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Research article

The evaluation and optimization of the agricultural sustainable development based on a data-driven approach: A case from Northern Anhui

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A R T I C L E I N F O

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A B S T R A C T

The sustainable advancement of agriculture stands as the fundamental cornerstone of sustainable human progress. This study introduces a data-centric methodological framework founded upon the holistic delineation of measurement, feature assessment, and pathway enhancement for agricultural sustainability. Initially, the research articulates a comprehensive evaluative schema incorporating sub-dimensions encompassing agricultural production, agricultural economics, the agricultural resource environment, and rural society, grounded in sustainable development theory. Subsequently, it devises a methodological apparatus for assessing and enhancing sustainable development capabilities, employing entropy evaluation methods and exploratory spatial data analysis techniques. Employing North Anhui as a case study, the viability of this approach is substantiated. The empirical inquiry conducted within this article operationalizes comprehensive evaluation and explores pathways for optimizing agricultural sustainability, focusing on the period spanning 2011 to 2020 in Northern Anhui. The findings affirm the feasibility and efficacy of the data-driven approach. Recommendations derived from the empirical exploration of agricultural sustainability pathways at the local level offer valuable insights for governmental authorities and policymakers. This research endeavor could be extrapolated to other geographical locales worldwide, fostering innovative strides in the sustainable development of regional agriculture.

1. Introduction

Amidst the escalating global energy and environmental crises, sustainable development has emerged as a paramount concept in global developmental discourse [1]. Within this context, sustainable agricultural development assumes primacy as the foundational cornerstone and guarantor of global economic and social sustainability [2]. Nonetheless, the pervasive paradigm of extensive agricultural development has profoundly impeded the sustainable evolution of agriculture [3]. Presently, agricultural advancement confronts multifaceted challenges, encompassing ecological and environmental issues such as water scarcity, soil pollution, and declining soil fertility, alongside constraints imposed by labor shortages and the absence of intrinsic impetus for agricultural progress [4].

According to the Global Food Crisis Report of 2022 released by the Food and Agriculture Organization of the United Nations (FAO),

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51 nations, comprising approximately 193 million individuals, grappled with acute food crises or a worsening of food insecurity, marking a surge of 40 million people since 2020. The World Commission on Environment and Development (WCED) underscores that sustainable agricultural development entails augmenting agricultural productivity and net income within the framework of extant agricultural production, catering to the escalating demands of a burgeoning global population, stewarding and conserving natural resources, and fostering a virtuous ecological and environmental cycle [5]. Thus, sustainable agricultural development emerges as an indispensable imperative for agricultural production and progress [6], bearing profound significance for global agricultural advancement.

2. Literature reviews

As a pivotal pillar of human sustainable development, the sustainable evolution of agriculture has perennially captivated the scholarly attention of researchers worldwide [7]. Recently, scholars have approached the sustainable development of agriculture from diverse vantage points and perspectives.

Primarily, numerous scholars are pioneering innovations and conducting research endeavors aimed at developing novel crop varieties and refining planting technologies, thereby envisaging a tangible contribution to the sustainable progression of local agriculture. For instance, Md. Anwar Hossen has elucidated the intricacies surrounding the challenges and potentialities inherent in rice transplanting technology, contending that the sustainable adoption of mechanical rice transplanting techniques can engender a paradigm shift towards rice sustainability [8]. Additionally, investigations into the ramifications of novel microbial inoculation methods on agriculture and their environmental implications vis-à-vis sugar cane cultivation and production have been undertaken [9,10]. Furthermore, certain researchers have delved into the ramifications of crop planting patterns [11] and planting conditions [12] on agricultural sustainability, encapsulating these inquiries within the ambit of agricultural technological advancement.

Conversely, the trajectory of agricultural sustainable development is intricately intertwined with a plethora of factors, prompting scholarly exploration from various quarters [13]. For instance, investigations have delved into the influence of agricultural reform policies [14,15] and environmental regulations [16] on the sustainable evolution of agriculture. Additionally, the ramifications of climate change [17] and endeavors to enhance the efficiency of agricultural energy utilization have garnered attention. Notably, Vida Dabkienė underscores the significance of agricultural energy efficiency as a pivotal determinant of agricultural sustainable development, exemplified by his examination of energy utilization efficacy in Lithuanian agriculture [18,19].

Furthermore, researchers have scrutinized the impacts of diverse factors on agricultural sustainability, encompassing practices such as crop rotation [20], financial regulations [21], sustainable irrigation methods [22], transportation logistics, and the integration of internet-based information technology services [23]. Meanwhile, Naser Valizadeh and Dariush Hayati [24] have conducted surveys among wheat growers in Fars province, Iran, to delineate the principal determinants of agricultural sustainability, subsequently devising and validating an agricultural sustainability index through empirical measurement and testing.

In recent years, within the backdrop of the global dual-carbon imperative, scholars have increasingly turned their attention beyond the traditional domains of food security and economic viability within agriculture to scrutinize the environmental implications of agricultural production [25,26]. Presently, the imperative of fostering a harmonious coexistence between agriculture and the environment has emerged as an inexorable prerequisite for the sustainable progression of agriculture. Scholars have embarked on diverse inquiries to elucidate this nexus.

Some researchers have devised the Agricultural Carbon Footprint Index (AFI) to probe the environmental repercussions of various agricultural practices [19]. Mo Li and Qiang Fu have investigated the allocation of agricultural water and land resources, factoring in economic and social constraints [27]. Others have delved into issues such as the sustainable utilization of agricultural land within economic ecosystems [28], the interplay between agricultural ecology and environmental degradation [29], the differential impacts of varied agricultural irrigation methods on energy conservation and emissions reduction [30], and the influence of rice deep plowing on carbon emissions from agricultural land [31].

In terms of assessing the level of agricultural sustainability, Kaveri Ashok et al. utilized the SAFARI model to scrutinize India's agricultural landscape, proposing strategies to achieve an adequate and sustainable food supply while evaluating the corresponding impacts on energy conservation and greenhouse gas emission reduction [32]. Moreover, extant literature predominantly focuses on specific index measurements, such as the Agricultural Sustainable Conservation and Innovation Index [33], the measurement of agricultural ecological efficiency levels [34], and composite indices of agriculture [35]. However, consensus remains elusive regarding the selection of indicators to comprehensively ascertain agricultural sustainability [36].

Throughout extant research, a predominant focus has been on innovative and organic agricultural practices [37]. However, within the limited literature addressing the measurement of agricultural sustainability, the emphasis has largely been on isolated index measurements, such as innovation indices or system coordination indices [38]. Yet, the comprehensive and precise assessment of agricultural sustainability serves as the linchpin for evaluating the level of sustainable agricultural development and constitutes the foundational pillar for its enhancement.Moreover, agricultural development is intricately linked to a myriad of factors, notably agricultural pollution, environmental conservation, and rural development. Consequently, there exists an urgent imperative to establish a composite evaluation framework that comprehensively and objectively measures agricultural sustainability. Furthermore, addressing the challenges of agricultural sustainability necessitates the effective management of external factors influencing its trajectory. Despite the diverse array of factors impacting agricultural sustainability, the choice of evaluation methods varies. Common methodologies include the Grey Correlation Analysis Model [39], the Improved Entropy Coefficient-TOPSIS Method [40], the Fairness Evaluation Model [41], the Intuitionistic Fuzzy-TOPSIS Method [42], and the Multiple Attribute Comprehensive Evaluation Method with Incomplete Information [43]. While each of these methods possesses distinct strengths within their respective domains, they predominantly represent isolated approaches rather than comprising an integrated methodology within a holistic evaluation system, thus lacking a cohesive theoretical framework.

In this context, the present paper advances a data-driven methodology [44] to gauge and assess the level of agricultural sustainable development from a multidimensional standpoint, subsequently delving into the underlying influencing factors and mechanisms through the establishment of an econometric model. Subsequently, empirical investigation is conducted, utilizing Northern Anhui as a case study. Drawing from the empirical findings, recommendations are formulated for enhancing agricultural sustainability in this region. The outcomes of this research endeavor hold significant implications, serving as a reference for elucidating the regional agricultural sustainable development level and identifying extant challenges. Additionally, the recommendations derived from this study offer valuable insights for relevant policymakers and decision-makers tasked with fostering sustainable agricultural development.

The article structure is delineated as follows: Section 3 expounds on the methodology and method flow employed in the study. Subsequently, Section 4 presents the empirical investigation of the method system across the six cities of North Anhui. Section 5 engages in a comprehensive discussion of the findings. Finally, Section 6 encapsulates the conclusions drawn from the study and outlines avenues for future research.

3. Materials and methods

In this section, we present the data-driven methodological flow adopted in this article. It comprehensively outlines the entire process encompassing data collection, data processing, the framework of the data model, and the evaluation of conclusions.

3.1. Method flow

This paper introduces a methodological system for measuring, evaluating, and optimizing agricultural sustainability. The methodological flow of the research is illustrated in Fig. 1.

3.2. Data collection

Agricultural sustainable development constitutes a subsystem within the broader framework of sustainable development theory. Hence, guided by the characteristics and imperatives of sustainable development strategies and drawing upon prior research, we have

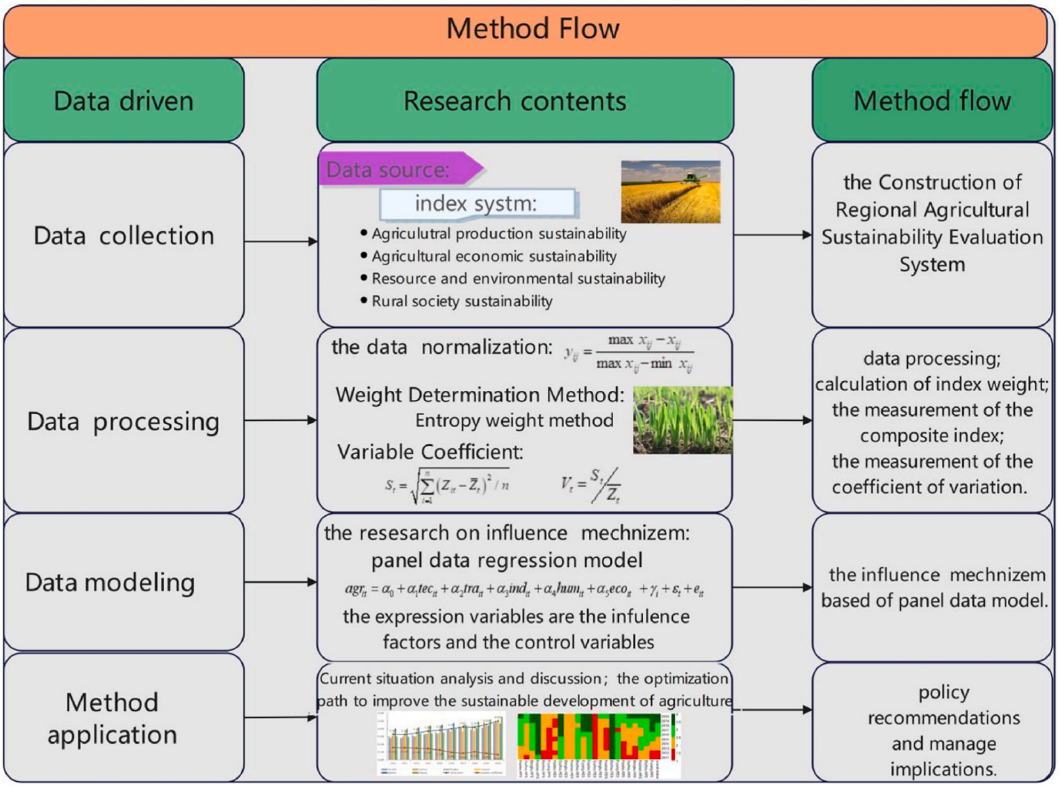

Fig. 1. The method flow chart.

structured an indicator system comprising four dimensions to assess the level of agricultural sustainable development. These dimensions encompass the sustainability of agricultural production, agricultural economics, the agricultural ecological environment, and rural society sustainability (as delineated in Table 1). The index system is hierarchically organized into three layers: the target layer, criterion layer, and index layer. The target layer serves as the overarching reflection of the agricultural sustainable development level across all cities in Northern Anhui. The criterion layer represents the subsystems within agricultural sustainability, while the index layer comprises 21 indicators. Specifically, the agricultural production subsystem encompasses 6 indicators, the agricultural economics subsystem comprises 5 indicators, the resource and environment sustainable development subsystem includes 4 indices, and the agricultural and rural society subsystem comprises 6 indices.

3.3. Data processing

The data utilized in this study were sourced from the "Anhui Provincial Statistical Yearbook" and the "Anhui Provincial Agricultural Statistical Yearbook." In cases where data was missing, it was imputed through recursive methods or mean supplementation. Prior to data analysis, the original data underwent dimensionless processing to ensure uniformity and comparability across variables.

3.3.1. Weight determination and index synthesis

The entropy method serves as an objective assignment technique, deducing weights by quantifying the dispersion level of each index. Fundamentally, this method operates on the principle that indicators exhibiting greater dispersion wield a proportionately higher influence on the composite index, while those with lesser dispersion exert diminished influence. The rationale behind selecting this method lies in its capacity to mitigate subjective biases, thereby ensuring the objectivity of results. The specific data processing protocol unfolds as follows.

Initially, data standardization is undertaken. Employing the range method, we normalize the raw data, ensuring values fall within the range of zero to one. Distinct standardized formulas are employed for positive and negative indices, as outlined below:

Table 1
Data collection of Evaluation to Agricultural Sustainable Development.

Dimension (criterion layer)	Index (Indicator layer)	Index Calculation(unit)	Indicator attributes	Weight
Sustainable of Agricultural Production (0.32)	Degree of Agricultural Mechanization	Total mechanical power/cultivated land area(kW/hm^2)	+	0.0327
	Degree of agricultural Electrification	Rural electricity consumption/rural population(km.h/person)	+	0.0933
	Agricultural labor Productivity	Value-added value of agriculture, forestry, animal husbandry and fishery/rural population(yuan/per capita)	+	0.0489
	per unit area grain output	Grain output/cultivated land area (ton/ha)	+	0.0483
	Effective irrigation rate	Effective irrigation area/cultivated land area (%)	+	0.0225
	Agricultural scale Degree	Crop sown area/rural population (ha/per capita)	+	0.0745
Sustainable of Agricultural Economic (0.2972)	Rural population size	Rural population/total population (%)	+	0.0338
	Growth level of the Agricultural economy	The Growth rate of the added value of agriculture, forestry, animal husbandry and fishery (%)	+	0.0318
	The primary industry compares its productivity	The proportion of output value of the primary industry in GDP/ proportion of employed personnel in primary industry in the total employed population(/)	+	0.0755
	Rural Engel coefficient	Food and clothing expenditure/Consumption Expenditure of rural residents (%)	-	0.0401
	Agricultural economic development potential	The total output value of agriculture, forestry, animal husbandry and fishery service industry accounts for the total output value of agriculture, forestry, animal husbandry and fishery (%)	+	0.1161
Sustainable of Resources and Environment (0.151)	consumption resources	agricultural film usage/sown area(kg/ha)	-	0.0558
	agricultural and rural environmental pollution	agriculture diesel volume/sown area(kg/ha)	-	0.0274
		the amount of fertilizer applied/sown area(kg/ha)	-	0.0129
		pesticide application/sown area(kg/ha)	-	0.0553
Sustainable of rural society (0.2313)	Farmers' income level	Per capita net income of countryside(yuan/per capita)	+	0.0448
	Urban-rural income gap	The disposable income of urban residents/the net income of the countryside (/)	-	0.0242
	Strength of Urban-rural dual structure	(The proportion of GDP of the secondary and tertiary industries/The proportion of people employed in the secondary and tertiary industries)/(The proportion of GDP in the primary industry/The proportion of employment personnel in the primary industry) (/)	-	0.0456
	Rural consumption level	Retail sales of consumer goods in the countryside/retail sales of social consumer goods worldwide)(/)	+	0.0404
	Financial support for agriculture	per capita Local government expenditure on agriculture, forestry and water conservancy in the countryside(yuan/per capita)	+	0.0503
	Medical and health level	number of village clinics per thousand people in the countryside(/per thousand per capita)	+	0.0261

If the index is positive, the normalization method is shown in Equation (1).

$$y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

If the index is negative, the normalization method is shown in Equation (2).

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

Where x_{ij} is the primary data, y_{ij} represent the normalized data. And i represents the label of the individual, and j is the index label. Moreover, the positive and the negative indices have given in Table 1. And the positive index is the index that the larger the value, the higher level of agricultural and rural sustainable development, while the negative index is the index that the larger the value, the lower the level of agricultural and rural sustainable development. The definition of the positive and negative index is based on the connotation setting of sustainable development.

Moreover, to preempt the occurrence of null data, which could potentially disrupt subsequent data processing post-normalization, we adopt a precautionary measure. Specifically, we incorporate a nominal value of 0.01 to the normalized data set.Thus, we set $y'_{ij} = y_{ij} + 0.01$.

This paper employs the entropy weight method to determine the weights of agricultural sustainable development indices, ensuring objective weighting without loss of information. The underlying principle of the entropy method is to ascertain index weights based on the information content of each index. Indices exhibiting greater entropy values signify a higher degree of variation and consequently merit a larger weight. The procedural steps are outlined as follows:

Firstly, the entropy values were determined using equation (3).

$$E_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} y'_{ij} \cdot \ln\left(y'_{ij}\right) \tag{3}$$

where n represents the size of the observations.

And then we calculate the indicator weight using equation (4) based on E_j.

$$d_j = 1 - E_j \tag{4}$$

Thirdly, the weight were normalized according to formula (5).

$$w_j = d_j \Big/ \sum d_j \tag{5}$$

And then we calculate the comprehensive index of agriculture sustainable development using equation (6).

$$Z_i = \sum_{j=1} y'_{ij} \cdot w_j \tag{6}$$

Finally, to ensure the comparability of results, we normalize the comprehensive index values to fall within a standardized range of 0–1.

3.3.2. *The method of variable coefficient*

The variable coefficient serves as a conventional metric for quantifying the relative disparity of an eigenvalue across different years within the entire study area. A higher value indicates greater relative differences in the specific eigenvalue, while a lower value signifies diminished disparity. This paper utilizes the variable coefficient to gauge the relative differences in the agricultural sustainable development index among cities in Northern Anhui, aiming to discern the overarching evolutionary trends in agricultural sustainable development across the region. The calculation formula are shown in (7)and (8).

$$S_t = \sqrt{\sum_{i=1}^{n} (Z_{it} - \overline{Z}_t)^2 \Big/ n} \tag{7}$$

$$V_t = S_t / \overline{Z_t} \tag{8}$$

Here, Z_{it} denotes the agricultural sustainable development index value of area i in t year, and $\overline{Z}_t$ represents the average value of the index of each city in Northern Anhui in the year of t, S_t is the variance of the index value and V_t is the variable coefficient of the sustainability in agricultural of Northern Anhui.

3.4. *Driving mechanism analysis of agricultural sustainable development*

In light of the preceding analysis, discernible spatial variations in the degree of sustainable development are evident across disparate regions. Consequently, there exists a compelling imperative to delve into and scrutinize the underlying mechanisms driving agricultural sustainable development, thereby illuminating potential avenues for optimizing its trajectory. This study endeavors to elucidate the mechanism and advancement pathways of agricultural sustainability through the lens of a panel data model. The ensuing analysis is structured around the following model (9) construction.

$$agr_{it} = \alpha_0 + \alpha_1 tec_{it} + \alpha_2 tra_{it} + \alpha_3 ind_{it} + \alpha_4 hum_{it} + \alpha_5 eco_{it} + \gamma_i + \varepsilon_t + e_{it} \tag{9}$$

In the model, the variable agr_{it} refers to the agricultural sustainable development index measured above, α_0 is intercept term, and $\alpha_1 \cdots \alpha_5$ are the regression coefficients of each influencing factor; γ_i represents the fixed effect of the city numbered as i, ε_t is the fixed effect at the t moment; e_{it} is the random error term of the model.

Within the model, variable selection is conducted in accordance with the influence factors identified in theoretical analyses [45, 46]. Table 2 delineates the implications of the indices, the rationale behind variable selection, and the causal mechanisms through which each index impacts agricultural sustainable development.

4. Case study

This study employs the aforementioned methodology to investigate the agricultural sustainable development capacity and its determinants in North Anhui. Subsequently, we put forth policy recommendations aimed at enhancing agricultural sustainability in the region based on the research findings. Additionally, we synthesize managerial insights for the regional government gleaned from our analysis.

4.1. Background

Anhui Province, spanning from 114°54′E to 119°37′E and 29°41′N to 34°38′N, is situated in eastern China. North Anhui, located within the northern region of the province, encompasses a total land area of 39,200 km^2. It comprises the cities of Huaibei, Suzhou, Bozhou, Bengbu, Huainan, and Fuyang, as depicted in Fig. 2. Renowned as a significant grain-production base, North Anhui contributes notably to the province's agricultural output. In 2022, Anhui's total grain production ranked fourth in China, with North Anhui alone contributing 55.03 % to this total. However, despite its agricultural productivity, North Anhui lags behind economically. The per capita disposable income in rural areas stood at ¥16,839.83 in 2021, below both the provincial average of ¥18,368 and the national average of ¥18,931.

Conducting assessments of agricultural sustainability, synthesizing experiences from agricultural advantages, and identifying agricultural deficiencies in Northern Anhui are pivotal endeavors for effectively addressing the region's sustainable agricultural development. These studies collectively contribute to enhancing the overall sustainability of Anhui Province.

Table 2
Variable Selection and Interpretation in the model.

Index code	Index Implication	Variable selection	Influence Mechanism
tec_{it}	the capacity of scientific and technological innovation	Three kinds of patent authorization per capita	Scientific and technological innovation is an important driving force of the modern economic system, it helps improve the efficiency of agricultural production and develop innovative agriculture
tra_{it}	the transportation infrastructure	the density of the road network	The improvement of transportation infrastructure, especially the rural road facilities helps to reduce transaction costs among the market entities. So that the operating subject can optimize the allocation of resources in a larger space range, and it can promote inclusive rural growth and foster momentum for agricultural and rural development
ind_{it}	the upgrading of an industrial structure	the proportion of total output of secondary and tertiary industries in GDP	the upgrading of the industrial structure can improve the form of the rural industry and the advanced industrial structure can promote the adjustment of agricultural industrial structure in a certain extent, it makes the industrial structure of agricultural transform from low to advanced, optimize the drivers of rural development , and further stimulates the development potential of agricultural economy.
hum_{it}	human capital	the share of rural labor force population	The labor force population is the basis of the development of the agriculture, and the backbone of agricultural production and rural development. Theoretically speaking, human capital about agriculture has an important positive effect on the sustainability of agriculture at present stage
eco_{it}	the economic strength of the region	per capita GDP in comparable prices	The sustainable development of agriculture has a big deal with the policy support of the government, and the economic strength can provide financial support for the policy of benefiting farmers, that is, the stronger the economic strength, the greater the government's financial support for agriculture may be and the more it can promote the sustainable development level of agriculture

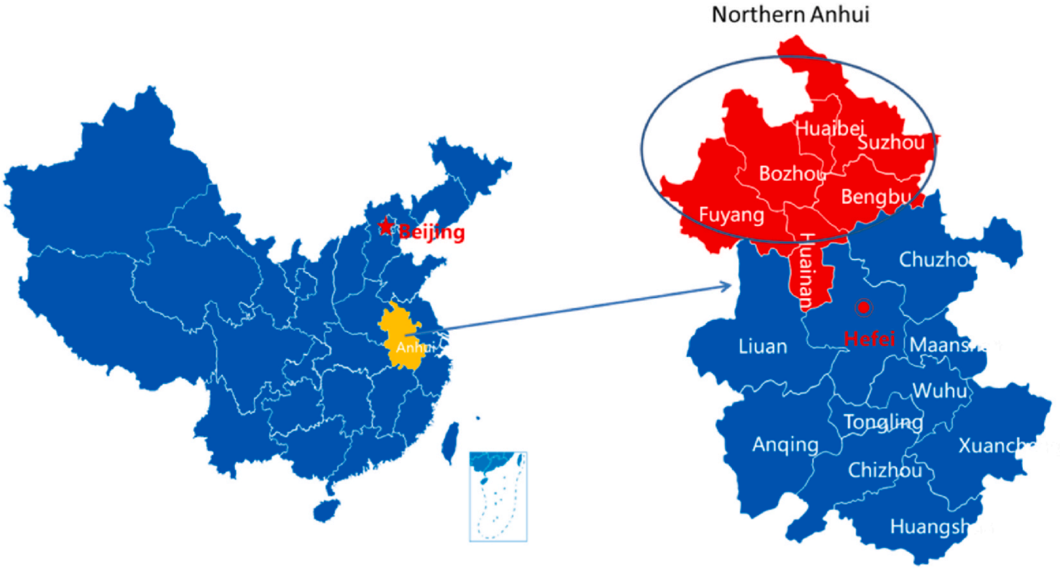

Fig. 2. The study area of northern Anhui.

4.2. Results

4.2.1. Weight determination and assignment

The index weights within the Agricultural Sustainable Development Index system are determined using the entropy method, with the outcomes detailed in Table 1. Notably, the weights assigned to each subsystem within the system layer are as follows: agricultural production system (0.320), agricultural economic system (0.2962), agricultural and rural society system (0.2313), and resources and environment system (0.1510). It is discernible that the agricultural production and agricultural economic systems collectively hold a substantial weight of approximately 30 %, underscoring their pivotal roles as focal points within the framework of agricultural sustainable development.

Examining the specific index weights, variations emerge among the indicators. The indicator with the highest weight is agricultural development potential, accounting for 0.1161, whereas indicators such as the amount of chemical fertilizer applied in agriculture and the income gap between urban and rural areas carry the lowest weight of 0.0371. This discrepancy highlights a gap of 0.079 between them. However, it is worth noting that the disparity in weights among the evaluation indicators is generally minimal, suggesting a balanced consideration across the spectrum of factors assessed.

4.2.2. Results of regional characteristics of development level in agricultural sustainable

Table 3 and Fig. 3 depict the sustainable development levels and trends of each city in Northern Anhui from 2011 to 2020. Over the past decade, the average annual agricultural sustainability index for Northern Anhui stood at 0.395. Analysis of temporal patterns reveals a consistent upward trajectory in the agricultural sustainable development levels across all cities in Northern Anhui during the survey period, with 2020 marking the peak level. Over the ten-year span, the growth rate reached an impressive 52.4 %, with Fuyang experiencing the highest growth rate at 86.6 % and Bozhou registering the lowest at 15.5 %. Notably, there was a setback in the agricultural sustainability index in 2018, followed by a rapid recovery. This occurrence can be attributed to significant declines in composite indices observed in Huaibei, Huainan, and Bozhou in 2018.The status of agricultural sustainability in 2020 varies across cities, with Suzhou, Huainan, and Fuyang surpassing the average level of agricultural sustainable development. Conversely, Huaibei and Bozhou exhibit the lowest levels, with Bozhou notably demonstrating a decline compared to its status a decade ago. This

Table 3
the Evaluation of Agricultural Sustainable Development: the years 2011–2020.

city	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	mean	ranking
Huaibei	0.299	0.281	0.316	0.328	0.356	0.385	0.429	0.386	0.414	0.469	0.366	5
Suzhou	0.280	0.288	0.301	0.332	0.339	0.396	0.416	0.441	0.481	0.508	0.378	4
Bengbu	0.309	0.309	0.304	0.339	0.350	0.365	0.362	0.371	0.435	0.482	0.363	6
Huainan	0.377	0.375	0.398	0.435	0.428	0.383	0.462	0.421	0.437	0.513	0.423	2
BoZhou	0.407	0.401	0.422	0.440	0.452	0.475	0.450	0.409	0.442	0.470	0.437	1
Fuyang	0.298	0.296	0.339	0.341	0.353	0.398	0.429	0.492	0.517	0.556	0.402	3
mean	0.328	0.325	0.347	0.369	0.380	0.401	0.425	0.420	0.454	0.500	0.395	
Variable coefficient	0.156	0.155	0.148	0.144	0.126	0.096	0.083	0.103	0.083	0.067	0.116	

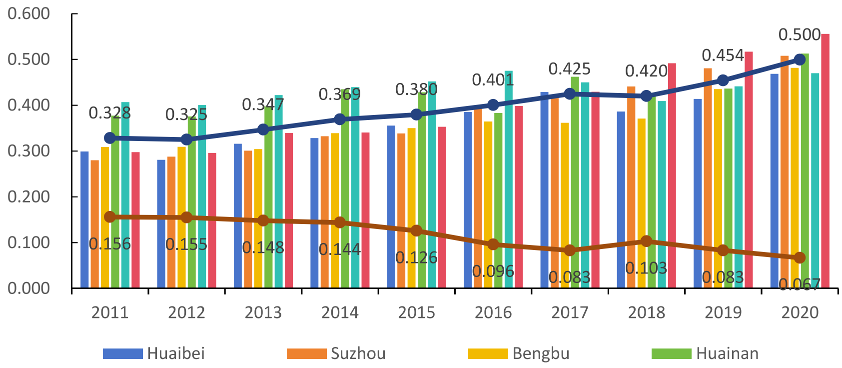

Fig. 3. The Trend of the Agricultural Sustainable Development index in the recent decade.

observation suggests that Bozhou's agricultural sustainable development performance has not been as robust as that of other cities in Northern Anhui over the past decade. Furthermore, the mean value of the variable coefficient stands at 0.116, indicative of a continuous decline in the variation trend.

From a regional standpoint, the cities with average agricultural sustainable development indices ranked from highest to lowest over the past decade are Bozhou (0.437), Huainan (0.423), Fuyang (0.402), Suzhou (0.378), Huaibei (0.366), and Bengbu (0.363). Notably, Huaibei experienced a significant decline in agricultural sustainable development in 2018, followed by a gradual recovery. This downturn can be attributed to the adverse impacts of a flood disaster, which heavily affected agriculture and rural areas, consequently influencing the agricultural production and economy of Huaibei. In the initial years, Bengbu and Suzhou exhibited lower scores; however, with robust guidance from local governments and policy interventions, both cities have witnessed substantial improvements in agricultural sustainable development since 2019. Bozhou, renowned as an agricultural hub, boasts the highest composite score for agricultural sustainable development. Its prominence in the cultivation of Chinese herbal medicine contributes significantly to its high level of agricultural sustainability.

4.2.3. The sub-dimensional characteristics of agricultural sustainable development

Figs. 4–7 illustrate the trends of agricultural sustainability in terms of production, economics, resources and environment, and rural society for each city in Northern Anhui from 2011 to 2020. These figures provide insights not only into the average levels and individual variations but also consider the temporal dimension, thereby capturing the overall trends and individual disparities across the specified domains.

Fig. 4 presents the results of agricultural production sustainability, revealing a consistent upward trend in the mean level of agricultural production sustainability in Northern Anhui, rising from 0.062 in 2011 to 0.127 in 2020. Huainan consistently exhibits absolute dominance in agricultural production sustainability from 2011 to 2017, although its advantage weakened in 2018, it remains the highest among all cities. Conversely, despite Fuyang's steady upward trend, it consistently maintains the lowest score in agricultural production sustainability among the cities in Northern Anhui, thus indicating a persistent weakness in this aspect. The levels of agricultural production sustainability in Huaibei and Bengbu are comparable, positioning them as the cities second only to Huainan in this regard. Meanwhile, Suzhou and Bozhou exhibit weaker performance compared to Huaibei and Bengbu, falling below the mean level of all six cities. Notably, Suzhou and Bozhou demonstrate upward trajectories, indicating improvements over time.

Fig. 5 illustrates the results of agricultural economic sustainability, indicating a gradual increase in the mean level from 0.097 in 2011 to 0.120 in 2020, albeit with a lower growth rate. Notably, there was a period of decline from 2011 to 2015, followed by slow growth with fluctuations. Among the cities, Fuyang and Suzhou exhibit a continuous growth pattern in agricultural economics, with

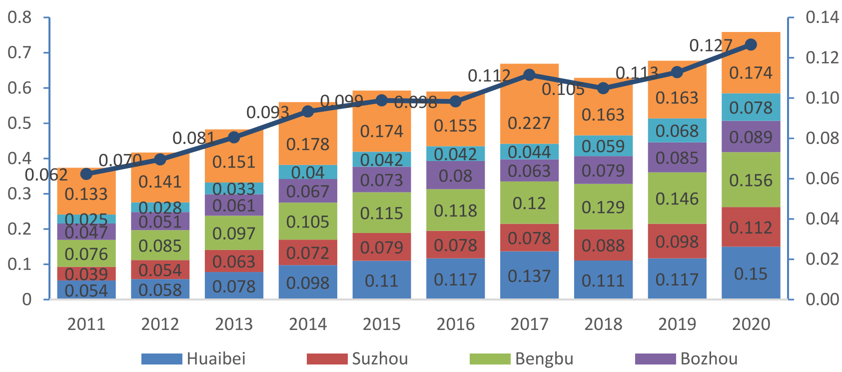

Fig. 4. The Status of each city in Agricultural Production Sustainability from 2011 to 2020.

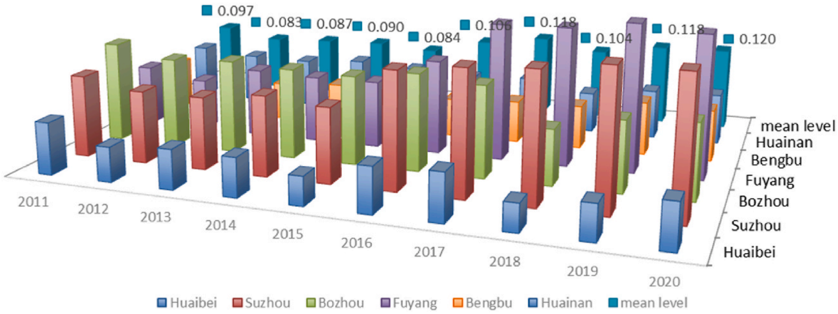

Fig. 5. The Status of each city in Agricultural Economic Sustainability from 2011 to 2020.

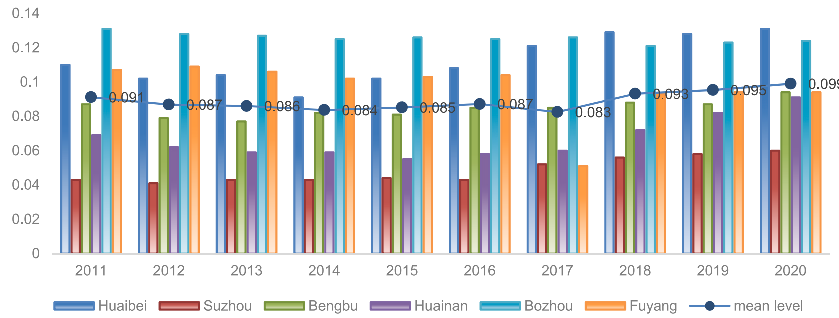

Fig. 6. The Trends of each city in Agricultural Resource and Environmental Sustainability from 2011 to 2020.

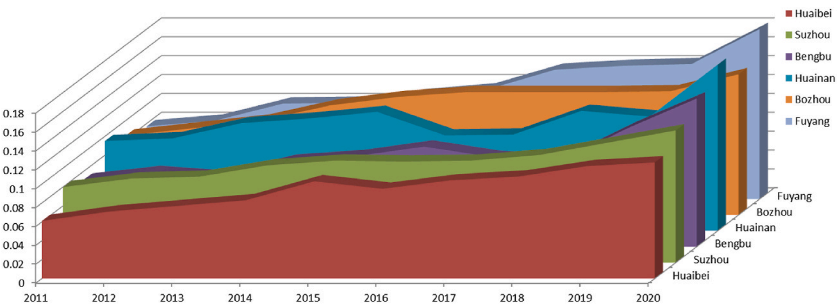

Fig. 7. The Trends of each city in Rural Society Sustainability from 2011 to 2020.

significantly higher agricultural economic sustainability indices compared to other cities in Northern Anhui. Conversely, Bozhou experiences a decline in agricultural economic sustainability, despite maintaining a steady status and holding the top position until 2017; a sudden drop occurs thereafter. This decline can be attributed primarily to the negative growth rate in the total output value of agriculture, forestry, animal husbandry, and fishery in 2018. Huaibei, Bengbu, and Huainan demonstrate relatively low levels of sustainability in agricultural economics, with no significant upward trends observed in the past decade.

Fig. 6 depicts the status of agricultural resource and environmental sustainability, indicating an increase in the mean level from 0.091 to 0.099. This suggests that alongside the high-quality development of the Chinese economy, agriculture in Northern Anhui is progressing towards resource and environment-friendly practices. However, disparities exist among the cities in Northern Anhui. Bozhou and Huaibei exhibit significant advantages over the other cities in terms of agricultural resource and environmental sustainability. Conversely, Suzhou consistently demonstrates lower sustainability over the past decade. This can be attributed to the excessive use of agricultural fertilizers and pesticides, which ultimately leads to severe pollution of the agricultural production environment, thereby posing a significant threat to the sustainable development of agriculture.

Fig. 7 displays the status of rural society sustainability, revealing a continuous increase in the overall sustainability except for a slight decline in 2016. The comprehensive index value rises from 0.078 in 2011 to 0.154 in 2020, indicating positive progress in rural society sustainability over the past decade. However, Huaibei consistently demonstrates relatively lower scores in rural society sustainability over the recent ten years. Conversely, Fuyang achieves the highest value in rural society sustainability in 2017. Huainan initially holds the highest value from 2011 to 2015, but subsequently experiences a decline, maintaining a relatively stable level until

2020.

To showcase the status of agricultural sustainable development levels overall and across sub-dimensions, Mean and Standard Deviation from Mean (STD) [47] were employed. The status of each city was categorized into different groups based on the following criteria:

Unsustainable: the index value ≤ Mean - STD.

Relatively unsustainable: Mean-STD <the index value ≤ Mean.

Relatively sustainable: Mean ≤ the index value ≤ Mean + STD.

Sustainable: the index value≥Mean + STD.

Fig. 8 illustrates the status of agricultural sustainable development in sub-dimensions, where APS represents agricultural production sustainability, AES represents agricultural economic sustainability, RES represents resource and environmental sustainability in agriculture, and ARS represents agricultural rural society sustainability. The results of agricultural production sustainability indicate that only Huaibei, Bengbu, and Huainan achieved sustainability in 2020. Fuyang exhibited unsustainable status from 2011 to 2017 and remained relatively unsustainable since 2018. In terms of agricultural economic sustainability, only Suzhou and Fuyang attained sustainability in 2020, while Bengbu and Huainan remained relatively unsustainable. Resource and environmental sustainability results reveal that only Huaibei and Bozhou achieved sustainability in 2020. Suzhou consistently exhibited relatively unsustainable status over the past decade, while Bengbu and Huainan transitioned from relatively unsustainable to relatively sustainable states in 2020. Regarding rural society sustainability, all cities except Huaibei maintained sustainability, with Huaibei demonstrating relatively sustainable status.

Table 4 provides an overview of the status and ranking of agricultural sustainable development based on the comprehensive index and sub-dimensions in 2020. From highest to lowest, the sequence of agricultural sustainability comprehensive index is as follows: Fuyang (0.556), Huainan (0.513), Suzhou (0.508), Bengbu (0.482), Bozhou (0.470), and Huaibei (0.469). Notably, Fuyang emerges with the highest agricultural sustainability in 2020, contrasting with the average over the recent decade. Despite Bozhou historically holding the highest average level, it has fallen behind significantly in recent years, as the other years, apart from 2020, contributed to pulling the average higher. Conversely, the agricultural sustainability levels of Huaibei and Bozhou lagged behind in 2020 compared to previous years.

4.2.4. Driving mechanism of agricultural sustainability

The paper measures the agricultural sustainable development level in Northern Anhui from a comprehensive perspective and then comprehensively evaluates and analysis its agricultural sustainability. While agricultural sustainability is the result of many multifaceted effects. Expecting to explore the influencing factors of sustainable agricultural development, this paper explores the driving factors of the agricultural sustainable development level from five aspects including science and technology level, industrial structure, traffic condition, human capital and local economic strength based on previous studies. In the paper, the panel data from six cities in northern Anhui from 2011 to 2020 were used to construct the panel regression model. However, the results of the F test showed the $F = 0.75$ of the individual fixed-effects model which is less than critical value $F_{0.01}(9,44) = 2.9$, thus it is not appropriate to individual fixed effect model, this paper adopt mixed Pool regression model to explore the impacts of the five drivers. Although the fixed effects model was not significant, there are other reasons for applying the mixed regression model of panel data. the panel data can avoid the influence of the model endogeneity on the model estimation to some extent, on the other hand, it increases the sample data and improves the reliability of the sample estimation. The output results are shown in Table 5.

Among various drivers, *tec* and *ind* have no significant impact on the sustainable development of agriculture in Northern Anhui, while *tra*, *hum* and *eco* have a significant impact. The analysis is as follows.

The findings suggest that the advancement of science and technology has not significantly promoted agricultural sustainable development in Northern Anhui. One possible explanation is the relatively low proportion of agricultural science and technology innovation patents compared to other types of patents per capita. Additionally, the transformation of agricultural science and technology innovations requires time for their benefits to accrue and contribute to agricultural development. On the other hand,

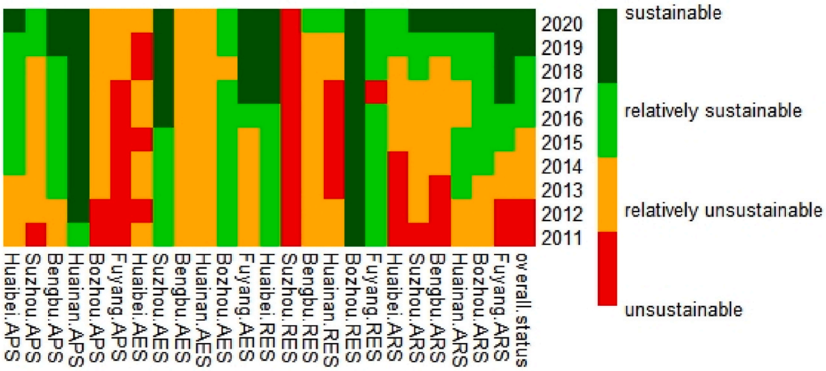

Fig. 8. The Status of the Agricultural Sustainable Development in sub-dimension.

Table 4
The comprehensive index of agricultural sustainable in 2020.

city	Comprehensive index		Agricultural production		Agricultural economic		Resource and environment		Rural society	
	rank	value	rank	value	rank	value	rank	value	rank	value
Huaibei	6	0.469	3	0.150	6	0.064	1	0.131	6	0.123
Suzhou	3	0.508	4	0.112	2	0.197	6	0.060	5	0.140
Bengbu	4	0.482	2	0.156	4	0.074	3	0.0944	3	0.157
Huainan	2	0.513	1	0.174	5	0.073	5	0.091	2	0.176
Bozhou	5	0.470	5	0.089	3	0.108	2	0.124	4	0.149
Fuyang	1	0.556	6	0.078	1	0.204	4	0.0940	1	0.180

Table 5
The results of the mixed Pool OLS regression models.

variable	Regression coefficient	Standard deviation	P-value
tec	0.002939	0.0026	0.255
tra	0.198155	0.0243	0.000***
ind	0.080133	0.1444	0.581
hum	0.115268	0.0661	0.086*
eco	−0.026838	0.0159	0.098*

***and *: represent the results are significant at the 1 % and 10 % levels respectively.

improvements in transportation infrastructure, particularly rural roads, have shown a significant positive impact on enhancing agricultural sustainability in the region. Better transportation infrastructure reduces the cost of production factor flow, fosters closer interaction between urban and rural areas, stimulates rural development, and ultimately contributes to the sustainable development of agriculture. However, the industrial structure level in Northern Anhui has not exhibited a significant influence on the sustainable development level of agriculture. This could be attributed to the relatively low advancement of the agricultural industrial structure and a lack of fully realized pathways for upgrading the industrial structure to enhance agricultural sustainability. Rural human resources in Northern Anhui have demonstrated a positive impact on local agricultural sustainability to some extent. These resources serve as a foundation for agricultural sustainable development, providing technical support, fostering innovation, and increasing the vitality of agricultural development. Surprisingly, economic strength has shown a certain negative influence on the sustainable development level of agriculture during the study period. This could be due to the predominant contribution of secondary and tertiary industries to the economy, with insufficient feedback mechanisms to support agriculture and rural areas.

Moreover, while the indices in the resource and environment sub-dimension are negative, they have shown a positive effect on economic development. This suggests a complex interplay between environmental factors and economic outcomes in the region.

4.2.5. Robustness test of driving mechanism

The robustness test of drivers aims to verify the stability and accuracy of their influence on the level of agricultural sustainability. To achieve this, we employ the control variable method, whereby additional factors impacting agricultural sustainability are included in the model alongside the original drivers. These control variables encompass factors such as highway freight volume, contribution rate of the tertiary industry, years of education of the population, and government receipts. For consistency, the panel data model continues to utilize a mixed regression model. The model calculation results, post-introduction of the control variables, are presented in Table 6. This analysis provides insight into the extent to which the original drivers remain influential in the presence of these additional control variables, thereby enhancing the robustness and reliability of our findings.

The results of the robustness test, as presented in Table 6, indicate that with the addition of other control variables, the direction of the influence relationship remains unchanged, and the degree of influence is similar. This suggests that the original drivers continue to exert a consistent and significant impact on the level of agricultural sustainability, even in the presence of additional factors. Such findings underscore the robustness and reliability of our initial conclusions regarding the drivers of agricultural sustainability in Northern Anhui.

5. Discussion

5.1. Compared with the existing literature

This paper contributes to the existing literature on sustainable development in Northern Anhui by constructing a sustainable agricultural development index system using the entropy method. The measurement results align generally with prior research findings [48,49]. However, this study offers several noteworthy contributions: Theoretically, the research expands the theoretical understanding of agricultural sustainable development by establishing a comprehensive evaluation system from multidimensional perspectives. By incorporating various dimensions such as science and technology, industrial structure, transportation, human capital, and economic strength, the study provides a more holistic view of agricultural sustainability. Additionally, the paper presents a

Table 6
Results of the robustness test.

Variable	Regression coefficient	Standard deviation	p-value
tec	0.003914	0.002763	0.1629
tra	0.179984	0.26887	0.0000***
ind	0.207560	0.0.186635	0.2714
hum	0.118064	0.066787	0.0832*
eco	−0.03759	0.019627	0.0612*

***and *: represent the results are significant at the 1 % and 10 % levels respectively.

theoretical framework and data-driven method system for evaluating, optimizing, and improving agricultural sustainable development. In practical terms, the data-driven method developed in this study can be applied to analyze the agricultural sustainable development of other regions, providing valuable insights for decision-makers and policymakers. By leveraging the results of this research, policymakers can make informed decisions to promote sustainable agricultural development, thereby contributing to the overall socio-economic development of the region.

5.2. *Policy implication*

Based on the results of agricultural sustainability level measurement and driver analysis in Northern Anhui, several policy implications emerge.

About government Measures for Sustainable Development, the findings underscore the importance of government measures in promoting sustainable development in agriculture. The Chinese government has implemented various initiatives to advance sustainability, such as promoting the concept of sustainable development, establishing carbon trading markets, and offering incentives for reducing carbon emissions. The increasing overall level of agricultural sustainability in Northern Anhui indicates the significant impact of these government measures in the agricultural sector.

In rural transportation network construction aspect, the construction of a robust rural transportation network is vital for supporting the national rural revitalization strategy. The empirical results from Northern Anhui suggest that the transportation network significantly promotes agricultural sustainable development. This underscores the importance of continued investment in rural infrastructure to facilitate the efficient flow of goods and services, thereby fostering agricultural sustainability.

Economic development serves as the foundation for regional progress, While, the empirical study in Northern Anhui reveals a negative relationship between economic strength and the sustainable development level of agriculture. This indicates that despite economic growth, the primary industry, including agriculture, may be lagging behind. Moreover, there may be insufficient local investment in sustainable agriculture, hindering the coordinated development of economic strength and sustainable agriculture. Policymakers should thus focus on incentivizing investment in sustainable agricultural practices to ensure the harmonious development of the economy and agriculture.

6. Conclusions and recommendation

Accurately measuring and reasonably evaluating the level of agricultural sustainable development as well as identifying facilitating and restrictive factors, hold great significance for promoting agricultural sustainability. Firstly, this paper adopts a sustainable development perspective to construct a comprehensive evaluation index system for agricultural sustainable development across four sub-dimensions. This enables a more comprehensive calculation of the level of agricultural sustainable development and enriches the theoretical basis of agricultural sustainability research. Furthermore, the paper proposes a data-driven method to measure agricultural sustainability and explore the mechanisms influencing agricultural sustainability. Using Northern Anhui as a case study, this research verifies the feasibility of the data-driven approach. Through the measurement, evaluation, and investigation of influencing factors pertaining to agricultural sustainable development in Northern Anhui, the results are as follows:

The overall level of sustainable agricultural development in Northern Anhui is experiencing an upward trend, yet there exists significant disparity among cities, with this difference showing a declining trajectory over time. While the starting point of agricultural production sustainability is modest, it exhibits a notable growth rate. Conversely, the agricultural economy has witnessed gradual expansion, albeit at a sluggish pace. Moreover, the sustainability of agricultural resources and the environment has seen limited improvement over the past decade, although rural social sustainability began at a relatively low level, noteworthy progress has been achieved. Analysis of the driving mechanisms reveals that scientific and technological advancements in Northern Anhui have not markedly enhanced the level of sustainable agricultural development. However, transportation infrastructure emerges as a pivotal factor in promoting agricultural sustainability. Furthermore, the advanced level of the agricultural industry remains relatively subdued, while rural human resources play a discernible role in facilitating sustainable agricultural development. Surprisingly, the local economic level fails to substantially contribute to the sustainable development of agriculture in Northern Anhui.

In light of the existing challenges facing sustainable agricultural development in Northern Anhui, the following policy suggestions are proposed.

Enhance Agricultural Science and Technology: To improve agricultural sustainability, there is a need to enhance the level of agricultural science and technology in Northern Anhui. This involves strengthening support for high-tech-enabled agriculture, focusing on innovations characterized by information, ecology, and wisdom. Local governments should increase their support for agricultural science and technology innovation to drive sustainable agricultural development forward.

Optimize Agricultural Industry Structure: Efforts should be made to upgrade and optimize the structure of the agricultural industry in Northern Anhui. This entails deepening the industrialization of agriculture and animal husbandry. Government agencies should work to optimize the agricultural industrial structure by providing support for secondary and tertiary industries. Measures should be taken to promote the processing of agricultural products, expand the development of the agricultural service industry, and facilitate the optimization and adjustment of the agricultural industrial structure.

Promote Environmentally Friendly Practices: There is a need to raise awareness about the environmental impact of inorganic fertilizers and pesticides. Public awareness campaigns should be launched to educate farmers and the wider community about the detrimental effects of these chemicals on the environment. Additionally, efforts should be made to optimize the utilization mode of agricultural resources and enhance rural environment construction. By adopting environmentally friendly practices, Northern Anhui can promote sustainable agricultural development while safeguarding the local environment.

Local government departments should prioritize the adoption of eco-friendly agricultural practices and augment financial assistance to the agricultural sector, concurrently striving to diminish agriculture's reliance on environmental resources.

However, the study of driving mechanisms may not encompass a comprehensive array of influencing factors. Throughout the research process, insufficient attention has been directed towards spatial integration, spatial agglomeration, and the effects of government policies. These represent critical areas warranting further investigation and analysis.

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Data availability statement

The data presented in this study are available on request from the first author.

CRediT authorship contribution statement

Fengwei Gao: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Zhuangzhuang Li:** Methodology, Investigation, Data curation. **Pei Zhang:** Visualization, Validation. **Yimin Wu:** Writing – review & editing, Validation, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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