A Study on the Pathways for Promoting Agricultural Modernization in the Hainan Free Trade Port Through New-Quality Productive Forces

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ABSTRACT The construction of the Hainan Free Trade Port has created an environment for agricultural modernization by opening up the system, unfettering the flow of factors and upgrading industry. To reveal the paths of how new-quality productive forces promote the modernization of agriculture in Hainan, this paper builds an evaluation index system on production efficiency, technological innovation, digital empowerment, green transformation, industrial integration, and open circulation. For measurement and analysis, an obstacle degree model and entropy weighting model which is comprehensive evaluation model were used. The results indicate that, during 2018–2024, the comprehensive agricultural modernization index of Hainan has increased from 0.392 to 0.588, where digital empowerment, technological innovation, and open circulation have contributed 53.0% to the index increase, and the sub-indices such as cold chain coverage, processing and conversion, commercialization of scientific and technological results, and quality traceability are the main limitations of the comprehensive agricultural modernization. The conclusions suggest that the institutional setting of the Free Trade Port should take advantage of the synergy of technology platforms, digital government, cold chain processing and brand certification to foster the transformation of Hainan's tropical specialty agriculture into high quality and modern agriculture.

INDEX TERMS Hainan Free Trade Port; new-quality productive forces; agricultural modernization; digital empowerment; obstacle factors

I. INTRODUCTION

The techniques of machine learning, deep learning, remote sensing, and intelligent sensing are becoming more and more important in agricultural production, management and decision making. The study of precision agriculture has changed from single image recognition to multi-source data fusion, unmanned aerial survey, automatic irrigation and intelligent management based on scenario. Radočaj et al. used bibliometric methods to trace the research evolution of machine learning and deep learning in precision agriculture remote sensing, noting that intelligent remote sensing analysis has become a crucial technological foundation for agricultural monitoring [1]; Gafaar et al. combined machine learning with drone technology for automated irrigation and crop management, enhancing the real-time control capabilities of agricultural production processes [2]; Morchid et al. further analyzed sustainable irrigation management from the perspectives of the Internet of Things (IoT) and machine learning, demonstrating that the coupling between data collection, status recognition, and intelligent decision-making is strengthening [3]. In terms of crop identification and disease monitoring, deep learning models have been widely used for UAV-based leaf disease detection [4], and the integration of remote sensing with autonomous robots has also enhanced the automation of field operations [5]. At the same time, the systematic integration of smart sensing, the Internet of Things, and artificial intelligence in agriculture continues to deepen [6]; UAV-based vegetation indices and machine learning methods can be used for weed identification in vineyards [7], and the application of machine learning in soil health and crop improvement also provides algorithmic support for sustainable agricultural development [8]. Current research is mainly focused on particular technologies or production scenarios, and there is still a lack of analysis of the mechanisms by which the new quality of production reorganizes the elements of agriculture and promotes the modernization of agriculture within the framework of the Free Trade Port.

Based on the "institutional environment—elements of new-quality productive forces—industrial scenarios—modernization performance" analytical framework, this study uses the entropy weighting method, comprehensive evaluation model and obstacle degree model to measure the modernization level of Hainan's agriculture, the factor contribution structure and the main obstacle factors from 2018 to 2024. Compared to the current studies of smart agriculture, the innovation of this study is the integration of digital empowerment, technological innovation, open circulation, green transformation and industrial integration into a comprehensive evaluation system, as well as the linkage to Hainan's unique scenarios, including the South Breeding Seed Industry, tropical fruits, winter melons and vegetables, and marine fisheries. The study identified that digital empowerment, technological innovation and processing and transformation and cold-chain coverage, processing and conversion, and research outcomes implementation, the key constraints. The achievements have yielded quantifiable results and given a strong boost to the Hainan Free Trade Port's work to promote the high-quality modernization of its unique tropical agricultural industry with new-quality productive forces.

II. THEORETICAL FOUNDATION

The key to the modernisation of agriculture with new-quality productive forces is to reform the agricultural production system by means of technology, data elements, green technologies and organisational transformation. It is not only to substitute human labor with intelligent equipment, but to also improve the efficiency of the whole agricultural value chain by using the methods like high-quality seed breeding, precision cultivation, intelligent identification of pests and diseases and process of processing and transformation, quality traceability, etc. [9]. This effect is enhanced by the institutional environment of the Hainan Free Trade Port. Efficient and concentrated allocation of agricultural factors towards the use of agricultural science and technology, introduction of germplasm resources, distribution of agricultural products, and clustering of agribusinesses can be promoted through institutional arrangements like the facilitation of trade, cross-border capital flows, talent recruitment and data flow in a secure and orderly manner, which can reduce the costs for agricultural science and technology cooperation, introduction of germplasm resources, distribution of agricultural products, and clustering of agribusinesses. Meanwhile, the transformation of new quality productive forces is based on Hainan's tropical specialty industries. The industries like South Breeding Seed Industry, tropical fruits, winter melons and vegetables, marine fisheries, rubber and coconut, and Wenchang chicken not only become platforms for scientific and technological innovations to be applied to, but also link together the brand development, cold chain logistics, green certification and expansion to the international market. They play important roles in Hainan's agricultural modernization, which is aimed at building a unique competitive advantage.

III. RESEARCH METHODOLOGY

A. RESEARCH FRAMEWORK DESIGN

The research framework is based on the technological chain of "institutional environment—factor inputs—industrial transformation—modernization performance" [10]. The research object is the agriculture system of Hainan Province, the time is from 2018 to 2024, and the spatial scope covers cities and counties with distinct agricultural functions, such as Haikou , Sanya , Danzhou , Wenchang , Qionghai , Chengmai , Ledong , Lingshui and Dongfang. The front end of the framework involves variables of institutional environment for the Free Trade Port, such as trade facilitation, openness and cooperation, data flow, financial support and the clustering of entities related to agriculture; the middle part of the framework involves the variables of new-quality productive forces, including technological innovation, digital empowerment, green and low-carbon development, talent development, and organizational development; the back end of the framework involves the variables of agricultural modernization performance, including production efficiency, extension of the industrial chain, green development, open circulation and increased farmers' income.

The specific process includes:

First, to set up the evaluation indicators of agricultural modernization and supporting indicators of new-quality productive forces, and determine the attributes of the indicators;

Second, standardization of the data of different units and calculation of weights by the entropy weighting method;

Third, calculation of overall index of agricultural modernization in Hainan and the contribution of new-quality productive forces;

Fourth, use the obstacle degree model to determine the key restricting factors and return to specific scenarios for matching and correspondence, such as the South Breeding Seed Industry, tropical fruits, winter melons and vegetables, and marine aquaculture [11].

B. CONSTRUCTION OF THE INDICATOR SYSTEM

The indicator system is a three-layer system, which includes the objective layer, the criterion layer and the indicator layer. The objective layer is the agricultural modernization level of Hainan, and the criterion layer, which is based on the value chain of how new-quality productive forces promote agricultural modernization, consists of seven aspects: production efficiency, technological innovation, digital empowerment, green transformation, industrial integration, open circulation and farmers' income [12]. The indicator layer doesn't simply use the traditional indicators in agriculture so as to measure the agricultural yield but pays attention to those indicators reflecting the institutional conditions of Hainan Free Trade Port and the context of tropical agriculture. They are the output value of the South Breeding Seed Industry, the conversion rate of agricultural products for processing, the proportion of cold chain coverage, the proportion of agricultural product quality traceability, the number of export-oriented agribusinesses, the number of Agricultural Internet of Things (AIoT) application sites, and the number of green food certifications.

Three principles were followed when selecting the indicators:

First, measurability, meaning that indicators must be obtainable from statistical yearbooks and publicly available information from agricultural and rural affairs departments, commerce departments, and municipal/county authorities;

Second, interpretability, meaning that indicators must be correlated with specific elements of new-quality productive forces;

Third, they must be actionable, meaning that the results of the indicators should point to specific industrial pathways, such as the export capacity for tropical fruits and aquatic products, the output value of the South Breeding Seed Industry, and traceability coverage, which is related to the alignment of quality standards in the open environment of the Free Trade Port. The indicator attributes are shown as positive or negative indicator, for example, the intensity of fertilizer and pesticide application and agricultural carbon emission intensity are shown as negative indicator, and other indicators related to efficiency, innovation, openness and benefits are shown as positive indicators [13]. The indicator system is shown in Table 1.

C. NOTES ON DATA SOURCES

Data collection involves the use of annual provincial level data, cross sectional city/county data as well as industry specific data. The annual data at the provincial level are mainly used to analyze the trends of Hainan's agricultural modernization from 2018 to 2024; cross-sectional data of cities and counties are used for comparison; and industry-level data are used to verify the use of new-quality productive forces, such as the South Breeding Seed Industry, tropical fruits, winter melons and vegetables, marine fishery industry, rubber and coconut industry [14]. Data sources are the Hainan Statistical Yearbook, the Hainan Province Statistical Bulletin of National Economy and Social Development, the Hainan Province Department of Agriculture and Rural Affairs, the Hainan Province Department of Commerce, Haikou Customs and publicly available information from municipal and county governments.

All the data was pre-processed using the same method. Values were interpolated for continuous indicators that had no more than 2 missing years and indicators with > 20% missing data were not included in the comprehensive assessment. Monetary indicators were brought to comparable prices, ratio indicators to their percentage value and scale indicators to per capita, per unit of area, or per unit of output value. To prevent extreme fluctuations between individual years to affect the weight allocation, outliers were removed at the 5% level [15]. The data structure is shown in Table 2.

D. COMPREHENSIVE EVALUATION MODEL SETUP

Due to differences in units among the agricultural modernization indicators, the raw data are first dimensionless [16]. Let x_{ij} denote the raw value of the i th study subject for the j th indicator, x'_{ij} denote the standardized value, and q_j denote the indicator's directional variable. When $q_j = 1$, the indicator is positive; when $q_j = -1$, the indicator is negative. The standardization process is as follows:

$$x'_{ij} = \begin{cases} \dfrac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}, & q_j = 1, \\ \dfrac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}, & q_j = -1 \end{cases} \tag{1}$$

The Entropy Weight Method (EWM) is employed to reduce the effect of subjective weighting in the weight determination phase [17]. In this method, the weighting is established by the degree of dispersion of indicators; the greater the difference between the indicators, the greater their capacity to differentiate the degree of modernisation of agriculture and the greater the respective weights [18]. The calculation process is as follows:

$$\begin{aligned} p_{ij} &= \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}}, \\ e_j &= -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij}, \\ w_j &= \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \end{aligned} \tag{2}$$

where p_{ij} represents the proportion of the j th indicator in the i th study subject, e_j represents information entropy, w_j represents the indicator weight, n represents the number of study subjects, and m represents the number of indicators. If $p_{ij} = 0$, the calculation is adjusted to the minimum value of $10^{-6}$to prevent logarithmic operations from failing [19].

The comprehensive evaluation index is obtained by weighted summation:

$$S_i = \sum_{j=1}^{m} w_j x'_{ij} \tag{3}$$

where S_i represents the comprehensive agricultural modernization index for the i th year or city/county. A higher index value indicates a higher level of agricultural modernization [20]. In the application of this model, we first calculate the whole province's annual index to determine the trend of development between 2018 and 2024; then calculate the cross sectional indices of the cities and counties, and compare the differences between the Tropical Specialty Agricultural Zone, the Urban Agricultural Zone, the Sea Fishing Zone, and the South Breeding Science and Technology Cluster.

TABLE I. Evaluation Indicator System for Agricultural Modernization in Hainan

Criteria Level	Core Indicators	Indicator Attribute
Production Efficiency	Agricultural labor productivity, agricultural output value per unit of cultivated land, proportion of protected-culture agriculture area	Positive
Technological Innovation	Intensity of agricultural R&D investment, number of agricultural patents, output value of the South Breeding Seed Industry	Positive
Digital Empowerment	Number of agricultural IoT application sites, quality traceability coverage rate, and rural e-commerce transaction volume	Positive
Green Transition	Number of Green Food certifications, area under water-saving irrigation, intensity of fertilizer and pesticide use	Forward/Reverse
Industrial Integration	Agricultural product processing conversion rate, number of leading enterprises, number of branded agricultural products	Positive
Open Distribution	Agricultural product export value, cold chain coverage rate, number of export-oriented agribusinesses	Positive
Farmers' Income	Per capita disposable income of rural residents, proportion of business income, number of farming households supported by new types of business entities	Positive

TABLE II. Data Sources and Processing Methods

Data Type	Time Range	Spatial Level	Primary Source	Processing Methods
Agricultural Development Data	2018–2024	Hainan Province, cities, and counties	Statistical Yearbooks, Statistical Bulletins	Adjusted for uniform units and comparable prices
Science and Technology Innovation Data	2018–2024	Provincial, Industrial Parks	Agriculture and Rural Affairs Departments, Science and Technology Departments	Missing Value Interpolation, Normalization of Patent Counts
Digital Agriculture Data	2018–2024	Cities, counties, and industrial parks	Publicly available government data, industry reports	Verification and normalization of location data
Open and Circulating Data	2018–2024	Provincial and port levels	Data from commerce departments and customs	Unified metrics for export value and circulation scale
Industry-Specific Data	Last Three Years	Key Industries	Industrial Park Data and Publicly Available Corporate Information	Scenario classification, indicator mapping

E. METHOD FOR IDENTIFYING OBSTACLE FACTORS

On the basis of the overall evaluation, the identification of the barrier factors can be used to determine which indicators are restricting the progress of agricultural modernization in Hainan [21]. Since the composite index can only reflect the level of development but cannot directly reveal the sources of shortcomings, an obstacle degree model is constructed based on standardized values and indicator weights. Let O_{ij} represent the obstacle degree of the th indicator j for the th study subject i , calculated as follows:

$$O_{ij} = \frac{w_j(1 - x'_{ij})}{\sum_{j=1}^{m} w_j(1 - x'_{ij})} \times 100\% \tag{4}$$

where w_j represents the weight of the j th indicator, x'_{ij} represents the standardized value of that indicator, and $1 - x'_{ij}$ represents the degree to which the indicator deviates from the ideal state. The higher level of barriers means that the indicator is not only more important but also has serious real deficiencies, which puts more pressure on the modernisation of agriculture [22].

The application of the model consists of three steps: indicator level, standard level, and scenario level. According to the obstacle degree, the index layer extracts the top 10 obstacle factors, and decides whether the key constraints are the cold chain coverage, the processing transformation, the transformation project, the coverage of quality tracing, and the application site of the Internet of Things in agriculture. In the South Breeding Seed Industry, the emphasis is placed on commercialization of science and technology and open cooperation on germplasm resources; in the case of tropical fruits, the emphasis is on cold-chain preservation, classification, processing, and brand certification; in the case of winter melons and vegetables, the emphasis is on green pest control and traceability; in marine fisheries, the emphasis is on intelligent aquaculture, cold chain processing and compliance with export standards.

In order to prevent variations in one year from affecting the order of barriers, barrier factors shall be determined using an average over the last three years; for those with large yearly fluctuations, the CV shall be calculated at the same time to determine if the barrier constitutes a permanent deficiency [23]. Eventually, this establishes a "high-weight — low-level-strong constraint" selection rule, which allows the subsequent pathway design to move from generic recommendations to targeted improvements.

IV. RESULTS ANALYSIS

A. RESULTS OF MEASURING HAINAN'S AGRICULTURAL MODERNIZATION LEVEL

Based on the aforementioned comprehensive evaluation model, the comprehensive index of agricultural modernization in Hainan has increased from 0.392 to 0.588 from 2018 to 2024, with an average annual growth rate of about 6.99%, but there has been no uniform growth rate. The index grew relatively slowly from 2018 (0.392) to 2020 (0.447), mainly because of low scores for facility agriculture, processing and value adding activities, and digital applications; and as shown in Figure 1, the index experienced rapid growth since 2021, when it stood at 0.491, to 2024 (0.588), particularly in the open distribution, quality traceability, and rural e-commerce indicators. The production efficiency index increased from 0.418 to 0.553, which is less than the increase in the digital empowerment and open distribution indexes. This shows that, more than expansion of output, the growth in agricultural modernisation has been due to the development of distribution system and the connectivity of data.

Spatial analysis shows a trend that nodes with high scores are located in coastal regions, and that nodes in traditional agriculture areas in the central and western regions score relatively weaker. As indicated in Figure 2, Sanya, Haikou and Wenchang have high values (with indices of 0.643, 0.618 and 0.597 respectively), while Ledong, Lingshui and Dongfang have low values (with indices of below 0.530). The high value areas were mostly due to the concentration of southern breeding technology, port facilities, cold chain facilities, and the lack of smart agricultural facilities, whereas the low value areas were due to the lack of processing chains, brand certification, and due to coverage of smart agricultural facilities.

B. ANALYSIS OF THE CONTRIBUTION OF NEW-QUALITY PRODUCTIVE FORCES

The criterion-level score was combined with the entropy-weighted score to get the contribution structure of the elements of new-quality productive forces to the overall index of agricultural modernization. Digital empowerment had the largest contribution at 18.7%, followed by scientific and technological innovation (17.9%) and open circulation (16.4%) as can be seen in Figure 3. In total, these three factors contributed 53.0% of the total and were the main factors that drive agricultural modernization in Hainan. Digital empowerment is particularly high in the domains of production to sales linkage, price responsiveness and visibility in the distribution process, and is mainly driven by quality traceability coverage, scale of rural e-commerce transactions and number of agricultural IoT application sites. The contribution of technological innovation focuses on output value of the South Breeding Seed Industry, agricultural patents and the transfer of technology, but the degree of technological innovation in ordinary farm enterprises is not as high as that in agricultural parks and leading enterprises.

The green transformation, industrial integration, production efficiency and the farmers' income have contributed 13.9%, 14.8%, 10.5% and 7.8% respectively. The radar chart outline shows that the elements of Hainan's new-quality productive forces have not developed evenly, but show a structure with obvious outward expansion of the digital, technological and openness dimensions, and some contraction of the income and production dimensions. From these results, it can be seen that new-quality productive forces have been focused on entering the R&D of the seed industry, establishing traceability of the distribution channel, realizing cross-regional sales and transforming platform operation, while the transmission to farmers' income conversion and deep processing of the product and wide use of equipment in production sites are still lagging behind.

C. MAJOR OBSTACLES TO AGRICULTURAL MODERNIZATION

Based on the results of the calculation of obstacle degree, the key problems of Hainan's agricultural modernization are mainly to extend the industrial chain, improve distribution system, and promote the commercialization of scientific and technological achievements. As shown in Figure 4, the obstacle degree for cold chain coverage is 12.6%, followed by the agricultural product processing conversion rate (11.4%), the number of projects for commercializing scientific and technological achievements (9.8%), the agricultural IoT application sites (9.2%) and the quality traceability coverage rate (8.5%). The sum of top five obstacle degrees is 51.5% to create a clear Pareto concentration effect. This means that the constraining factors lie not so much at the start and end of technology transformation within the industrial chain, but are rather found in the middle range.

The obstacle index of open circulation is 22.1%, industrial integration is 20.4% and digital empowerment is 18.7%, which is higher than that of production efficiency and farmer income as shown in Figure 5. Cold chain coverage is the most critical, as the tropical fruits, aquatic products and winter melons and vegetables have high demand for refrigerated transport; transport radius, logistics cost and loss control are critical due to the geographical location of the island. The high barrier index for processing conversion rates shows that certain agricultural products are still being sold at their primary form, as fresh products, and not standardized, packaged and/or branded products. The barrier index of technology transfer projects is higher than the quantity of agricultural patent, and it indicates that the innovation resources in Hainan are not limited, but the innovation transfer chain from innovation achievements to enterprises (cooperatives and farmers) is still not perfect.

D. APPLICATION RESULTS IN KEY INDUSTRIAL SCENARIOS

In order to test the explanatory power of the indicator measurement results at the industry level, the five factors were mapped into the main agricultural scenarios of Hainan, namely, science and technology innovation, digital empowerment, open circulation, green transition, and industry integration. The index is obtained by weighting the standardized scores of indicators associated with each scenario, with emphasis on monitoring the actual integration of new quality productivity at various stages in the industry chain. The results are shown in Table 3.

The results in Table 3 show that the use of new quality productive forces in Hainan's agriculture shows scenario-specific differentiation. The South Breeding Seed Industry is technology-oriented, while the Tropical Fruit and Sea Fishing is distributed; the Green Standard for the Winter Melons

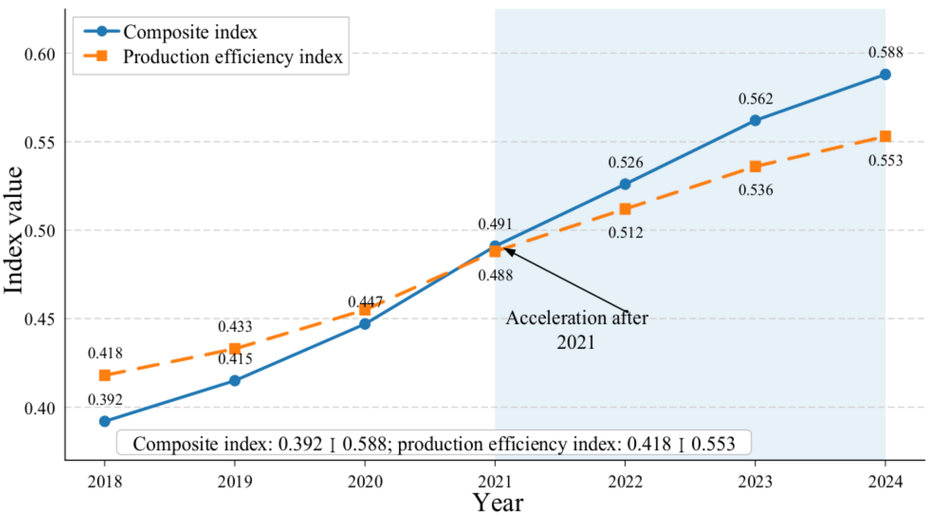

Fig. 1. Changes in Hainan's Comprehensive Agricultural Modernization Index

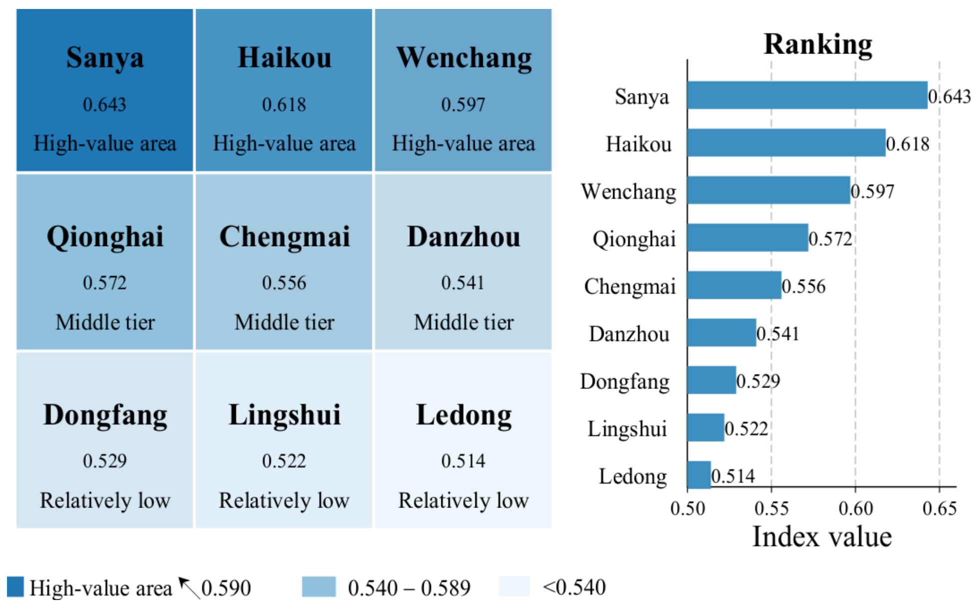

Fig. 2. Spatial Heat Map of Agricultural Modernization Levels by City and County

TABLE III. Application Results of New-Quality Productive Forces in Key Industrial Scenarios

Industrial Scenario	Technological Innovation	Digital Empowerment	Green Transition	Industrial Convergence	Open Circulation	Key Bottlenecks
South Breeding Seed Industry	0.78	0.63	0.56	0.54	0.61	Insufficient technology transfer and corporate adoption
Tropical fruits	0.59	0.66	0.62	0.52	0.69	Insufficient capacity for value-added processing and cold chain logistics
Winter vegetables	0.55	0.61	0.67	0.49	0.64	Traceability and green pest control entail higher costs
Marine Fisheries	0.62	0.58	0.6	0.63	0.71	Insufficient Coordination Between Smart Aquaculture and Export Standards
Rubber and Coconuts	0.51	0.49	0.64	0.57	0.52	Insufficient Product Development Maturity and Brand Premium

and Vegetables; and the Rubber and Coconut Sectors are based on the restructuring of the industry. These differences suggest that pathway design must be based on production.

E. DRIVING EFFECTS UNDER THE FREE TRADE PORT INSTITUTIONAL ENVIRONMENT

The Free Trade Port's institutional environment has played an important role in the modernization of agriculture by means of open circulation, technology synergy, digital gov-

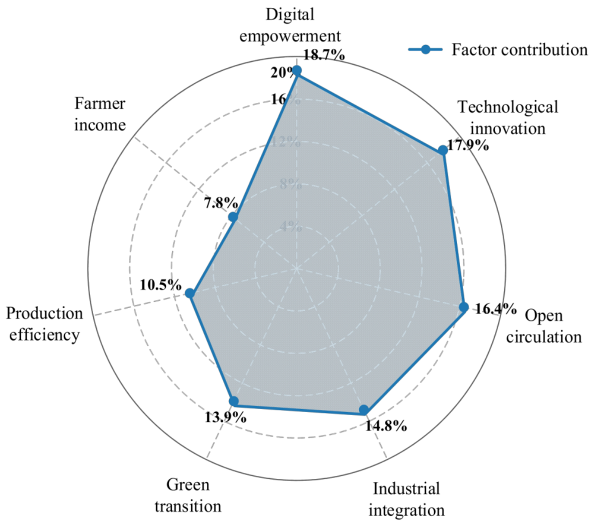

Fig. 3. Radar Chart Analysis of the Contribution of New-Quality Productive Forces

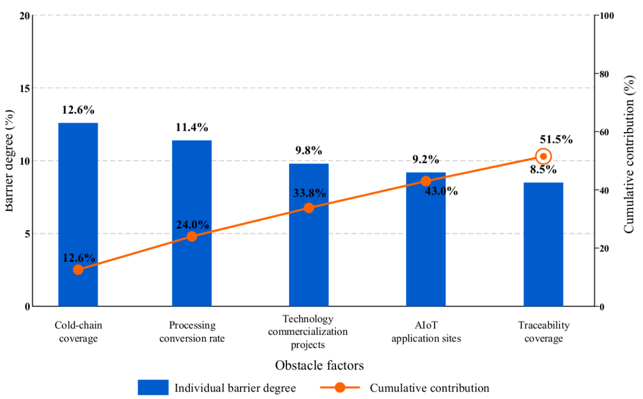

Fig. 4. Pareto Analysis of Major Obstacles to Agricultural Modernization

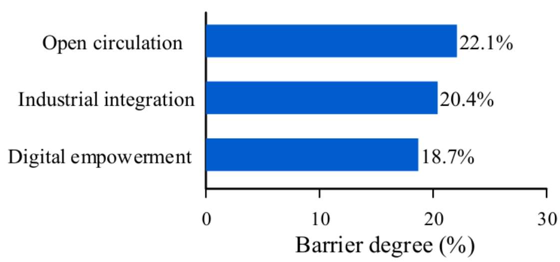

Fig. 5. Aggregated Analysis of Obstacle Levels by Criterion Layer

ernance and industry integration. As illustrated in Figure 6, the volume of trade facilitation flows into free circulation amounts to 22.1 per cent, which is mainly attributable to the export of agricultural products, off-island distribution, and port services; the proportion of technological cooperation that flows to technology innovation is 23.4%, mainly corresponding to the South Breeding Seed Industry, the agricultural research and development platforms, and the clustering of agricultural enterprises; the weight of the orderly data flows towards digital empowerment is 18.6%, mainly corresponding to quality traceability, rural electronic commerce, and production monitoring; and the weight of financial resources and entities clustering towards industry integration is 16.9%.

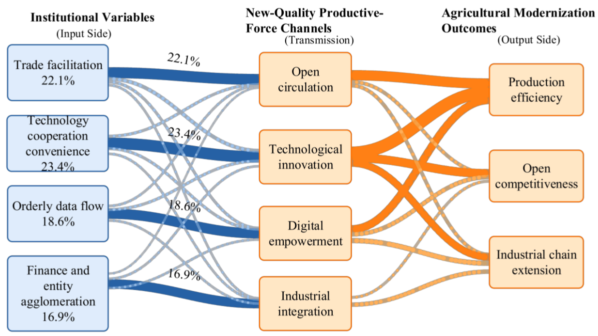

Fig. 6. Pathway Diagram of How the Free Trade Port's Institutional Environment Drives Agricultural Modernization

The Sankey chart shows that the system variables of the Free Trade Port are not directly reflected in the growth of the agricultural modernization index, but rather in the technological, financial, digital, and industrial organizational phases. The digital governance process is not as outstanding as science and technology cooperation, but it is closely related to quality traceability, brand recognition and cross-region sales.

V. CONCLUSION

According to the measurement results, the condition of factor contribution, the obstacles identified, and the validation of industry scenarios, the key to Hainan Free Trade Port's agricultural modernization and new quality productive force is not to rely on single-technology investment but to achieve the complementary transformation of science and technology capabilities, data capabilities, distribution capabilities, and industrial organization capabilities, under the premise of institutional opening.

1) Hainan's agricultural modernization is characterized by new-quality productive forces as the impetus of its modernization process. The overall index of agricultural modernization has consistently increased from 2018 to 2024, showing that Hainan's agriculture has been transforming from relying on traditional resources to a joint promotion model with technology, digitalization and openness. Especially, digital empowerment, technological innovation and open distribution accounted for 53.0%, that is, the expansion of the scale of agricultural production is not the main factor for agricultural modernization, but the improvement of quality traceability, rural e-commerce, agricultural Internet of Things (IoT), South Breeding Seed Industry and the ability of cross-regional distribution. The result is consistent with the fact that the development of Hainan's tropical specialty agriculture, and it shows that the new-quality productive forces in the agricultural industry are mainly manifested as "information connectivity, technology transfer and market responsiveness".

2) Institutional settings of the Free Trade Port are highly amplifying agricultural modernization. From the Sankey diagram, it can be observed that facilitation of scientific and technological cooperation and trade facilitation are the most powerful institutional inputs going into technological innovation and open circulation, respectively. It means that the open policies of Hainan Free Trade Port are not the direct farmers' performance, but through the reduction of the costs of scientific and technological cooperation, germplasm resource introduction, agricultural product circulation, and clustering of agricultural-related entities to promote the utilization of agricultural factors and improve the efficiency of agricultural factor allocation. Different from agricultural modernization in other regions, the uniqueness of Hainan is that institutional openness can link the agricultural production end with the international market, the agricultural seed industry platform, the cold chain logistics system and the standard certification system, creating an export-oriented path of agricultural modernization based on the platform and scenario.

3) When it comes to the concentration of obstacle factors, it shows the lack of the middle and later stages of the transformation chain of new-quality productive forces. Top five obstacle factors: Cold-chain coverage, Agricultural product processing conversion rate, Number of technology transfer projects, Agricultural IoT application sites and Quality traceability coverage occupy 51.5% in total degree of obstacles. It means that there is no lack of foundation industries or specialty products in the agricultural modernization of Hainan, but there are problems of low utilization rate of technological achievement by enterprises, cooperatives and farmers; low transformation rate of fresh production into processed, branded and standardized products; and the unevenness of digital infrastructure in the production side. In the future, the design of the path should no longer be vague, but should focus on specific aspects, such as the cold chain, processing, traceability, certification, and pilot-scale promotion, to revitalize agriculture through science and technology.

4) There is a need for a differentiated approach which has been demonstrated in key industrial scenarios. The "South Breeding" seed industry scenario has a high match index, and the seed industry should be the main force to build technological innovation and open cooperation; the cold chain, traceability and green standards are more important for the development of tropical fruits, winter melons and vegetables, and marine fisheries, and the deficiencies of distribution and processing should be given priority; rubber, coconuts, and Wenchang chickens will need more in the way of value-added through brand certification, deep processing, and industrial integration. Hence, the process of agricultural modernization in Hainan should be changed from a unique and all-over approach to a scenario-based approach, thereby constructing a tiered advancing system of agriculture with technology as the focus in the south, seed breeding as the focus in traditional agriculture, equipment as the focus in marine fisheries, distribution as the focus in tropical fruits and vegetables, and certification as the focus in specialty brands.

The research results reveal that the modernization degree of agriculture in Hainan province has been continuously increasing from 2018 to 2024. Digital empowerment, technological innovation and open distribution channels were the main driving forces of the new-quality productive forces. Technological cooperation, trade facilitation, data exchange and concentration of market players all contributed to the enhancement of the efficiency of allocating agricultural factors in the Free Trade Port institutional setting. The focus on the obstacles are in the mid-to-back-end stages of cold-chain coverage, processing and conversion, scientific and technical achievement implementation, Internet-of-things (IoT) applications, and quality traceability. This means that in order to realize the agricultural modernization in Hainan, it is not enough to strengthen the production capacity, but also to enhance the ability to extend the production chain and transform the production into value. Some indicators have to rely on an annual statistics and publicly-available disaggregated data at the city/county level, and more effort is required to enhance the support of micro-level industry samples, based on limitations in data disclosure standards and the completeness of city/county-level disaggregated data. In the future, enterprise, cooperative and farmer level data could be additionally integrated. This would enable key industries including the South Breeding Seed Industry, tropical fruits and marine fisheries to come up with more accurate roadmap on changing the existing productive forces into new quality productive forces based on scenario-based assessments.

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