

A Study on the Measurement of Modernization Levels in the Sugar Industry Chain Based on the Entropy-Weighted TOPSIS Method: A Case Study of Guangxi, China

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Abstract: With the in-depth implementation of the green development philosophy and the comprehensive advancement of industrial chain modernization, establishing an industrial evaluation system tailored to regional characteristics is of great significance for promoting high-quality industrial development. Taking the sugar industry in Guangxi, China, as the subject, this study integrates the structural characteristics of the "cultivation-processing-comprehensive utilization" industrial chain. It constructs an indicator system for measuring the modernization level of the sugar industry chain from four dimensions—value-added upgrading, technological innovation, green and ecological development, and spatial agglomeration—and employs the TOPSIS method to conduct empirical measurement and analysis of the modernization level of Guangxi's sugar industry chain from 2021 to 2025. The study found that the modernization level of the sugar industry industrial chain in Guangxi is showing a steady upward trend. Among these dimensions, the level of technological innovation has the most significant impact on the overall modernization level, serving as the core driving force for industrial chain optimization; the level of value-added upgrading has achieved relatively rapid growth, reflecting a positive trend of the industrial chain extending toward high-value-added segments. However, the development of green and ecological sustainability and spatial agglomeration lags behind, becoming key bottlenecks constraining the synergy and sustainable development of the industrial chain. This study aims to provide a theoretical basis and practical reference for the modernization and transformation of the sugar industry industrial chain in Guangxi, as well as methodological insights for the

evaluation and optimization of similar industrial chains.

Keywords: Industrial Chain Modernization; TOPSIS Method; Sugar Industry; Guangxi

1. Introduction

As a vital strategic commodity closely tied to the national economy and people's livelihood, the stability and development of the sugar industry directly impact national food security and economic resilience [1]. However, China's sugar industry has long faced structural challenges such as high production costs, heavy reliance on imports, and insufficient product value-added. Against the dual backdrop of the global green development trend and the modernization of industrial chains, promoting the upgrading of the sugar industry toward high efficiency, high value, and sustainability has become a core issue for ensuring industrial security and enhancing international competitiveness. Establishing a scientific evaluation system that is tailored to regional characteristics and comprehensively reflects the level of industrial chain modernization holds significant theoretical value and practical urgency for accurately diagnosing development trends and guiding industrial optimization and upgrading. Existing research can be broadly categorized into two main strands: industrial practice exploration and innovation in evaluation methods. Regarding industrial practice exploration, existing studies have closely tracked China's sugar industry, expanding from single-stage processes to system integration, thereby demonstrating the practical potential for circular economy and full-industry-chain transformation. Regarding evaluation methods, TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) has gained widespread favor due to its ability to systematically address complex, multi-dimensional, and multi-objective

evaluation problems [2]. Scholars have continuously advanced its localization and innovation in specific application scenarios; for example, Bi et al. [3] and Ou et al. [4] respectively applied the DTOPSIS method and the Grey Relation-TOPSIS method to conduct a comprehensive evaluation of the agronomic traits of sugarcane varieties, verifying the method's applicability in the agricultural sector; Liu and Zhang [5] and Lamrini et al. [6] expanded its application boundaries in the fields of student evaluation and big data decision-making, respectively; while Wang et al. [7] enhanced the robustness of the evaluation through method integration. A review of existing research reveals that, despite substantial achievements, there remains room for further exploration, which forms the starting point of this study. First, regarding research perspectives, most studies either focus on a specific segment of the industrial chain (such as mechanized planting or the circular economy) or emphasize macro-level descriptions and the introduction of international case studies. There is a lack of a dedicated, comprehensive evaluation framework that closely aligns with the intrinsic logic of the sugar industry's full "planting-processing-comprehensive utilization" chain and systematically integrates the multidimensional aspects of modernization, including value creation (high-end development), technology-driven innovation, environmental friendliness (ecological sustainability), and spatial optimization (clustering). Second, regarding methodological application, although methods such as TOPSIS have been widely discussed and applied in agriculture and other fields, empirical research that systematically and specifically integrates these methods into the measurement of multi-dimensional modernization levels across the entire value chain—and conducts continuous dynamic assessments of core production areas—remains insufficient.

In light of this, this study focuses on Guangxi—the core of China's sugar industry—and aims to construct an indicator system for measuring the level of industrial chain modernization across four dimensions: high-end value, technological innovation, green ecology, and spatial agglomeration. This study will employ the TOPSIS method to conduct empirical measurement and dynamic analysis of Guangxi's sugar industry development data from

2021 to 2025. Through this study, we aim to: 1) scientifically and quantitatively characterize the overall progress of Guangxi's sugar industry modernization and the development status across each dimension; 2) accurately identify the core drivers of industrial upgrading and the key bottlenecks constraining sustainable development; 3) provide evidence-based decision-making support and theoretical references for the high-quality development and modernization transformation of the sugar industry in Guangxi and across China.

2. Construction of the Indicator System

2.1 Setting of Indicators for Each Dimension

Chusi [8] points out that the international sugar market experiences abnormal fluctuations caused by industry collusion and price manipulation; for example, the Tanzanian sugar industry once sparked strong public backlash due to corporate hoarding and price manipulation. Saloni et al. [9] note that India has linked the sugar industry to energy security through the National Biofuels Policy, vigorously promoting ethanol blending programs and extending the industrial chain through cogeneration using bagasse. These practices in value enhancement, technological innovation, and green transformation provide crucial references for the modernization of Guangxi's sugar industry.

The modernization of Guangxi's sugar industry has already been vividly demonstrated in practice. Taking Chongzuo City as an example, Guan et al. [10] highlight its circular economy model of "making full use of every part of the sugarcane," which epitomizes the multidimensional development examined in this study: molasses is converted into high-value-added yeast and rum (value enhancement), bagasse is upgraded from paper-making raw material to energy storage material (technological innovation), filter mud is returned to fields to form a green closed-loop (green ecology), and related industries cluster and develop in core production areas (spatial agglomeration). Based on these core characteristics and successful practices, this study constructs the following measurement indicator system: a framework comprising four dimensions—value upgrading, technological innovation, green ecology, and spatial agglomeration—with specific indicators set as

follows:

Technological innovation is shown in Table 1. high-end value is shown in Table 2, green

ecology is shown in Table 3, and spatial agglomeration is shown in Table 4.

Table 1. Measurement Indicators for Technological Innovation

Technological Innovation	2021	2022	2023	2024	2025
Indicators					
Comprehensive mechanization rate for sugarcane cultivation and harvesting	66.60%	-	69.07%	70.84%	72.12%
Promoted Area of Virus-Free Healthy Sugarcane Seedlings	382 mu	311 mu	355 mu	367 mu (planned)	367 mu (planned)
Coverage rate of high-yield sugarcane varieties	98%	98%	-	98.62%	98.70%
Percentage of in-house developed sugarcane varieties	-	38%	41.40%	-	43%

Table 2. High-End Value Measurement Indicators

Indicators	2021	2022	2023	2024	2025
Varieties of Premium Sugar Products	20+	20+	20+	20+	20+
Output value of the sugar industry's circular economy	8 billion yuan	8.079 billion yuan	11.2 billion yuan	26.878 billion yuan (estimated)	30 billion yuan (target)
Mixed sugar production (Guangxi)	6.0462 million tons	5.2703 million tons	6.1814 million tons	6.465 million tons	-
Production capacity of sugarcane bagasse eco-friendly products	10,000 metric tons	57,000 metric tons	120,000 metric tons (estimated)	150,000 tons	180,000 tons

Table 3. Green Ecological Measurement Indicators

Green and Ecological	2021	2022	2023	2024	2025
Indicators					
Comprehensive Utilization Rate of Sugarcane Leaves	30%	-	33.10%	31%+	40%+
Bagasse utilization rate	100%	100%	100%	100%	100%
Molasses utilization rate	100%	100%	100%	100%	100%

Table 4. Spatial Aggregation Measurement Indicators

Indicators	2021	2022	2023	2024	2025
Industrial Output Value of the Sugar Industrial Park	8.255 billion yuan	-	-	-	40 billion yuan
Sugar Cane Planting Area	11.15 million mu	-	11.2 million mu	11.24 million mu	11.35 million mu

2.2 System Development

1.2.1 Principles of construction

Based on theories such as industrial economics and agricultural modernization, and in conjunction with the intrinsic logic of Guangxi's sugar industry chain from cultivation to sales, indicators that accurately reflect core characteristics—including value creation, technological innovation, ecological sustainability, and spatial layout optimization—were selected to form an interconnected and comprehensive indicator network. For example, the "high-yield variety coverage rate" reflects the achievements of variety improvement based on genetic breeding theory. Indicators across various dimensions collectively reflect the state of industrial chain modernization from different perspectives, ensuring the scientific rigor and systematic nature of the evaluation. Priority is given to

indicators that are easy to collect, quantifiable, and from reliable sources. The definition, statistical scope, and calculation methods for each indicator are clearly defined (e.g., the "proportion of self-bred sugarcane varieties" is calculated using a fixed formula) to ensure practical feasibility. At the same time, room for adjustment is reserved to add, remove, or replace indicators in response to industry dynamics (e.g., adding new indicators for technological innovation or replacing weakened traditional indicators), ensuring the system remains aligned with the pace of industrial development. Based on industrial chain integration theory and a modernization evaluation framework, and integrating the core policy objectives of Guangxi's sugar industry, policy-oriented indicators such as "area of virus-free seedling promotion" are incorporated into the system. This unifies theoretical logic with practical industrial needs, ensuring that indicator design

complies with academic standards while serving actual development goals.

2.2.2 Construction method

Key indicators were extracted from the six core characteristics of Guangxi's sugar industry as follows:

(1) Industry Scale and Concentration: The industrial output value of the sugar industrial park should reflect the effectiveness of leading enterprises in driving collaboration among small and medium-sized factories, while "sugarcane planting area" reflects the regional concentration and scale of raw material production in the sugar industry. (2) Technological Progress: "High-yield variety coverage" focuses on varieties adapted to Guangxi's climate, such as those resistant to wind and drought, while "comprehensive mechanization rate for sugarcane cultivation, planting, and harvesting" reflects the level of modernization in sugarcane production and specifically indicates the degree of mechanization applied throughout the cultivation, planting, and harvesting processes. (3) Value Extension: This is divided into high-end sugar product categories and the output value of the sugar industry's circular economy. The former demonstrates the industry chain's ability to extend into high-value-added sugar products (such as specialty brown sugar and medicinal sugar), while the latter reflects the economic benefits derived from the comprehensive utilization of byproducts such as bagasse and molasses.

According to policy documents such as the **Report on the High-Quality Development of Guangxi's Sugar Industry**, in terms of policy drivers, the "area of virus-free seedling promotion" directly aligns with the high-quality seed breeding policies outlined in the 14th Five-Year Plan, focusing on the actual amount of high-quality seedlings planted following policy implementation; In terms of regional characteristics, it is essential to examine the industrial output value of the sugar industrial park located in Chongzuo. As the "Sugar Capital of China," Chongzuo's prominent resource advantage—accounting for one-third of Guangxi's and one-fifth of the nation's total sugarcane production—makes this indicator highly valuable for reference. Based on field survey data from the Guangxi Sugar Industry Group and the sugarcane-growing areas of Laibin City, redundant indicators were eliminated through correlation analysis; The

"comprehensive mechanization rate of production" was excluded due to its high correlation ($r > 0.8$) with the "comprehensive mechanization rate of cultivation, planting, and harvesting" to avoid information overlap; vague indicators (such as "sustainable development capacity") were replaced with concrete indicators (such as "off-field utilization rate of sugarcane leaves" and "utilization rate of bagasse").

2.2.3 System architecture

Based on the logical framework of the industrial ecosystem health evaluation model, and adhering to the principles of scientific rigor, comprehensiveness, representativeness, and measurability, an indicator system for evaluating the modernization level of Guangxi's sugar industry chain was constructed through a comprehensive analysis of existing research findings. This system encompasses the dimensions of technological innovation, high-value-added products, green ecology, and spatial agglomeration. The approach to selecting secondary indicators is as follows:

(1) Approach to Selecting Indicators for the Technological Innovation Dimension

Based on modern agricultural development theory and research by Zhou [11] et al. on technological progress in the sugar industry, and in conjunction with requirements for production mechanization and high-yield variety adoption, this study posits that the evaluation of technological innovation capacity in the sugar industry should encompass three aspects: the modernization level of production equipment, the extent of high-yield variety promotion, and the capability for independent variety R&D. However, given the diversity of indicators reflecting technological innovation, it is necessary to select secondary indicators that are representative and capable of effectively measuring the industry's overall technological progress. Consequently, this paper reviews and analyzes key technical indicators with high relevance from policy documents, industry reports, and existing research, and selects core indicators with complete data for each year from 2021 to 2025 as representative indicators. After comprehensive analysis, the comprehensive mechanization rate for sugarcane cultivation, harvesting, and processing; the area under cultivation of virus-free, healthy sugarcane seedlings; the coverage rate of high-quality sugarcane varieties; and the proportion of

domestically bred sugarcane varieties were ultimately selected as secondary indicators to characterize technological innovation. Among these, the comprehensive mechanization rate for sugarcane cultivation and harvesting directly reflects the level of modernization and efficiency in the production process; the area of cultivation using virus-free, healthy sugarcane seedlings and the coverage rate of high-quality sugarcane varieties jointly characterize the extent of adoption of high-quality seed technology; and the proportion of domestically bred sugarcane varieties primarily reflects the industry's core capabilities in germplasm innovation and independent R&D.

(2) Approach to Selecting Indicators for the High-Value Dimension

Within the theoretical framework of the circular economy and industrial chain extension, and with reference to industrial development reports from major sugarcane-producing regions (such as Chongzuo and Laibin), value creation capacity is primarily manifested in three aspects: the high-end orientation of product structure, the comprehensive utilization benefits of by-products, and the stable output of basic industries. To ensure the scientific rigor and quantifiability of the indicators, this study selects typical indicators that directly reflect the depth of industrial chain development and improvements in economic benefits. Therefore, based on the process and outcomes of value creation, this study selects the variety of high-end sugar products, the output value of the sugar industry's circular economy, the production volume of blended sugar, and the production capacity of environmentally friendly bagasse products as secondary indicators for the high-value dimension. The variety of high-end sugar products and the production capacity of environmentally friendly bagasse products respectively characterize the breadth and depth of the industrial chain's extension into high-value-added sectors from the perspectives of end-consumer goods and the high-value utilization of by-products; the output value of the sugar industry's circular economy comprehensively reflects the economic benefits generated by the comprehensive utilization of sugar by-products; and the output of blended sugar, as a foundational output indicator, reflects the stability and scale of the core production processes in the sugar industry.

(3) Approach to Selecting Indicators for the

Green Ecology Dimension

Based on theories of the circular economy and sustainable development, and drawing on Tong's [12] research on innovation and transformation in the sugar industry, the health of an industrial ecosystem is inseparable from improvements in resource efficiency and environmental protection levels during the production process. This dimension aims to examine the sugar industry's capacity to achieve green, low-carbon, and circular practices across the entire "farm-to-factory" supply chain. Therefore, this study focuses on the resource utilization efficiency of major waste streams, selecting the comprehensive utilization rate of sugarcane leaves removed from the field, the utilization rate of bagasse, and the utilization rate of molasses as secondary indicators for the green ecological dimension. The comprehensive utilization rate of sugarcane leaves off-field reflects the level of collection and resource recovery of major crop residue waste in the field; the utilization rates of bagasse and molasses, meanwhile, demonstrate the maturity of achieving efficient, high-value recycling of core processing by-products (bagasse) and liquid by-products (molasses).

(4) Approach to Selecting Indicators for the Spatial Aggregation Dimension

Based on industrial cluster theory and drawing on Cen's [1] research on sugar industry layout, the spatial concentration of an industry is a key factor influencing its resource allocation efficiency, collaborative innovation capacity, and risk-resilience. This dimension primarily examines the scale of sugar industry clusters in geographical space and the stability of the raw material base. Therefore, this study ultimately identifies the industrial output value of sugar industrial parks and the area under sugarcane cultivation as secondary indicators for the spatial agglomeration dimension. The industrial output value of sugar industrial parks directly reflects the agglomeration economic effects and output scale of core industrial parks, serving as a core quantitative indicator for measuring industrial concentration and regional competitiveness; the sugarcane cultivation area, on the other hand, reflects the spatial concentration and scale stability of raw material production at the source, constituting a fundamental condition for ensuring the security and sustainable development of the entire industrial chain. As shown in Table 5-Table 9.

Table 5. Metrics by Dimension

Target Layer	Criteria Layer		Metric Layer	Unit	Polarity
Level of Modernization of the Guangxi Sugar Industry Chain	Value-added upgrading	X1	Output Value of the Sugar Industry Circular Economy	Yuan	+
		X2	Mixed sugar production	tons	+
		X3	Production capacity of environmentally friendly bagasse products	tons	+
	Technological Innovation	X1	Coverage Rate of High-Yield Sugarcane Varieties	%	+
		X2	Proportion of Self-Developed Sugarcane Varieties	%	+
		X3	Area of promotion for virus-free, healthy sugarcane seedlings	mu	+
		X4	Comprehensive mechanization rate for sugarcane cultivation, planting, and harvesting	%	+
	Green and Ecological	X1	Molasses utilization rate	%	+
		X2	Comprehensive Utilization Rate of Sugarcane Leaves	%	+
		X3	Sugarcane bagasse utilization rate	%	+
Spatial Concentration	X1	Sugar Cane Planting Area	mu	+	
	X2	Industrial output value of sugarcane plantations	yuan	+	

Table 6. Upstream Cultivation

Indicators	Description
Comprehensive Mechanization Rate for Sugarcane Cultivation and Harvesting	Reflects the level of modernization in agricultural production, covering the planting, cultivation, and harvesting stages of sugarcane cultivation
Area of Promotion for Virus-Free, Healthy Sugarcane Seedlings	Reflects the extent of high-quality seedling technology promotion and contributes to improving seedling quality during the sugarcane planting stage
Coverage Rate of High-Quality Sugarcane Varieties	Reflects the prevalence of high-quality varieties and demonstrates the adoption of superior varieties during the sugarcane cultivation process
Proportion of self-bred sugarcane varieties	Reflects breeding innovation capabilities and provides a source of high-quality seeds for sugarcane cultivation
Sugar Cane Planting Area	Reflects the stability of raw material supply and serves as the foundational guarantee for sugar production

Table 7. Midstream Processing

Indicators	Description
Varieties of High-End Sugar Products	Number of high-end product varieties, such as refined sugar and organic sugar, reflecting the sugar industry's capacity for product diversification and high-end development
Output Value of the Sugar Industry's Circular Economy	Reflects the economic benefits of comprehensive utilization of sugar by-products, involving the processing and utilization of by-products during sugar processing
Mixed Sugar Output	Reflects the industry's basic production capacity and serves as a core output indicator in the sugar processing sector
Production capacity of environmentally friendly products made from bagasse	Reflects the level of high-value utilization of bagasse and represents the further processing and utilization of sugar processing by-products

Table 8. Downstream Extension

Indicators	Description
Comprehensive Utilization Rate of Sugarcane Leaves	Reflects the efficiency of resource utilization of sugarcane bagasse and can be regarded as the comprehensive utilization of waste in the downstream segment of the sugar industry chain, thereby realizing the extended value of resources
Bagasse Utilization Rate	Reflects the capacity for recycling by-products and further explores the utilization value of bagasse in downstream processes

Molasses Utilization Rate	Reflects the level of efficient utilization of by-products, ensuring that molasses—a processing by-product—is fully utilized in downstream applications
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Table 9. Support and Safeguards

Indicators	Description
Industrial Output Value of Sugar Industrial Parks	Reflects industrial concentration and economic scale; provides centralized support for production, R&D, and ancillary services along the sugar industry chain through the development of industrial parks

3. Measurement Methods and Model Construction

3.1 Methodological Principles and Applicability

Lamrini et al. [6] defined the TOPSIS method as a robust approach for multi-criteria decision-making. Its core principle is to select the alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. The positive ideal solution maximizes benefits and minimizes costs, while the negative ideal solution does the opposite. Liu et al. [5] proposed that the basic principle of the TOPSIS method is to measure the relative distance between the alternatives under evaluation and the positive and negative ideal solutions. By calculating the Euclidean distance between each alternative and both the positive and negative ideal solutions and determining the relative proximity, this serves as the basis for comprehensive evaluation and ranking. Behzadi et al. [2] have widely applied this method across various fields, including supply chain management, manufacturing, business and marketing, health management, and human resource management. This method is particularly suitable for complex systems lacking prior knowledge (such as the multidimensional evaluation of the sugar industry); by quantifying the comprehensive level through "distances from positive and negative ideal solutions," it provides an intuitive ranking of the strengths and weaknesses of various segments in Guangxi's sugar industry. Meanwhile, Bi et al. [3] employed the DTOPSIS method to comprehensively rank eight agronomic traits (such as yield, sugar content, and stress tolerance) of Guangxi sugarcane varieties, identifying the optimal variety, Guitang No. 49. Ou et al. [4] combined the Grey Relational Index with the TOPSIS method to validate the effectiveness of TOPSIS in the synergistic optimization of sugarcane pest and disease resistance and yield, which can be applied to the calculation of

weighting factors for high-end indicators in the sugar industry value chain. This study employs the TOPSIS method to automatically allocate weights based on data dispersion, thereby avoiding subjective bias, making it particularly suitable for evaluating complex systems lacking prior knowledge (such as multidimensional evaluations in the sugar industry). Researchers such as Wang et al. [7] frequently adopt a multi-method integration approach—combining entropy-weighted TOPSIS and VIKOR—in the field of environmental safety assessment to leverage the strengths of different algorithms and enhance the robustness and comparability of evaluation results. Li et al. [13] suggest that future research could draw on the "entropy-weighted AHP" model used in multi-source data fusion evaluations. Building on objective data, this approach would appropriately incorporate domain experts' subjective judgments regarding the importance of dimensions such as "value upgrading" and "green ecological development," thereby forming a hybrid weighting that combines objective and subjective factors. This would make the evaluation results more persuasive and provide greater practical guidance. It should be noted that Zhu et al. [14] found that while the entropy weighting method can avoid subjective bias, its weighting results are prone to distortion when data contain a large number of zero values or when indicators are categorized into hierarchical levels, which may lead to distorted decision-making. Huang [15] pointed out that in multi-criteria decision-making processes, Han et al. [16] noted that TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a classic multi-criteria decision-making method used for the comprehensive evaluation and ranking of a finite set of alternatives. Its core principle is that the optimal alternative should be closest to the positive ideal solution while being farthest from the negative ideal solution. By quantifying the comprehensive level through "distances from positive and negative ideal solutions," the relative strengths and weaknesses

of each stage in Guangxi's sugar industry can be intuitively ranked.

3.2 Data Processing and Weight Determination

This study employed the range-normalization

method to process the raw data and derive weights (see Reference [17] for the formula; see Reference [18] for the formulas for positive and negative indicators). The results are shown in Table 10.

Table 10. Data Weights

Indicator Name	Value	Indicator Name	Value	Indicator Name	Value	Indicator Name	Value
Value Premiumization X1	0.147	Technological Innovation X1	0.194	Green and Ecological Development X1	0	Spatial Agglomeration X1	0.101
High-end Value X2	0.0497	Technological Innovation X2	0.058	Green and Eco-Friendly X2	0.126	Spatial Agglomeration X2	0.070
High-end Value X3	0.065	Technological Innovation X3	0.050	Green and Eco-Friendly X3	0		
		Technological Innovation X4	0.074				

4. Measurement Results

4.1 Analysis of the Modernization Level of Each Dimension

The final dimension scores and composite scores calculated using the formula are as follows; the calculation process will not be repeated here. As shown in Table 11.

Table 12 presents the development achievements and contribution rankings of Guangxi's sugar industry across four modernization dimensions from 2021 to 2025. Overall, the modernization level of Guangxi's sugar industry has achieved a significant leap, with the composite score rising sharply from 0.115 to 0.989—an increase of 0.874—demonstrating robust overall development momentum over the five-year period. The "Value Upgrading" dimension rose from 0.044 to 0.328, an increase of 0.283. The steady improvement in this dimension reflects substantial progress in product value-added, brand building, and industrial chain extension, making it a key driver of industrial upgrading. The dimension of technological innovation rose from 0.073 to 0.365, an increase of 0.292, representing the largest contribution. As a core driving force, technological innovation has

yielded significant results in R&D, commercialization of research outcomes, and digital applications, serving as a key engine for the high-quality development of the sugar industry. The Spatial Aggregation dimension rose from zero to 0.171, an increase of 0.171. With the optimization of industrial layout and the initial emergence of cluster effects, this indicates that regional coordination and intensive development strategies have yielded results and possess the potential for further strengthening. The green and ecological dimension rose from zero to 0.126, an increase of 0.126. Although the sector started relatively late, the green transition has been steadily advancing, reflecting initial efforts in environmental standards and sustainable production. Continued strengthening is still required in the future. Odetta et al. [19] compared industrial symbiosis practices in the UK sugar industry. Their successful case studies indicate that establishing dedicated innovation teams, conducting in-depth strategic market analysis, identifying niche markets, and building robust partnerships with R&D institutions or downstream enterprises based on quality and technology are key to the high-value utilization of by-products and achieving a win-win outcome for both economic and environmental benefits.

Table 11. Analysis of Modernization Levels across Dimensions

Dimension Scores	High-End Value	Technological Innovation	Green and Ecological	Spatial Aggregation
2021	0.042	0.073	0	0
2022	0.069	0.017	0.020	0.030
2023	0.106	0.103	0.039	0.060
2024	0.272	0.316	0.013	0.098
2025	0.328	0.365	0.126	0.171
Overall Score				
2021	0.115			

2022	0.135
2023	0.308
2024	0.699
2025	0.989

Table 12. Growth and Contribution by Dimension, 2021–2025

Dimension	2021 score	2025 score	Growth	Contribution Ranking
Value Upgrading	0.044	0.328	0.283	2
Technology Innovation	0.073	0.365	0.292	1
Green and Ecological	0	0.126	0.126	4
Spatial Agglomeration	0	0.171	0.171	3
Overall	0.115	0.989	0.874	

4.2 Analysis of the Modernization Level of the Guangxi Sugar Industry

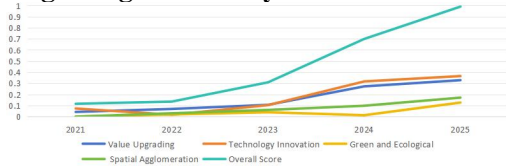


Figure 1. Comparison of the Modernization Level of the Sugar Industry by Year

Figure 1 presents a year-by-year comparison of the modernization level of the sugar industry. Derived from Table 11, this figure visually illustrates the temporal variations and overall trends in the industry’s modernization level across different years.

To accurately depict the development trends of each dimension and the dynamic changes in growth drivers, this study employed a quadratic regression model to fit the scores of the four dimensions. By calculating the first-order derivative of the model, the marginal effect formula was systematically derived (as shown in Table 13-Table 16), which precisely report the annual marginal effect estimates for the four dimensions, quantifying the instantaneous contribution of each dimension to the modernization level of the sugar industry.

Table 13. Marginal Effects of Value-Added Upgrading

Year	Value Upgrading
2021	0.042
2022	0.069
2023	0.106
2024	0.272
2025	0.328

Quadratic Regression Formula:

The trend of value high-end development is fitted

$$y = 0.0134x^2 - 54.042x + 54585 \quad (1)$$

by a quadratic regression model, expressed as:

Where:

y: Value high-end index, the quantitative

indicator reflecting the degree of value high-end development;

x: Year, the calendar year corresponding to the observation or prediction

$R^2 = 0.9499$: Coefficient of determination, representing the goodness of fit of the quadratic regression model, where a value close to 1 indicates a high degree of consistency between the model and observed data.



Figure 2. Marginal Effect of Value Upgrading

Marginal Effect Formula: The marginal effect of value high-end development is derived from the quadratic regression model, expressed as:

$$Y = 0.0268X - 54.042 \quad (2)$$

Where:

Y: Marginal effect of value high-end development, representing the instantaneous rate of change in the value high-end index with respect to the year;

X: Year, the calendar year corresponding to the calculation of the marginal effect.

Table 14. Marginal Effects of Technology Innovation Upgrading

Year	Technology Innovation
2021	0.073
2022	0.017
2023	0.103
2024	0.316
2025	0.365

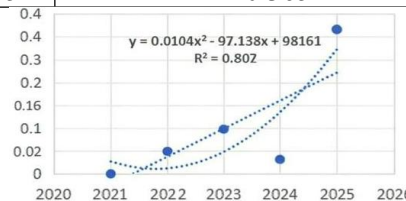


Figure 3. Marginal Effect of Technology Innovation

Quadratic Regression Formula:

The trend of technological innovation upgrading is fitted

$$y = 0.024x^2 - 97.133x + 98161 \quad (3)$$

by a quadratic regression model, expressed as:

Where:

y: Technological innovation upgrading index, the quantitative indicator reflecting the degree of technological innovation upgrading;

x: Year, the calendar year corresponding to the observation or prediction;

$R^2 = 0.8907$: Coefficient of determination, representing the goodness of fit of the quadratic regression model, where a value close to 1 indicates a high degree of consistency between the model and observed data.

Marginal Effect Formula:

The marginal effect of technological innovation upgrading is derived from the quadratic regression model, expressed as:

$$Y = 0.048X - 97.133 \quad (4)$$

Where:

Y: Marginal effect of technological innovation upgrading, representing the instantaneous rate of change in the technological innovation upgrading index with respect to the year;

X: Year, the calendar year corresponding to the calculation of the marginal effect.

Table 15. Marginal Effects of Green Ecological Development

Year	Green and Ecological
2021	0
2022	0.020
2023	0.039
2024	0.013
2025	0.126

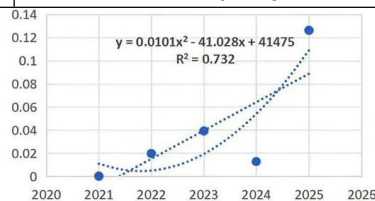


Figure 4. Marginal Effects of Green and Ecological

Quadratic Regression Formula:

The trend of green ecological upgrading is fitted by a quadratic regression model, expressed as:

$$y = 0.0101x^2 - 41.028x + 41475 \quad (5)$$

Where:

y: Green ecological upgrading index, the quantitative indicator reflecting the degree of green ecological upgrading;

x: Year, the calendar year corresponding to the observation or prediction;

$R^2 = 0.732$: Coefficient of determination, representing the goodness of fit of the quadratic regression model, where a value close to 1 indicates a high degree of consistency between the model and observed data.

Marginal Effect Formula:

The marginal effect of green ecological upgrading is derived from the quadratic regression model, expressed as:

$$Y = 0.0202X - 41.028 \quad (6)$$

Where:

Y: Marginal effect of green ecological upgrading, representing the instantaneous rate of change in the green ecological upgrading index with respect to the year;

X: Year, the calendar year corresponding to the calculation of the marginal effect.

Table 16. Marginal Effects of Spatial Agglomeration

Year	Spatial Agglomeration
2021	0
2022	0.030
2023	0.060
2024	0.098
2025	0.171

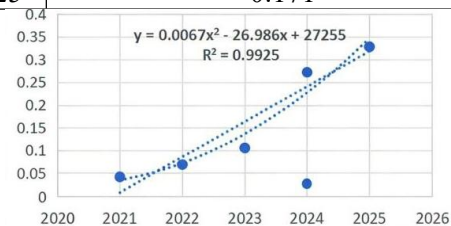


Figure 5. Marginal Effects of Spatial Agglomeration

Quadratic Regression Formula:

The trend of spatial agglomeration upgrading is fitted by a quadratic regression model, expressed as:

$$y = 0.0067x^2 - 26.986x + 27255 \quad (7)$$

Where:

y: Spatial agglomeration upgrading index, the quantitative indicator reflecting the degree of spatial agglomeration upgrading;

x: Year, the calendar year corresponding to the observation or prediction;

$R^2 = 0.9925$: Coefficient of determination, representing the goodness of fit of the quadratic regression model, where a value close to 1 indicates a high degree of consistency between the model and observed data.

Marginal Effect Formula:

The marginal effect of spatial agglomeration upgrading is derived from the quadratic regression model, expressed as:

$$Y = 0.0134X - 26.986 = -26.986 \quad (8)$$

Where:

Y: Marginal effect of spatial agglomeration upgrading, representing the instantaneous rate of change in the spatial agglomeration upgrading index with respect to the year;

X: Year, the calendar year corresponding to the calculation of the marginal effect.

Analysis of the dimension scores and marginal effects in Figure 1-Figure 5 reveals that the level of modernization in Guangxi's sugar industry exhibited an accelerating growth trend from 2021 to 2025, a trend primarily driven by the strong pull of the technological innovation dimension. The results indicate that the marginal effect values for each dimension continued to increase over the years, further corroborating the overall trend of accelerated growth. The driving role of the technological innovation dimension is notably reflected in three aspects: First, it makes the largest absolute contribution, with a value increase of approximately 0.294 over the five-year period, significantly higher than that of value-added upgrading (0.287), spatial agglomeration (0.170), and green ecological development (0.126), making it the core source of incremental growth; Second, it leads in final magnitude, with the dimension's value reaching 0.364 in 2025, accounting for nearly 40% of the total and providing the strongest current support for the level of modernization; Third, growth stability is notable. Although annual values exhibit short-term fluctuations (0.073 → 0.016 → 0.103 → 0.316 → 0.364), the overall upward trend remains consistent without abrupt fluctuations, ensuring the sustainability of its driving force. From a structural perspective, Guangxi's sugar industry has transitioned from extensive expansion reliant on traditional factor inputs to a modern, quality- and efficiency-oriented industry driven by technological innovation and full-chain optimization. Among these, the technological innovation dimension has emerged as a key new growth driver, while the green and ecological dimension still has room for improvement. The growth characteristics corresponding to the marginal effects of each dimension are as follows: high-value-added growth exhibits explosive growth ($Y = 0.0268X - 54.042$), technological innovation growth shows rapid linear growth ($Y = 0.048X - 97.133$), green and ecological development exhibits moderate growth ($Y = 0.0101X - 41.028$), and spatial

agglomeration shows slight growth ($Y = 0.0067X - 26.986$).

Based on the slopes of the marginal effect formula above, it is evident that growth in all four dimensions has not slowed. The technological innovation dimension exhibits strong growth momentum and has become the "core engine," serving as the leading force driving development. In contrast, the growth momentum of the green ecology and spatial agglomeration dimensions has shown signs of fatigue and lacks sustained momentum, requiring continued strengthening. The next step should focus on enhancing the technological value-added of the industrial chain while paying attention to the coordinated development of regional industrial layout. Based on the "Sugar Industry Development Action Plan (2025–2027)" officially issued by the Department of Industry and Information Technology of the Guangxi Zhuang Autonomous Region in October 2025, and in accordance with the spirit of the plan, the specific content can be summarized into the following two core directions.

Enhancing the technological value-added of the industrial chain involves focusing on technological breakthroughs and intelligent upgrades to drive the transformation and upgrading of the sugarcane industry toward high-value sectors such as pharmaceutical-grade sugar and functional sugars, thereby achieving value enhancement across the entire chain.

Coordinating regional industrial layout, specifically by implementing the "Two Cores, One Pole, and Two Zones" spatial planning framework to establish a new industrial landscape characterized by complementary functions and coordinated development among manufacturing cores, innovation hubs, and radiation zones.

5. Conclusions and Recommendations

5.1 Conclusions

Based on the dimension scores for the modernization of Guangxi's sugar industry chain from 2021 to 2025, the two dimensions of technological innovation and high-end value creation demonstrate core developmental advantages. By 2025, their scores rose to 0.3647 and 0.3277, respectively—a more than fourfold increase from 0.0731 and 0.0422 in 2021—making them the key engines driving the

upgrading of the industry chain; In contrast, the dimensions of "Green and Ecological Development" and "Spatial Aggregation" have consistently remained in the low-score range, with 2025 scores of only 0.1263 and 0.1707, respectively—significantly lagging behind the top two advantageous dimensions. In particular, the shortcoming of failing to achieve high-value resource utilization for waste materials such as bagasse has constrained the sugar industry's green transition process, becoming a key bottleneck in the advancement of industrial chain modernization.

(1) Technological innovation creates a virtuous cycle of "technological breakthroughs leading to efficiency improvements." As noted earlier, technological innovation serves as the "core source of incremental growth" driving overall expansion, a conclusion supported by the data: The five-year growth rate (0.2916) for the technological innovation dimension exceeds that of all other dimensions, and its score has consistently surpassed 0.3 from 2024 to 2025. The slope of the marginal effect formula ($Y = 0.048X - 97.133$) is the steepest, indicating that technological investments—such as the promotion of intelligent sugar production equipment and process improvements—have achieved rapid increases in production efficiency, serving as the "core engine" for the modernization of the industrial chain.

(2) Value upgrading exhibits an explosive trend of "product upgrading and value-added growth." The score for the value upgrading dimension in 2025 increased 6.7-fold compared to 2021, and the marginal effect formula ($Y = 0.0268X - 54.042$) reflects characteristics of explosive growth. Which aligns with the aforementioned practice of "promoting the transformation and upgrading of sugarcane sugar toward high-value sectors such as pharmaceutical-grade sugar and functional sugars." This demonstrates that optimizing the structure of end products has become a key driver for enhancing the value of the industrial chain, effectively reducing the market risks associated with the single product of traditional white sugar.

(3) "Sluggish growth" in the green and ecological dimension, with environmental transformation lagging behind. The five-year increment in the green and ecological dimension was only 0.1263, and the slope of the marginal effect formula ($Y = 0.0101X - 41.028$) was the

smallest. Furthermore, the 2024 score (0.0126) saw a significant decline compared to 2023 (0.0391). This reflects insufficient investment by Guangxi's sugar industry in areas such as clean production and waste recycling (e.g., deep processing of bagasse and molasses). Research also indicates that the comprehensive utilization rate of waste materials like bagasse still has room for improvement; most have not yet achieved high-value resource utilization, which constrains the industry's green transition. This is inconsistent with the requirements for "high-quality development" of the industrial chain, and environmental costs have gradually become a hidden constraint on industrial expansion.

(4) "Insufficient synergy" in spatial agglomeration, resulting in low layout efficiency. Although the score for the spatial agglomeration dimension has increased year by year, it remains below 0.2 in 2025, and the annual growth rate has been flat (with annual increments from 2021 to 2025 all below 0.05). The marginal effect formula ($Y = 0.0067X - 26.986$) reflects this pattern of weak growth. Currently, the sugar industry in Guangxi suffers from "dispersed layout and misallocation of resources." The significant spatial distance between upstream and downstream enterprises leads to high logistics costs, and the lack of a unified data-sharing platform across regions makes it difficult to improve coordination efficiency.

5.2 Recommendations

Building on the two key strengths of technological innovation and high-value-added development, we should deepen technological breakthroughs and industrial chain upgrades to strengthen the sector's leading role. Simultaneously, by addressing critical shortcomings in green ecological development and spatial agglomeration, we should optimize resource allocation and spatial planning to precisely target bottlenecks and achieve breakthroughs, thereby enhancing the quality and efficiency of development.

(1) Technological Innovation Dimension: Leveraging existing technological strengths, focus on "key technology breakthroughs + commercialization of research outcomes." "On one hand, collaborate with universities and research institutions to establish a "Sugar Industry Technology Innovation Program," prioritizing breakthroughs in core technologies

such as oligosaccharide extraction and zero-discharge of sugar production wastewater, and increasing the proportion of R&D funding from the current level to over 3%. On the other hand, promote the commercialization of technological achievements, aiming for an 80% adoption rate of intelligent sugar production equipment in key sugar mills by 2027, further amplifying the advantage of "rapid linear growth" and ensuring that the score for this dimension remains stable at 0.4 or above.

(2) High-Value Dimension: Sustain the explosive growth momentum and deepen the "product diversification + branding" strategy. In line with the guidance of the "Sugar Industry Development Action Plan," accelerate the construction of production lines for pharmaceutical-grade sugar and functional sugars, aiming to increase the proportion of high-value-added products to over 40% by 2027; simultaneously, cultivate regional public brands and enhance product premium pricing through the "Guangxi Sugar" geographical indication certification, driving the score for the high-value dimension toward 0.5.

(3) Green and Ecological Dimension: Implement a dual-drive strategy of "environmental compliance requirements + policy incentives." First, mandate that sugar mills with an annual production capacity of 100,000 tons or more be equipped with waste treatment facilities; achieve a comprehensive utilization rate of 95% for bagasse and a deep processing rate of 85% for molasses by 2026, raising the score for the green and ecological dimension to 0.2. Second, establish a "green transition subsidy" to provide tax breaks for enterprises undertaking clean production upgrades; use policy incentives to stimulate investment in environmental protection and prevent the score from declining again.

(4) Spatial Aggregation Dimension: Implement the "Two Cores, One Pole, and Two Zones" plan to build a "spatial synergy + information interconnection" system. Focusing on the two major core production areas of Nanning and Chongzuo, we will build sugar industry parks to guide the clustering of upstream and downstream enterprises. By 2027, we aim to reduce logistics costs within these core production areas by 15%. Concurrently, we will establish the "Guangxi Sugar Industry Big Data Platform" to integrate data across the entire chain—from cultivation to processing and sales—thereby breaking down "information

silos." This will drive the score for the spatial agglomeration dimension to exceed 0.25 and strengthen the momentum for sustained growth.

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