions but instead depends on sustained investment in production factors together with the gradual development of supporting infrastructure. Recent empirical evidence further demonstrates that the diffusion of digital technologies within the agricultural sector follows a nonlinear spatial threshold pattern [11], as illustrated in Figure 7. During the initial phase of digital transformation, substantial investment in network infrastructure and cold chain facilities increases depreciation and operating costs, which may temporarily reduce profit margins. However, once digital technology adoption exceeds the critical threshold, the costs associated with information acquisition and contract verification decline considerably, enabling agricultural enterprises to capture greater international brand premiums [12]. Accordingly, the implementation of brand traceability and deep-processing initiatives under A3 should be preceded by adequate infrastructure development, ensuring that investment expansion is aligned with existing operational capabilities rather than being pursued prematurely.

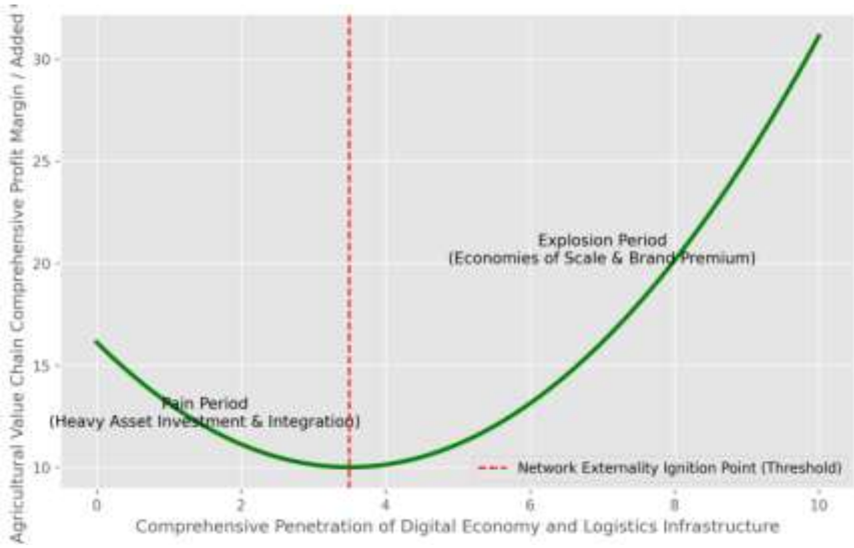

Fig.7: The U-Shaped Evolution Curve of the Digital Economy Enabling the Upgrading of the Agricultural Value Chain

5.3 Anchor the Macro Provincial Situation of Henan and the Constraints on Food Security

MCDM applications should be tailored to the specific characteristics and developmental priorities of the region under investigation. As a strategically important province responsible for safeguarding China's national food security, Henan must pursue agricultural upgrading and international market expansion without compromising staple food production [4]. Within this strategic framework, the role of CBEC should be reflected through the integration of anti-counterfeiting and traceability technologies under the A1 strategy, thereby enabling high-quality local staple food products and their processed derivatives to satisfy international quality requirements and strengthen their competitiveness in overseas markets. In addition, the expansion of digital commerce networks can facilitate the bidirectional flow of rural digital public services, lower the hidden transaction and operational costs associated with agricultural production, and establish a sustainable development cycle that simultaneously safeguards food security while supporting continuous growth in farmers' disposable income.

Moreover, although the policy environment has been identified as a major driving force within the evaluation framework, and both central and local governments have actively promoted the "Digital Commerce Empowering Agriculture" initiatives, A4, which focuses on financial support and talent development, ranks fourth among the evaluated strategic alternatives. This ranking should not be interpreted as indicating that financial resources and human capital are of limited importance.

Rather, it reflects the current stage of Henan's digital transformation, where the transition from the initial development phase to the acceleration stage places greater priority on strengthening logistics infrastructure and digital platform capabilities. In comparison, the development of multidisciplinary digital professionals and the establishment of a comprehensive green financial system represent long-term strategic objectives that require sustained investment and continuous support through a well-developed education–innovation integration system [16].

6. CONCLUSION

This study developed an integrated Fuzzy DEMATEL-ANP-TOPSIS decision-support framework and applied it to Henan Province to evaluate strategies for agricultural value chain upgrading in the context of the digital economy. The proposed framework successfully identified the causal relationships among key evaluation criteria, determined their relative importance, and prioritised strategic alternatives, demonstrating its effectiveness as a robust tool for supporting complex agricultural policy decisions. The findings indicate that strengthening cold chain logistics infrastructure should be the foremost priority, as origin-based forward cold chain facilities and cross-border transportation hubs exert the greatest influence on agricultural value chain upgrading. At the same time, accelerating the development of digital infrastructure, including provincial agricultural big data platforms and blockchain-based traceability systems, can improve information transparency, reduce transaction costs, and enhance the international competitiveness of agricultural products. The results further suggest that initiatives related to brand internationalisation and deep processing should be implemented progressively after the necessary digital and logistics foundations have been established. Although financial support and talent development received a relatively lower strategic priority, they remain essential for sustaining long-term digital agricultural transformation through continuous investment in green finance and industry–education collaboration. Overall, the integration of fuzzy set theory with multiple decision-making techniques confirms the scientific reliability and robustness of the proposed MCDM framework for evaluating regional agricultural development strategies. Future research may incorporate System Dynamics simulation or panel data econometric approaches to investigate the long-term evolution of the identified key factors and further strengthen strategic decision-making for agricultural value chain development [39], [40].

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