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Agricultural Eco-Efficiency: Challenges and Progress

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Abstract: The research on agricultural eco-efficiency has become an important point to deeply understand the interaction between ecological and environmental conditions and socio-economic factors as well as realize the coordinated development of agricultural economic development and environmental protection. (1) Background: This paper attempts to provide scientific support for the healthy and stable development of the agricultural economy and the sustainable development of ecological agriculture. (2) Methods: From a comprehensive perspective, this paper systematically analyze the overall situation, development trend, key fields, and hot fields of agricultural eco-efficiency in the past two decades. It consists of two complementary parts, including systematic quantitative literature review (based on CiteSpace) and traditional literature review. (3) Results: Agricultural eco-efficiency has evolved significantly with the popularization of agricultural machinery and the wide application of science and technology in the field of agricultural ecology. Its future development relies on the advances in our knowledge on theories and hypothesis, evaluation methods, impact on “socio-economic ecological” system, and drivers and regulation of agricultural eco-efficiency. For each of these fields, we find that challenges still exist. At present, the quantitative methods and index selection are not unified. We should deeply analyze the internal and external driving force of the development and change of ecological efficiency by constructing a complete theoretical framework for the research of agricultural ecological efficiency. At the same time, new technologies and methods are needed to evaluate agricultural eco-efficiency, and a balanced consensus between the improvement of agricultural eco-efficiency and the improvement of the ecological environment should be formed through empirical research.

Keywords: agricultural eco-efficiency; sustainable development; literature review; progress and prospect



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1. Introduction

Agriculture is the basic industry supporting the construction and development of the national economy. Since the reform and opening-up, China's agricultural production has grown swiftly, grain production has increased gradually, and agricultural economic output has enhanced significantly. However, agricultural development also faces profound challenges. On the one hand, agriculture's long-term sustainability faces significant challenges; over-exploitation of agricultural resources, excessive use of agricultural inputs, over-exploitation of groundwater, and the superposition of internal and external sources of pollution in agriculture are all major sources of challenge. On the other hand, agricultural ecosystem degradation is obvious; water and soil resources management, ecological compensation, and other institutional mechanisms are not sound; and water and soil resources constraints are increasingly tight, so it is very urgent to promote sustainable agricultural development [1–3]. High-intensity and rough traditional agricultural production methods have led to structural imbalance and the functional degradation of farmland ecosystems, which has attracted extensive attention [4]. How to balance food security with sustainable utilization of agricultural resources is not only an important challenge for the sustainable development of agriculture but is also the embodiment of putting the construction of ecological civilization in a prominent position in the field of agricultural eco-efficiency [5,6].

In recent years, China has achieved great advances in agricultural science and technology as well as in the economy and society. The following social, economic, and environmental challenges, however, significantly limit agricultural growth [7]. Eco-efficiency is an important index to measure the ability of sustainable development. It is introduced into the field of agriculture to form agricultural eco-efficiency (AEE). AEE is the efficiency of agricultural production, implying that the maximum agricultural economic output can be achieved with the least amount of resource consumption and pollution for a given set of material factor inputs [8]. The evaluation combines economic output, resource input, and environmental impact in the process of agricultural production. Some scholars have tried to measure the specific value of AEE in different regions, such as Italy and China. Measuring AEE is conducive to promoting the sustainable utilization of agricultural resources, realizing resource conservation and pollutant emission reduction on the basis of meeting human demand for agricultural products, and then promoting the sustainable development of regional agriculture [3,9]. The number of AEE research projects and accompanying papers has expanded considerably in recent years, but a comprehensive and systematic bibliometric analysis is lacking. In order to improve agricultural resource utilization and ensure the construction of agricultural eco-civilization, effectively sorting out the progress of agricultural eco-efficiency research, exploring the inner connection of the research results, refining their development laws, and integrating research resources and research strength is critical. In contrast, research focuses on AEE, which has been changing and adapting. As a result, the network connection between research aims and public concerns in different times must be defined. There are a few questions that must be addressed.

- (1) What is the general trend of AEE research?
- (2) What are the salient milestones and hot issues in AEE research?
- (3) What are the major areas of AEE research?
- (4) What are the challenges and future directions of AEE research?

2. Materials and Methods

The literature data in this paper are obtained from the Web of Science Core Collection, which could help researchers better grasp relevant topics and seek research breakthroughs and innovations by quickly discovering the research direction and development trend concerned by domestic and foreign authorities and selecting appropriate journals for submission [10]. This paper uses CiteSpace to draw various knowledge graphs. CiteSpace is a visual analysis software for scientific metrology research, and the literature data come from the Web of Science Core Collection. Compared with other renowned databases, WoS Core Collection, one of the largest and most famous citation databases, is a unique citation index where users can easily retrieve citation and trace the origin and history of a research by indexing all metadata output, including citing and cited references. In order to ensure the accuracy and reliability of literature analysis results and present the accurate research situation of AEE by foreign authors, based on several research questions, the inclusion/exclusion criteria for 268 literatures preliminarily retrieved were formulated (Table 1). The search prerequisites of AEE research were set as follows (Figure 1): "AEE = Agricultural eco-efficiency", with AEE as the theme, time span from 1900–2021, the language is English, and the literature categories are articles and review articles, excluding non-academic papers, such as meetings, proceedings, papers, and book chapters (Table 1). There are 197 records selected after excluding the literature irrelevant to the research subject. Based on Citespace.5.8.R3 (New York, USA), we set the parameters as follows: the cutting time is set as 1a (year), the threshold positioning is Top 50, and the node type is keyword [11]. Co-occurrence analysis helps us understand the distribution of object texts in the field of science domain. Relying on the keyword co-occurrence analysis of 197 records related to AEE, the literature was macroscopically visualized, and the network graph was obtained so that we could analyze AEE research frontiers and knowledge relationships.

Table 1. Inclusion and exclusion criteria in the literature review strategies.

	Inclusion Criteria	Exclusion Criteria
Database selection	WoS Core Collection	Not WoS Core Collection in WoS
Research theme	Focusing on AEE (e.g., theories and hypothesis, evaluation methods, impacts, drivers and regulation)	Irrelevant to AEE
Research subjects	Foreign authors	Domestic authors
Language	English	Non-English
Literature categories	Articles and review articles	Meetings, proceedings, papers, book chapters

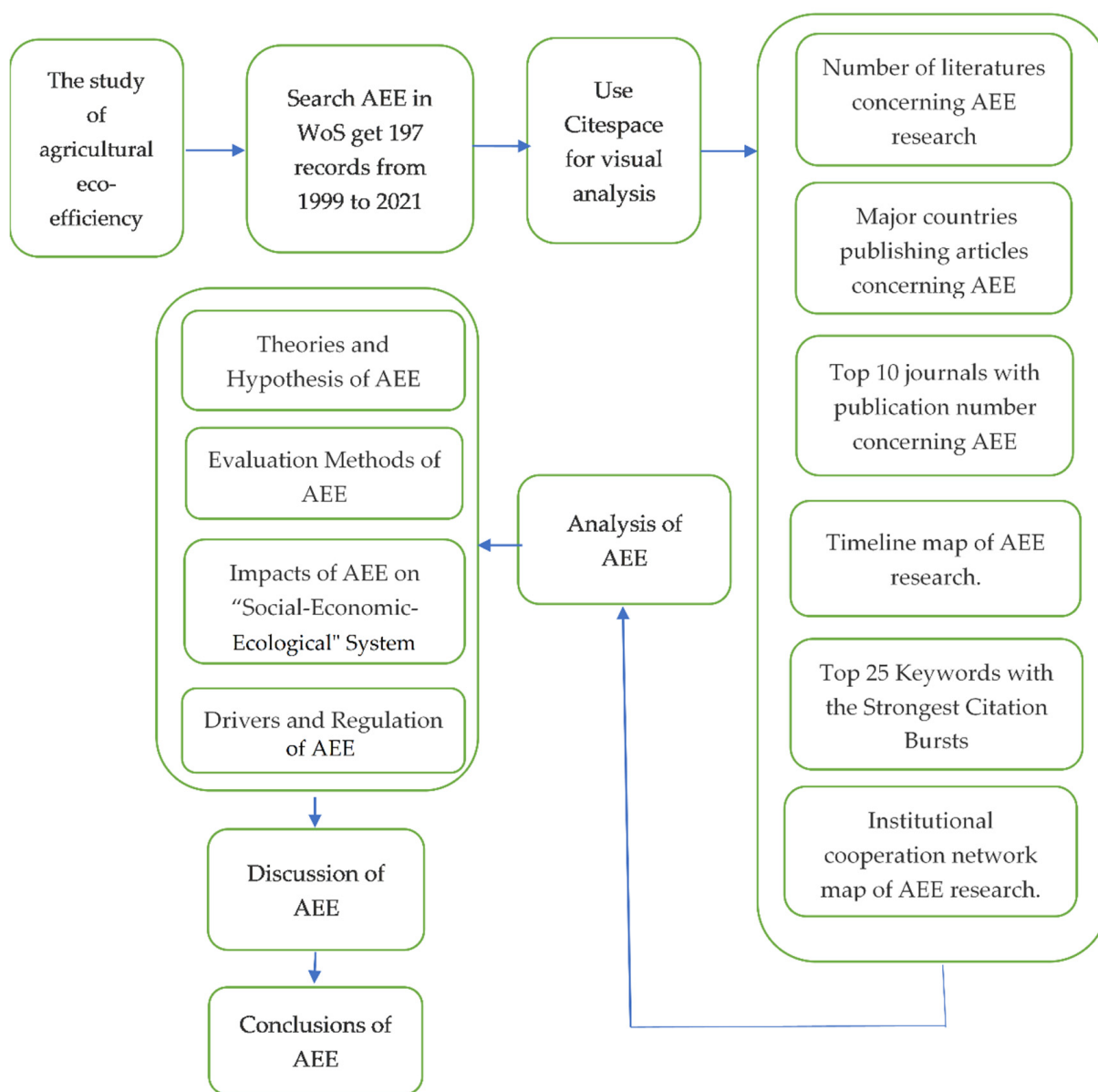


Figure 1. Method flow chart.

This review consists of two complementary parts, namely the systematic quantitative literature review (Section 3) and traditional literature review (Section 4). Systematic quantitative literature review (based on CiteSpace) establishes logical relations in the visual

network through some factors, such as node size, network connectivity, and co-occurrence, to show the academic hotspots and research trends in this discipline field. Compared with traditional literature review, this method does not need to constantly search for relevant literature to form its own systematic understanding of the field, but it is unable to deeply review previous research. In order to make up for the shortcomings of systematic quantitative strategy, this paper further carries out the traditional literature review. Based on collecting many relevant literatures, comprehensive analysis and comments can help researchers understand the research overview and development direction in a short time, but it is often limited by the personal views of experts and the incomplete collection of data. Therefore, the combination of the two complementary strategies can make up for their respective shortcomings and, more importantly, provide strong support and demonstration for better research of AEE.

3. Results

3.1. An Overview of AEE Research

The comprehensive analysis of the number and time of documents is helpful to observe the different forms of research in a certain field in different periods. The amount and trend of published literature concerning AEE research from 1999 to 2021 were analyzed (Figure 2). We found that the amount of literatures in this field showed a fluctuating upward trend, with a rapid increase in the number of published papers after 2013. According to the number of annual publications, it can be roughly divided into two stages as follows: (1) in the initial stage (1999–2013), few annual publications were published before 2009, and a slow growth trend started in 2010. The number of papers published at this stage is relatively small, with no more than five papers published annually, indicating that the research results have failed to attract sufficient attention from the academic community, and the research results are fewer and less influential. (2) In the rapid development stage (2014–2021), the number of publications increased significantly compared with the previous period, and there was an explosive growth from 2019 to 2020. Research on AEE gradually gained attention, and scholars carried out a series of research work with various methods and perspectives from different disciplines and perspectives. To further grasp the research trends in this research field, we needed to conduct data mining of the literature in more depth to capture key information and analyze its research hotspots.

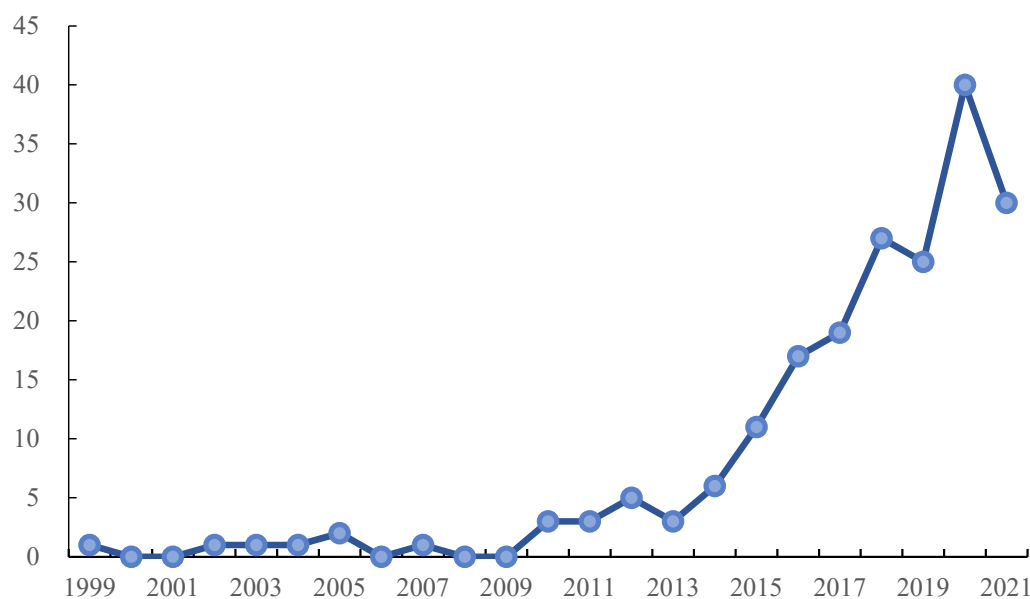


Figure 2. Quantity of literatures concerning agricultural eco-efficiency research from 1999 to 2021.

According to data from Web of Science, by the end of 2021, the top three countries in terms of the number of papers on AEE research were China (47), France (12), and

the United States (22), followed by Germany, Greece, Italy, Australia, Sweden, Ireland, and the Netherlands (Table 2). Research on AEE has attracted extensive attention in various fields. Statistical analysis shows that AEE-related research has been published in SCI/SSCI-indexed journals covering a wide range of disciplines and fields, such as ecology, environmental science, sociology, and economics. The top 10 journals with publication volume are J Clean Prod, J Environment Manage, Ecological Economics, Agricultural Systems, Science of the Total Environment, Agriculture Ecosystems & Environment, European Journal of Operational Research, Journal of Industrial Ecology, International Journal of Life Cycle Assessment, and European Journal of Agronomy (Figure 3).

Table 2. Major countries publishing articles concerning AEE.

Rank	Country	Number of Articles	Centrality ^a
1	China	47	0.45
2	France	12	0.21
3	USA	22	0.19
4	Germany	13	0.17
5	Greece	7	0.15
6	Italy	18	0.12
7	Australia	8	0.12
8	Sweden	3	0.1
9	Ireland	2	0.1
10	Netherlands	6	0.09

Note: ^a Centrality is an indicator to measure the importance of nodes in the network [12]. The larger the value of centrality is, the more the number of publications cooperated with other countries.

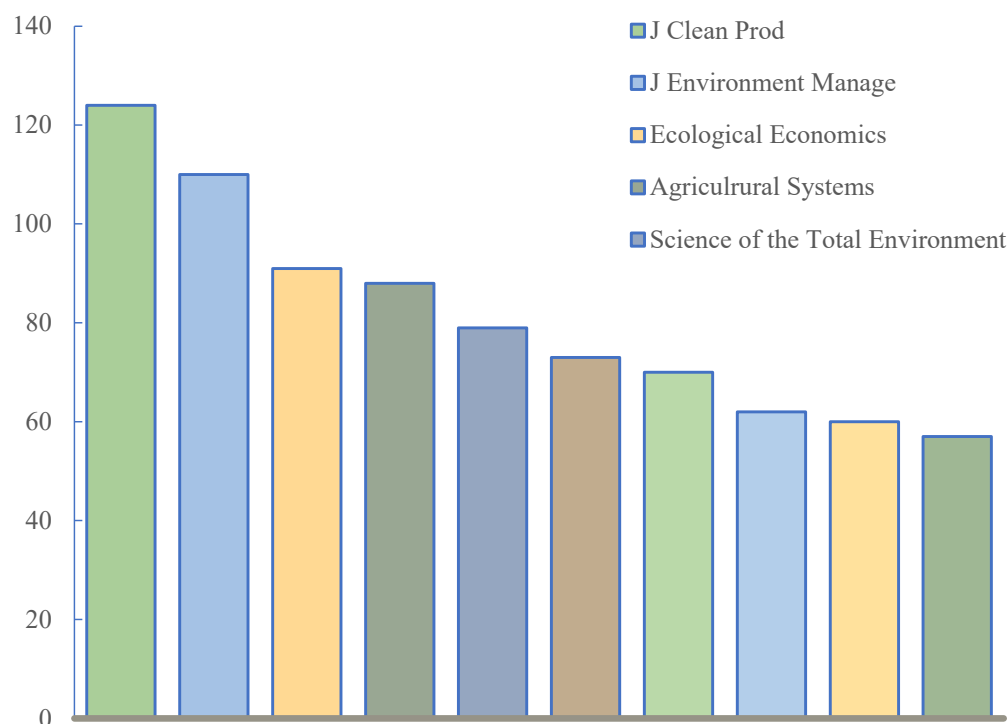


Figure 3. The top 10 journals with publication number concerning agricultural eco-efficiency during 1990–2021.

3.2. Evolving Research Hot Topics

3.2.1. Analysis of Keywords and Hot Topics Distribution

CiteSpace provides three visualization types, including cluster, timeline, and time-zone views. One of them is the timeline view, which focuses on establishing the relationship between clusters as well as the temporal range of literature inside a specific cluster. CiteSpace was used to analyze the keywords and hot problems associated with AEE research

from 1999 (there were few AEE literature earlier to this). It provides two measures for evaluating the impact of atlas rendering: modularity Q (Q) and weighted mean silhouette (S). In general, the Q value ranges between 0 and 1, and Q greater than 0.3 implies that the community structure has been considerably fragmented. The weighted mean silhouette is used to assess the homogeneity of the cluster. The higher the value, the more trustworthy the cluster's members will be. $S > 0.7$ indicates that the clustering is both efficient and compelling [13]. The result showed the modularity Q and weighted mean silhouette of the cluster analysis are 0.4356 and 0.7672, respectively, indicating that the model clustering results are scientific and reasonable. Finally, the timeline map of AEE research from 1999 to 2021 was obtained (Figure 4). Related research hot topics can be roughly divided into 10 categories, i.e., environmental impact, agriculture, industrial ecology, productivity, eco-efficiency, agricultural sector, yield gap, decoupling, farming systems, and natural fibers. There are 10 keywords with a frequency of more than 25, i.e., agriculture, eco-efficiency, life cycle assessment, environmental performance, agricultural sustainability, data envelopment analysis, greenhouse gas emission, energy use, environmental efficiency, and technical efficiency. Through the analysis of high-frequency words, it was found that the keywords of AEE research cover a wide range, and there are obvious differences in the research focus and hot topics at different stages. In general, it can be divided into the following three stages:

- (1) Slow growth stage (1999–2010): This stage began to focus on agriculture, ecological efficiency, and life-cycle review. The concept of ecological efficiency was firstly put forward by Schaltegger, a famous German scholar, in the early 1990s [14]. In the following decade, academies completed multifaceted and in-depth research around the concept.
- (2) Fluctuant rising stage (2010–2016): At this stage, research on environmental performance, agricultural sustainability, and greenhouse gas emissions gradually attracted attention. With the rapid development of agriculture, agricultural pollution became increasingly serious. The research focused on how to improve agricultural output and reduce agricultural production pollution to promote agricultural ecological improvement, which is an important issue for agricultural sustainable development.
- (3) Rapid development stage (2016–2021): Against the background of the accelerating process of new industrialization, the improvement of agricultural productivity brought more and more serious problems of environmental pollution and resource waste, which will directly and seriously affect the long-term development of agriculture. Experts and scholars have done research on AEE from different angles and levels, including technical efficiency, land use, wastewater reuse, industrial ecology, common agricultural policy, carbon emission, and other details related to agricultural eco-efficiency.

3.2.2. Burst Words Analysis

The keyword emergence analysis can reflect the sudden explosive growth in the attention of a research topic in a research field within a certain period, which can show the research frontier in related research fields. Keywords are a high summary of the topics and contents of the studied literature, and their frequencies can know to a certain extent the research hotspots in the subject area in a certain time period. Burst words represent the phenomenon that the keywords to be investigated transitioned in a short period of time. It can emphasize the mutation through the investigation of word frequency. Burst terms detection in CiteSpace is used to detect emergent keywords in the AEE research from 1999 to 2021, and 25 emergent words were detected, with the highest burst intensity being soil (Table 3). It can be seen from Table 2 that there are obvious differences in research focus and hot areas at different stages. From 2010 to 2011, most of the research on AEE focused on the impact of yield, decision support, and management on ecological efficiency, which indicates that the academic community recognized the impact of energy use on agricultural eco-efficiency earlier. After 2011, academic research on AEE was gradually

refined. From 2011 to 2016, research topics, such as agricultural production, water, soil, and crop, received more attention. From 2016 to 2021, relevant research paid more attention to the evaluation and influencing factors of AEE. Using eco-efficiency research methods, such as data envelopment analysis (DEA) and life-cycle assessment (LCA), the driving factors of AEE, sustainable and green development, and ecological intensification will become hot topics in the future.

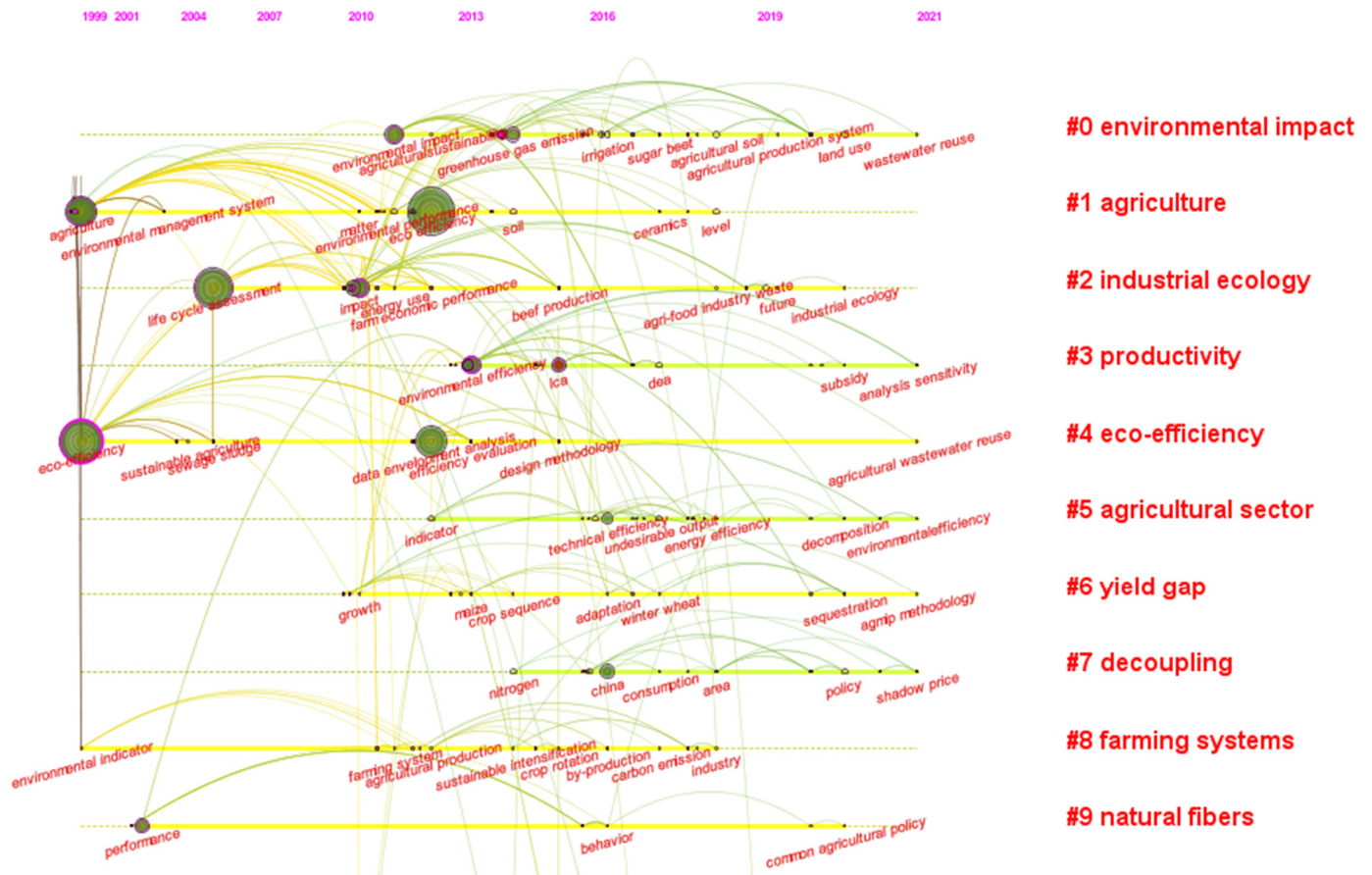


Figure 4. Timeline map of agricultural eco-efficiency research.

3.2.3. Analysis of Institutional Cooperation Network

Research collaboration network mapping is used to study the cooperation among research subjects in a disciplinary field. Citespace provides three levels of research collaboration network analysis: micro (author), middle (institution), and macro (country). The institutional cooperation network map can show how institutions are connected to each other and the contribution of each institution in the field of AEE research. Through analyzing the major research institutions and cooperation networks of AEE research, we found that AEE research received extensive attention in 57 countries and 226 research institutions around the world, yielding 226 nodes, 256 connections, and a network density of 0.0101 (Figure 5). Research institutions were dominated by universities, with the Chinese Academy of Sciences occupying the central location in the cooperation network in the field of AEE research with the largest number of articles at 14. It is followed by China Agricultural University, University of Chinese Academy of Sciences, and Poznan University of Economics and Business, all with more than five articles. In addition, Ohio State University, University of Valencia, University of Thessaly, and Agroscope Reckenholz Tanikon Res Stn ART have also published more fruitful work. By further analyzing the degree of cooperation and closeness between various institutions, we found that a clear network of collaborative research institutions centered on the Chinese Academy of Sciences has been formed. In addition, there is a lack of cooperation and communication among

other research institutions with different research focus, and this pattern is not conducive to the sharing of research information and the development of the research system. Therefore, cooperation and communication among various related research institutions need to be strengthened in the future.

Table 3. Top 25 Keywords with the Strongest Citation Bursts during 1999–2021.

Keywords	Year	Strength ^a	Begin	End	1999–2021 ^b
yield	1999	1.72	2010	2013	
decision support	1999	1.58	2010	2014	
management	1999	1.02	2010	2014	
energy use	1999	1.69	2011	2014	
firm	1999	1.21	2011	2013	
indicator	1999	2.35	2012	2016	
agricultural production	1999	1.02	2012	2017	
output	1999	1.55	2013	2017	
water	1999	1.41	2013	2016	
ecological intensification	1999	1.24	2013	2014	
maize	1999	1.16	2013	2017	
soil	1999	2.96	2014	2015	
environmental impact	1999	1.32	2015	2016	
crop	1999	1.43	2016	2017	
assessment ICA	1999	1.24	2016	2017	
CO ₂ emission	1999	1.07	2016	2017	
driver	1999	1.05	2016	2017	
DEA	1999	1.84	2017	2019	
cropping system	1999	1.53	2017	2019	
ICA	1999	1.33	2017	2018	
bioenergy	1999	1.33	2018	2019	
ecosystem service	1999	2.3	2019	2021	
future	1999	1.53	2019	2021	
intensification	1999	1.21	2019	2021	
food	1999	1.08	2019	2021	

Note: ^a Strength is an indicator to measure the degree of a burst event. The larger the value is, the more active the keyword is in the research field. ^b The red line indicates the year with active burst words, and the blue line indicates the year with inactive burst word.



Figure 5. Institutional cooperation network map of AEE research.

4. Key Fields and Hot Topics of AEE Research

4.1. Theories and Hypothesis of AEE

The increase in demand for agricultural products due to the population boom accelerated the transformation from traditional agriculture to petroleum agriculture. In various stages of agricultural development, agricultural production activities have a certain impact on the agricultural ecological environment at different levels. After the 1970s, with the development of “industrialized agriculture” and “petroleum agriculture”, a large amount of investment in agricultural machinery, chemical fertilizers, and pesticides not only improved the efficiency of agricultural production but also caused increasing environment pollution, such as the deterioration of land fertility and serious pollution of agricultural water sources [15]. With the aggravation of the negative effects and the rising voice of sustainable development at home and abroad, promoting the development of agricultural ecology has attracted more and more attention. The basic index to measure the development level of agricultural ecology is agricultural ecological efficiency.

Human activities have modified the mode of agricultural production. As the population grows, increasing demand for food leads to the continuous improvement of agricultural output, which has brought about severe environmental problems. Western academic circles generally believe that the core affecting agricultural development lies in the improvement of production efficiency. Schultz (1975), a famous economist, proposed that the analysis of the regional distribution of agricultural modernization should start with agricultural production efficiency [16]. The above research is limited to the role of a single factor on production efficiency, while in reality, the factors influencing production efficiency are diverse. Based on it, Robert Merton Solow (1957), a Nobel economics laureate, proposed Total Factor Productivity (TFP), which plays an important role in the growth of agricultural production and its variability [17]. Schaltegger and Sturm (1992), German scholars, firstly proposed “ecological efficiency”, that is, the ratio of economic growth to environmental impact, at the World Business Council for Sustainable Development (WBCSD) [14]. Subsequently, scholars in related research fields successively defined the concept of ecological efficiency from different dimensions. In 1995, Fussler introduced eco-efficiency to China [18]. After years of research, Chinese scholars have made great achievements in the field. The healthy and stable development of agriculture is the foundation of a country. Agricultural eco-efficiency is the extension and expansion of ecological efficiency in the agricultural field, that is, to obtain as much agricultural output as possible with less natural resource consumption and environmental pollution within the ecosystem in certain degree [2,18]. After the reform and opening-up, due to the support of “bonus system”, petroleum agricultural production has made great achievements, but it has also produced negative effects, such as overuse of resources and environmental pollution, thus facing great challenges of the sustainable development of agriculture [2]. Scholars have carried out research on the conceptual connotation, theoretical models, evaluation methods, and driving mechanisms of AEE. Different scholars have different definitions of the concept of agricultural ecological efficiency, but the general direction remains the same. Some scholars believe that AEE is not only to minimize resource consumption and pollution emission but also to meet human needs for food and quality of life on the premise of ensuring sustainable development in the process of agricultural production. However, this definition ignores the environmental impact of the efficient utilization of agricultural resources on agricultural production activities [19]. Other scholars argue that agricultural production efficiency is an input-output ratio based on economic objectives, resource inputs, and environmental impacts, reflecting the sustainable development of agriculture [3]. AEE is an important indicator for evaluating the capability of agricultural sustainable development, which has certain theoretical and practical significance for formulating agricultural sustainable development policies.

Based on the special socio-economic and socio-ecology, some scholars probed the theoretical framework and hypotheses of AEE. Grossman and Kruger (1995), famous American environmental economists, put forward the improved hypothesis of “Environmental

Kuznets Curve". The hypothesis holds that in the process of economic growth, the expansion of economic scale requires more resource investment and causes more pollution emissions [20]. In addition, the promotion and application of new technologies, the optimization and upgrading of the industrial structure, and the development and utilization of clean energy have brought positive technological progress and structural effects on environmental quality [21]. Guo, B. (2020) systematically evaluated the temporal and spatial evolution, spatial correlation characteristics, and external driving mechanism of China's AEE and analyzed the basic characteristics of agricultural production [1]. The results show that the spatial heterogeneity of agricultural production efficiency gradually appears. At the same time, the differences of natural factors, such as diversity index, NDVI, and socio-economic factors, such as GDP ratio, affect AEE [22]. Multi-stakeholder initiatives (MSIs) have become the main institutional approach to promoting sustainability on a global scale. Konefal, J (2019) found two distinct sustainable agriculture visions. The first is to pay attention to AEE on the premise of sufficient resources, and the second is to maintain a flexible agricultural ecosystem to achieve progressive improvement in sustainability [1]. The study of AEE is of great significance to alleviate the contradiction between agricultural production and ecological environment and promote agricultural sustainable development. Therefore, how to accurately and completely define, objectively and comprehensively evaluate, and improve AEE has become an important part of agricultural economic development.

4.2. Evaluation Methods of AEE

Ecological efficiency is a measure index that is used to measure the impact on the ecological environment, while the production unit obtains output of economic activities [23]. There are many evaluation methods of AEE in academic circles, including the ratio analysis, life-cycle assessment (LCA), ecological footprint analysis, stochastic frontier analysis (SFA), emergy analysis, and data envelopment analysis (DEA).

4.2.1. Ratio Analysis

The connotation of eco-efficiency mainly includes ecological and economic efficiency [24]. Most of the early AEE evaluation methods used the ratio of economic value to resource and environmental impact. Nowadays, there is no unified and clear accounting method for evaluating AEE. The formula proposed by the World Business Council for Sustainable Development (WBSCD) is generally accepted by scholars [3], and its calculation formula is

$$\text{Eco - efficiency} = \frac{\text{economic value of the product}}{\text{environmental impact of the product formation}}$$

The evaluation of AEE by ratio method can be reflected in the negative impact on the environment (such as fertilizer residue and soil productivity decline) and the positive impact (such as absorption of carbon dioxide and reduction of noise) in the process of agricultural production [25]. The ratio method formula of AEE can be further expressed as

$$\text{AEE} = \frac{\text{economic value of agricultural products}}{\text{negative environmental effects} - \text{positive environmental effects produced by agricultural products}}$$

To a certain extent, it reflects the impact of economic development on the environment, but the output side of production is considered, and the input side is ignored. However, the root cause of the environmental impact of economic development is on the input side [26,27]. Therefore, the method makes it difficult to distinguish different environmental impacts and cannot provide elastic support for decision makers.

4.2.2. Life Cycle Assessment (LCA)

Life-cycle assessment originated in the 1960s. The existence of energy problems, such as resource consumption and oil crisis, had a significant impact on social development, which led to people's exploration of energy utilization. Until the 1990s, the research on sustainable development was becoming increasingly mature. The life-cycle assessment

method was proposed by the Society of Environmental Toxicology and Chemistry and the International Organization for Standardization [28,29]. Its formula is

$$\frac{\text{Ecopoints}}{\text{kg}} = \frac{\text{Emissions}_A}{\text{Emissions}_T} \times \frac{1}{\text{Emissions}_T}$$

where Ecopoints represents ecological factors, kg represents waste emissions, the subscript A represents the actual environmental load, and T represents the ideal environmental load.

The method is mainly used to evaluate the potential environmental impact of a product in the whole life cycle and quantify it, obtaining ecological efficiency [30,31]. Due to the disadvantages of difficult boundary determination, complex data selection, and strong subjectivity, the credibility is not only often controversial, but it is difficult to make inter-regional comparisons.

4.2.3. Ecological Footprint Analysis

Ecological footprint analysis was proposed by Canadian ecologist Rees (1992) and then developed and improved by his student Wackernagel [32]. By measuring the gap between the demand of human activities for ecological services and the ecological services actually provided by nature, it evaluates whether the regional economic development is within the carrying capacity of the ecosystem. When human demand is less than the ecological carrying capacity, the natural resources of the region are in surplus in agro-ecosystem; conversely, it shows that the natural resources in this area are over-consumed and in deficit [33,34]. The method is widely used because of its simple operation, global comparability, and strong applicability. However, there are some shortcomings, such as single evaluation index, which cannot comprehensively reflect the ecological function.

4.2.4. Stochastic Frontier Analysis (SFA)

Stochastic frontier analysis is a parameter analysis method that is widely used in the calculation of efficiency [35]. This method was first proposed by Farrell in 1957, who calculated the cost efficiency of American agriculture and divided it into technical efficiency and allocative efficiency [36]. In 1977, Aigner, Mecusen, and Van Den Broeck independently proposed and elaborated the method [37]. The general basic form of SFA is

$$y_{it} = f(x_{it}, t) \times \exp(v_{it}, u_{it})$$

where y_{it} represents the output and input elements of i in period t , t is time, $f(\cdot)$ represents the calculated production function, v_{it} is the random error term of the equation, and u_{it} is other error terms of the equation and picks the minus.

By using the method, the original production function is first determined, the actual output value and the maximum expected output value are calculated, then the two are compared, and finally the error term of the function is divided into two independent error terms: invalid rate term and random error term. This method fully takes into account the role of the random error term on the individual efficiency [38,39]. Therefore, the assessment is more accurate than the DEA. However, the method can only analyze single-output study units, and when there are complex correlations between input indicators, the evaluation results tend to have larger errors.

4.2.5. Emery Analysis (EMA)

Emery analysis, first proposed by American ecologist H.T.Odum, is a quantitative and comprehensive measurement method for a "nature-economy-society" composite ecosystem. Based on the emery theory, the method converts different types and incomparable energy in the eco-economic system into the same standard solar energy value to balance the emery of various energy in the system and quantitatively analyzes the structure, function, and benefit of the eco-economic system [40,41]. The method can be used to evaluate the

ecological efficiency of the natural environment, carrying capacity, sustainable development, and energy utilization of the ecosystem in a certain period of time.

EMA is an approach developed at the interface between thermodynamics systems ecology. It can be used to obtain sustainability indicators and to assess the efficiency of a complex agricultural system and even all kinds of systems, such as countries and regions, while including resource, environmental, and economic values in the calculation and conducting comparative analysis in a comprehensive and integrated manner, which makes up for the deficiencies of traditional economics in which resource pricing is difficult [42,43]. However, the method also has defects, such as single evaluation index, lack of composite index, and geographical differences in energy value conversion rate.

4.2.6. Data Envelopment Analysis (DEA)

In 1978, A. Charnes, W.W. Cooper, and E. Rhodes proposed data envelopment analysis to evaluate the relative effectiveness of decision-making units, referred to as DEA. Since the emergence of the first DEA model CCR, a complete DEA research system of theory, method, and model has been formed. DEA model is a nonparametric analysis method based on the concept of relative probability to evaluate the relative effectiveness or benefit according to the same type of multi-input (input) and multi-output (output) decision unit (DMU) [44]. In the 1980s, the method was introduced to China and developed rapidly. In recent years, DEA has been widely used in efficiency in different fields. Anderson and Petersen (1993) put forward a three-stage super-efficiency DEA model, which allows the analysis and comparison of multiple decision units in the same production frontier [45]. Besides, the disadvantage of the traditional DEA is that it is easy to ignore the unexpected output in the calculation process and does not take into account the redundancy in the input and output variables, so it can not accurately reflect the actual efficiency [46–48]. Tone (2002) proposed the DEA-SBM, considering non-expected output and non-radial and non-angle, which effectively solved the shortcomings of DEA and truly reflected the actual efficiency [49].

4.3. The Impacts of AEE on “Social-Economic-Ecological” System

4.3.1. Impacts of AEE on Social Development

AEE is the result of the interaction between eco-environmental factors and socio-economic factors. Influential factors of AEE include agricultural endogenous environmental problems and exogenous socio-economic factors [50,51]. On the one hand, the application of various chemical fertilizers is related to the transformation and development of agriculture, which has a significant impact on agricultural output and input [52,53]. On the other hand, socio-economic systems and policies, especially those related to sustainable agricultural development, are important external factors, which play a crucial role in influencing AEE [54].

Considering the great differences in agricultural natural resource endowment and economic development level among regions, it can be divided into two corresponding urban areas and rural areas. Urban ecological efficiency is to integrate the construction of ecological civilization into the whole process of urbanization; reflect the characteristics of ecology, personalization, and humanism; and make the coordinated development of nature, society, economy, resources, and environment [51,55]. With the construction of rural revitalization and beautiful villages, rapid urbanization has exacerbated the pressure on the ecological environment. Rural revitalization is inherent in the new urbanization. The Rural revitalization for “three rural issues” are to solve the influx of a large number of rural migrant population into cities, rural hollowing out, and poverty in the process of rapid urbanization. It also includes the harmonious coexistence between man and nature, the modernization of rural governance system, and the reconstruction of urban-rural relations [56]. In view of rural regions, AEE is not only closely related to the form of rural land use but also restricted by agricultural production and rural ecological environment [57]. The strategy to alleviate the pressure of the ecological environment in rural areas is to

ensure that the quality of agricultural products meets people's needs on the premise of environmental and ecological sustainability and also makes ecological agriculture achieve greater development space [58]. Therefore, some scholars put forward that while ensuring the improvement of economic benefits of agricultural production, we need to pay more attention to ecological and environmental protection, make use of the development of agricultural economy to realize the coordination with environmental protection, and promote the sustainable progress of agricultural production [18,59].

4.3.2. Impacts of AEE on Economic Growth

The basic requirement of agricultural development is to realize the sustainable development of ecological agriculture. The agricultural production level is related to the nation's overall economic level. As the Ministry of Agriculture has increased the support of policies to support and benefit agriculture, it has provided a strong guarantee for the development of agricultural economy [60]. With the growing development of society and economy, great changes have taken place in the agricultural production mode, but compared with the rise and rapid development of other industries, the development of agricultural economy is not satisfactory [61]. Due to the rapid population growth and the increasing pressure of economic development, industrialization and urbanization have produced serious damage to the rural ecological environment, which adversely affects the stable and good development of the agricultural economy. Based on the current rural ecological environment, industrialization pollution is more serious, which has a serious impact on rural people's life [60,62]. In response to these negative effects, some scholars point out that we should strengthen the use of high and new science and technology on the basis of traditional agriculture, improve the yield of crops, promote the rapid growth of agricultural economy, and form certain social and ecological benefits [45]. At the same time, it is also necessary to pay attention to the use of ecological economic development model, reduce environmental pollution and waste of resources, optimize and improve the rural ecological environment, promote the healthy and sustainable development of agriculture, and improve the development speed of agriculture [63]. In addition, from the perspective of the industrial chain, some scholars believe that in order to realize the effective development of agricultural economy, we would constantly adjust the agricultural industrialization structure based on our own advantages, create and develop unique products, and closely connect various links and subjects, such as agricultural R&D, production, processing, storage and transportation, marketing, brand, experience, consumption, and service [31]. With the agricultural industrialization consortium as the carrier; public platform of "industry, University, research, and application" as the carrier; and the construction of grain "production, storage, transportation, and marketing" system as the starting point, the whole agricultural industry chain could be built so as to promote the development of agricultural economy and improve the actual utilization efficiency of agricultural resources [64,65].

Production efficiency has always been the hot-spot issue researched by scholars throughout the world and plays an important role in the field of economics. As the basic element of agricultural production, land plays a role in regulating agricultural resources and realizing the coordinated development of agricultural economic development and environmental protection [2]. The internal driving force of AEE is the scarcity of agricultural water and soil resources, which are manifested in the difficulty in carrying out land-scale management and changing the traditional mode of production. The large-scale land is a different agricultural production and management mode from the current small-scale peasant mode of operation management, which is not only conducive to the implementation of agricultural modernization techniques but also conducive to the scientific and rational use of agricultural production mode [66]. Compared with the impact of land fragmentation on the control of agricultural output and input, large-scale production can reduce the input and consumption of natural resources in the process of agricultural production and contribute to the improvement of AEE [62]. The interaction mechanism between land-scale

level and agricultural production efficiency and its impact on the agricultural economy and ecological sustainable development has attracted extensive attention.

4.3.3. Impacts of AEE on Ecosystem Services

Agricultural ecosystem is an ecological economic system, which is produced and evolved from a natural ecosystem. With the advancement of agricultural modernization, in order to meet the social demand for agricultural products, a large amount of material and energy have been invested in agriculture from the outside so that the agricultural ecosystem has evolved into a highly open ecosystem [10]. Due to the influence of biological, cultural, socio-economic, and environmental factors, the agricultural ecosystem is dynamic and especially vulnerable to human interference. Some scholars evaluate the value of ecosystem services through ecosystem indicators, such as domestic pollution emissions, agricultural pollution emissions, and investment in agricultural pollution control [67–69]. The development of agriculture enlightens us that in the process of agricultural production, we must always pay attention to improving the ecological environment, reducing resource consumption, increasing external income, continuously enhancing the efficiency of energy transformation and material circulation in the agricultural system, and improving the production capacity of the ecosystem itself.

Due to the development of industry, the increase of population, the lag of agricultural infrastructure construction, and the influence of extensive management mode, the sustainable development of agriculture is facing severe challenges [58]. How to balance the improvement of AEE with the improvement of the ecological environment has become a very important issue. The abuse of agricultural chemicals, such as pesticides and chemical fertilizers, destroys the stability of the agricultural ecosystem. Insufficient input of organic fertilizer and soil erosion lead to the deterioration of rational properties of farmland [19]. In view of the environment that has caused serious ecological damage, how should we maintain the agricultural ecosystem and build multi-functional ecological agriculture? While ensuring that the quality of agricultural products meets people's needs and the economic benefits of agricultural production, we need to pay more attention to ecological and environmental protection and realize the coordination between agricultural economic development and environmental protection so as to make ecological agriculture achieve greater development space. Only by realizing the protection of ecological environment can we fundamentally improve the efficiency of agricultural production [70–72]. In addition, it is necessary to repair the environment that has caused serious ecological damage in a scientific way and focus on prevention when the ecological environment has not been found to be damaged so as to maintain the sustainable development of agricultural ecosystem [53].

4.4. Drivers and Regulation of AEE

4.4.1. Research on the Driving Factors of AEE

In most cases, dynamic analysis of AEE is needed. The research on AEE driving factors is helpful to scientifically analyze the causes, influencing factors, and improvement ways of AEE loss and is of great significance to promote the rational allocation of agricultural resources and realize the efficient, coordinated, and sustainable development of agriculture [50,73]. In order to explore the influencing factors of AEE, scholars have used grey correlation model, panel threshold regression model, convergence test, and the Tobit model to analyze from different angles, such as agricultural development, macro environment, and policy support [74]. Various factors interact and influence each other, which have a comprehensive and complex impact on agricultural production and management activities and agricultural sustainable development. On the one hand, with the growth of population and the increase of people's demand for food, the use of agricultural chemicals has increased in the process of agricultural production [75]. On the other hand, agricultural development has still not been able to get rid of the dilemma of "petroleum agriculture" [76].

In terms of agricultural development, the density of agricultural machinery has become the first driving force, which is mainly reflected in the impact of the improvement of agricultural infrastructure and the application of environmentally friendly agricultural machinery on improving AEE [77]. Secondly, the scale economy effect of agricultural production has a significant positive impact on AEE and promotes the reform of agricultural production mode [78]. In addition, although the driving force of agricultural productivity and agricultural marketization is weakened, it still maintains a strong driving force. The improvement of agricultural production capacity means that farmers' income is higher, which provides a good foundation for the improvement of AEE [1]. The promotion of marketization will increase the use of agrochemical products in agricultural production for low value-added agricultural products, which are not conducive to the promotion of modern agricultural production methods [79].

In terms of macro environment, the driving effect of industrial structure, urbanization level, and urban-rural gap in AEE has weakened, while the role of scientific and technological support for the development of ecological agriculture has become increasingly prominent [6,18]. The popularization and application of science and technology in agricultural production not only promotes the adjustment of industrial structure and regional sustainable development but also provides technical support for the development of ecological agriculture [80]. In addition, the level of industrialization has a negative impact on AEE. With the improvement of industrialization, harmful substances, such as oil, began to be brought into agricultural production, increasing the unexpected output of agriculture, which led to the reduction of AEE to a great extent [31].

In terms of policy support, the rural land-right confirmation policy shows a strong driving force, which illustrates that the reform of land-use right and management right has not only revitalized land, a rural factor of production and liberated rural productivity, but also promoted the development of agricultural ecology [81]. However, due to the unreasonable expenditure structure of the fiscal policy of supporting and benefiting agriculture, most of the expenditure is spent on subsidies for elements, such as chemical fertilizers, pesticides, and agricultural machinery, that restrict the improvement of AEE [82].

4.4.2. Research on Optimal Regulation of AEE

At present, the root of many problems of AEE lies in the contradiction between agricultural economic growth and environmental protection. The reason is that in most cases, economic development and wealth growth are at the expense of ecological quality and environmental quality. How to deal with the unity of the economic benefits and environmental benefits is the key to the optimal regulation of AEE [70]. It was found that the optimization and regulation of AEE can be divided into direct regulation and indirect regulation. On the one hand, producers and operators regulate and control the relevant factors of the agricultural ecosystem, such as agricultural biology, agricultural environment, and structure and function of agricultural ecosystem [83]. On the other hand, through means and policies, such as finance, market price, industrial communications, science, technology, culture and education, administration, and justice, producers can regulate and control the agricultural ecosystem in the process of agricultural production activities [84]. The regulation of agricultural environment and the structure and function of agricultural ecosystem is an important way to optimize and control AEE. Agricultural environmental regulation is to improve the ecological environment of agricultural organisms by regulating agricultural technical facilities related to soil, climate, and air; changing adverse environmental conditions into advantages; or weakening the harm of adverse environmental factors to agricultural production activities [85] by optimizing and upgrading the structure and function of agricultural ecosystem, realizing agricultural industrialization, promoting the overall coordination of the three rural industries, and boosting the overall coordination of agricultural biology, agricultural environment, and system structure [86,87].

In view of the problems caused by AEE, relevant government departments have formulated a series of policies to realize the coordinated and sustainable development of

economy, society and ecological environment. The government put forward various agricultural policies, such as the national green development pilot area construction policy, green high-quality and efficient action policy, rural residential environment improvement support policy, agricultural non-point source pollution control support policy in the Yangtze River economic belt and the Yellow River Basin, northeast black land protection and utilization policy, chemical fertilizer and pesticide reduction and efficiency support policy, and the pilot policy of planting and breeding combined circular agriculture [36,88]. In 2014, the U.S. agriculture act mainly reformed the price support and income subsidy policy, agricultural insurance subsidy policy, and resource and environmental protection subsidy policy [84]. The EU Common Agricultural Policy promotes regional balanced development by reducing direct subsidies, decoupling subsidies, and establishing an environmental protection subsidy system [36]. Under the framework of WTO agricultural agreement, European, American, and Japanese countries adjust in a timely way and optimize agricultural subsidy policies and gradually shift the mode of agricultural subsidy to the “green box” policy more in line with WTO rules [89]. “21th Century Agenda in China” points out that “the sustainable development of agriculture and rural areas is the fundamental guarantee and priority area of China’s sustainable development” [90]. In addition, the development of efficient ecological agriculture is an effective way to correctly deal with the relationship between economic development and environmental protection. It is not only different from the “petroleum agriculture” with high input, high output, and high land productivity but also different from the organic agriculture with pure nature, self-circulation, and low labor productivity [3]. Ecological efficiency emphasizes the unity of the economic benefits and environmental benefits, which can become an important entry point for quantitative sustainable development at different levels.

5. Discussion

The above analysis indicates that there still exist some deficiencies on AEE research, which ought to be further improved. The literature on the impact of AEE on social and economic development and ecosystem services may teach us that the definition and index selection of AEE are not standardized, and the research is insufficient. It is worth debating whether the current AEE measurement method and index selection are scientifically sound and acceptable. At the moment, popular ecological efficiency research approaches are mainly monolithic, with the DEA model accounting for a sizable portion and no theoretical grounding [91,92]. Therefore, it is necessary to understand the internal and external driving force of the development and change of ecological efficiency from the source and deeper level, build the research theoretical framework of AEE, and then verify it with empirical analysis. With the increasingly tense constraints of agricultural resources and the continuous deterioration of the agricultural ecological environment, AEE has become a great focus in academia. The research has shifted from theoretical research, such as concept definition and significance to empirical research, mainly to the actual calculation, temporal, and spatial characteristics and influencing factors of AEE. In addition, agroecology covers a wide range, and scientific and accurate evaluation of its efficiency is a huge systematic project. In a word, the research on AEE is still in its infancy, and many problems have not reached a consensus. Bringing agricultural carbon emission and carbon sink into the efficient evaluation system can provide a reference for the sustainable development of agricultural ecosystem against a background of low-carbon agriculture and green agriculture [68,76].

5.1. AEE Research from the Perspective of Low Carbon

Low-carbon agriculture reduces carbon emissions as much as possible in the process of agricultural production and brings into full play of the function of agricultural carbon sink, that is, “increasing the carbon sink and reducing carbon emission”. The ultimate goal is low energy consumption, low emission, high carbon sink. and high efficiency in the process of agricultural production. At present, AEE research is scattered to a certain

extent, only focusing on the evaluation of ecological efficiency. Different from the industrial system, the agricultural system has dual functions of carbon emission and carbon sink. Agricultural production activities will produce a large number of greenhouse gas, but at the same time, the agricultural ecosystem also has a strong carbon sink function [93]. Compared with industrial carbon emissions, sources of agricultural carbon emissions are diverse, which can be summarized into the following three aspects: firstly, the input of agricultural means of production, carbon emissions generated in the process of agricultural energy consumption, and agricultural waste treatment; secondly, the amount of carbon sequestration in farmland ecosystem, that is, to measure the carbon sequestration function of crops; and third is the carbon emissions from breeding animals and livestock [94,95]. Because agricultural production activities have obvious external and internal characteristics, it is of great significance to integrate agricultural carbon emissions and carbon sinks into the agricultural efficiency evaluation system and investigate AEE from the perspective of low carbon. On the one hand, farmers' excessive input of chemical fertilizers and pesticides in the process of agricultural production or the use of wrong farming methods will lead to an increase in carbon emissions. If the environmental costs caused by agricultural carbon emissions are internalized, the level of agricultural output will decline significantly. On the other hand, if we do not consider carbon sequestration produced by crops, grasslands, and forests, we will underestimate agricultural efficiency. It can be seen that carbon emission and carbon sink are important aspects of negative and positive externalities of agricultural production activities. AEE research should be comprehensively and objectively evaluate the AEE from the perspective of low carbon, taking the carbon emissions generated in the process of agricultural production as unexpected output and agricultural carbon sink as ecological output [96].

5.2. The Impact of Farmland Ownership Confirmation Reform on AEE

By improving the stability, security, and integrity of land rights, the confirmation of agricultural land rights significantly reduces the input and use of chemical fertilizers and pesticides and helps to promote the ecological protection of cultivated land aiming at the reduction of chemical fertilizers and pesticides. Cultivated land is the material basis carrier to achieve sustainable agricultural development and maintain national food security. The foundation of cultivating land ecological protection is its property right protection. As the vivid practice of cultivated land property right protection and the basic content of agricultural land property right reform, agricultural land right confirmation has special significance for cultivated land ecological protection [81,97]. However, whether confirmation of agricultural land rights is conducive to the ecological development of agriculture remains to be tested by experience. On the one hand, the property rights of farmland owned by farmers are no longer incomplete and fuzzy, and farmers will be willing to make decisions to reduce the investment of chemical fertilizers and pesticides [97]. On the other hand, in view of agricultural profits, if farmers expect that reducing the corresponding input cannot reach the expected output level, farmers are likely to temporarily increase the input of chemical fertilizers and pesticides [72]. Since the usual time of chemical fertilizers and pesticides is earlier than the implementation time of their policies, the expected impact of this index is unknown. In general, after the reform of rural land ownership, the right boundary of rural land property rights is clearer, the land rights and functions are more complete, and the protection of rights and interests is more powerful, which is conducive to enhancing farmers' awareness of rural land protection. The way of agricultural land ownership confirmation directly affects the use of chemical fertilizers and pesticides in the process of agricultural production and is an important factor affecting AEE.

5.3. AEE Temporal and Spatial Characteristics and Influencing Factors

Firstly, the temporal evolution trend and spatial distribution characteristics of AEE were analyzed, and the temporal and spatial characteristics of AEE in China were discussed. It was found that from the perspective of regional differences, there is a regional imbalance

in the growth of AEE. The high-efficiency area of AEE is still dominated by the eastern coastal provinces, but it tends to transfer to the central and western regions [7,55]. From the perspective of time evolution, the overall AEE in China shows a fluctuating upward trend, and there are some inter-provincial differences [98]. The government should strengthen policy guidance, promote the diffusion of efficient production factors in the eastern region to the central and western regions, and gradually improve the AEE of medium- and low-efficiency areas. It can be seen that AEE is related to economic development and the overall requirements of industrial structure transformation and upgrading as well as the location conditions, resource endowment, and policy implementation effectivity and economic development level of each province.

In addition, the important driving factors of the temporal and spatial evolution of AEE were discussed from the overall national overall level and regional level. From the driving factors, the confirmation of agricultural land rights, the level of financial support for agriculture, per capita agricultural GDP, agricultural production capacity, agricultural machinery density, agricultural scale level, agricultural disaster rate, and industrialization and urbanization level play a driving role in AEE. From a national perspective, the ecological development of agriculture should start with the development of agriculture itself, make use of new environmental protection technologies, and clarify the ownership of land property rights [57]. From a regional perspective, all regions make full use of their respective regional advantages to develop ecological agriculture according to local conditions. Among them, the technological progress index contributes the most to the improvement of AEE [59]. Therefore, the key to improving AEE is to promote agricultural technology progress and management innovation and promote the transformation of extensive agricultural management mode to ecological energy consumption and intensive energy-consumption path.

6. Conclusions

AEE is an important index to evaluate the ability of agricultural sustainable development. The problem of eco-efficiency has been widely concerned by the public. The research on AEE is a complex system engineering under the background of increasingly serious agricultural pollution. Focusing on AEE, the purposes of this article are to investigate the progress of AEE research based on literature metrology software (CiteSpace) and literature systematic review, summarize the key areas and research hotspots of AEE research, and determine the challenges and put forward the potential direction of future research. Through systematic combing, it was found that there are some problems in the study of AEE, such as inconsistent concept definition, convergence of evaluation methods, and so on. Therefore, the index system of AEE evaluation should be improved in the future evaluation. Accurate evaluation of AEE is helpful to understand the real value of agricultural ecosystem, form an agricultural production mode of saving resources and protecting ecological environment, and then fundamentally solve the problems of agricultural ecosystem degradation and environmental pollution so as to lay a foundation for the sustainable development of agriculture. Through the above comprehensive analysis, we have drawn the following conclusions:

(1) From 1999 to 2021, the annual output of papers exhibited an upward trend, which experienced two stages of “slow development period” and “rapid development period”. This trend can be explained as a sign of the increasing importance of AEE in ensuring the construction of agricultural ecological civilization. However, the cooperation and communication between research institutions are insufficient, and an effective cooperation network has not been formed among research authors.

(2) Research on AEE is characterized by a clearer and more systematic analysis of resource utilization efficiency and environmental protection in agricultural development based on the comprehensive and complex influence of various factors. The key fields and hotspots of existing AEE research can be summarized into four aspects: (i) AEE theory and

assumptions; (ii) evaluation methods of AEE; (iii) the impact of AEE on “socio-economic ecological” system; and (iv) drivers and regulation of AEE.

(3) The complexity of AEE research requires the diversity of disciplines, evaluation methods, and research scale. It covers many disciplines and fields, such as ecology, economics, and environmental science, and integrates ratio analysis, life-cycle assessment, stochastic frontier analysis (SFA), ecological footprint analysis, emergy analysis, and data envelopment analysis (DEA). The research scale discusses the temporal and spatial evolution of AEE and its important driving factors from the national and regional levels. However, research on AEE is mainly based on the macro level, and the in-depth analysis at the micro level is not sufficient. Due to the complexity of the root causes of the deterioration of the agricultural ecological environment, there will be many ways to optimize and regulate AEE. At the same time, the improvement of relevant science and technology promotes the rapid growth of agricultural economy and forms certain social and ecological benefits.

(4) There are still many unsolved fundamental problems in the research on AEE. Theoretical research of AEE lags behind the research practice. Although considerable progress has been made in AEE research and related fields, there is no unified research theoretical framework. The pursuit of theoretical improvement should also strengthen the relationship between AEE and economic development, industrial structure transformation, and upgrading and location advantages so as to take the road of sustainable development and to ensure sustainable development. Based on the analysis of this paper, the research on AEE tends to be gradually mature and enriched in the more in-depth and detailed ways in the future research.

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