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Review

A Review of Climate-Smart Agriculture: Recent Advancements, Challenges, and Future Directions

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Abstract: Global climate change has posed serious threats to agricultural production. Reducing greenhouse gas (GHG) emissions and ensuring food security are considered the greatest challenges in this century. Climate-smart agriculture (CSA) is a concept that can provide a solution to the challenges that agricultural development faces. It can do so in a sustainable way by increasing adaptability, decreasing GHG emissions, and ensuring national food security. So far, little research has systematically reviewed the progresses in CSA in developing and in developed countries. A review on the recent advancements, challenges, and future directions of CSA will be quite timely and valuable. In this paper, the definition and development goals of CSA are identified. Then, the recent advancements of CSA in developing and in developed countries are reviewed. The existing problems and challenges in CSA are analyzed and pointed out. Finally, the proposals on prospects and directions for CSA in the future are proposed. Using advanced internet technology to ensure agricultural information security, improvement of cropping patterns, and management techniques, carrying out "internet + weather" service and improving the quality of agricultural service, and conducting agricultural weather index-based insurance are considered as the main direction of future development of CSA. This review provides new ideas and strategies for strengthening ecological environmental protection, promoting agricultural green development, and mitigating climate change.

Keywords: climate change; climate-smart agriculture; internet technology; management technology; cropping patterns; agricultural weather index-based insurance

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1. Introduction

Global warming is an indisputable scientific fact indicated by decades of meteorological observations [1]. GHG emitted by human activities traps heat in the atmosphere, leading to increases in global average temperature, and consequently global climate change [2,3]. In particular, the rise in temperature has increased by about 40% in the past 150 years, half of which has occurred in the past 30 years [1]. The increase of GHG concentration has wider impacts, such as more extreme weather events, deadly heat waves, severe drought, posing serious threats to agricultural production [4], and finally impacting net crop income [5] and farmland value [6]. Agriculture has a large carbon footprint, accounting for more than 25% of global anthropogenic GHG emissions [2]. Specifically, soil organic matter decomposition and crop residue burning are the main sources of carbon dioxide (CO_2) emissions in agriculture. Agricultural methane (CH_4) emission comes from the flooded soil under rice planting, intestinal fermentation in livestock digestive system, and decomposition of feces and crop residues in moist conditions. Agricultural nitrous oxide (N_2O) emission mainly comes from the nitrogenous soil, manure, and compost. Globally, economic and population growth are the most important driving factors for the increase of GHG emissions, which are projected to continue to increase in the future [7]. Therefore, reducing GHG emissions and ensuring food security are considered the greatest challenges of this century [8].

CSA commit to transform and reposition agricultural development to meet the climate change challenges [3]. The CSA framework provides a platform for assessing how livelihood assets operate and how they are affected by policy processes and structures, as well as the technologies needed for restorative agricultural transformation [9]. CSA seeks to intensify linkages among global, national, and local agricultural stakeholders by accelerating cross-scale adaptation and mitigation synergies [10]. Therefore, CSA presents a triple win effect, which can continuously improve agricultural production capacity, income, and adaptability to climate change, reduce and even eliminate GHG emissions, and thus promote the realization of national food security and sustainable development goals, providing a solution concept for the problems faced by global agricultural development [3,11].

Improved water management technologies, crop breeding, conservation agriculture, crop diversification planting, weather index-based insurance, integrated management practices of soil fertility, and other high and new technologies are all included in the scope of CSA [12]. Scientists have demonstrated, through a number of important studies on the CSA over the past few decades, that these CSA technologies and practices can increase productivity, income, and food security in various regions. For example, the adoption of improved crop varieties that adapt to environment stress can improve yield, farmers' income and food security [12], such as drought resistant bean [13] and drought tolerant maize [14]. Diversification of agricultural systems increases crop yields, stability, profitability, and other livelihood benefits [15,16]. For example, Assefa et al. [16] conducted experiments for three years with five cropping systems (improved varieties of rice-maize, rice-mung bean and rice-sunflower; traditional varieties of rice-mung bean and rice-fallow) in Bangladesh. They revealed that the crop yields in rice-maize and rice-sunflower double cropping systems were the highest, and that the average yield gap between improved varieties could reach 30%. In addition, application of integrated soil fertility management practices with cropping systems is highly associated with improved soil nutrient uptake and crop yields [17,18]. Mhlanga et al. [17] carried out an experimental study on the response of maize yield to the comprehensive effects of the cropping system and soil parameters in Zimbabwe. They found that the conventional tillage plus mulch and rotation (CT + M + R) system and no-tillage plus mulch and rotation (NT + M + R) system had the highest yields and Zn uptake. Application of some high and new technologies can also increase crop productivity, such as satellite remote sensing [19–21], internet of things [22,23], and artificial intelligence [24,25]. Agricultural remote sensing not only helps to manage the planning and strategies of agricultural production from regional to global scales, but also provides tactical control information for CSA operations on a farm scale. By combining the internet of things and artificial intelligence technologies, better insights can be effectively generated from field data collection, and farming methods can be systematically planned for obtaining the highest yield with the least manual labor. For instance, Astor et al. [19] used hyperspectral and RGB 3D UAV data to estimate the biomass of cabbage, tomatoes, and eggs in India. Wicaksono et al. [23] designed an internet of things system and applied it in rice planting and management for increasing agricultural land productivity in East Java.

Existing reviews on CSA tend to focus on either advanced technologies or practice aspects of CSA [12–23]. Although other than these reviews and overview efforts, to our knowledge, few studies have systematically reviewed the progresses, challenges, and future directions in CSA. Moreover, CSA has witnessed more rapid developments and advances in the last decade. A comprehensive review on the recent advancements, challenges, and future directions of CSA will be quite timely and valuable.

Here, this review is arranged as follows: Section 2 explains the definition and development goals of CSA; Section 3 introduces the recent advancements of CSA in different countries; Section 4 analyses the existing problems and challenges in CSA; and Section 5 proposes the future directions for CSA. This review provides new ideas and strategies for strengthening ecological environmental protection, promoting agricultural green development, and mitigating climate change.

2. Definition and Development Goals of CSA

The Food and Agriculture Organization of the United Nations (FAO) formally proposed CSA, food security, and climate change at the Hague Conference on agriculture in 2010. CSA is an agricultural production and development model that can sustainably improve agricultural efficiency, enhance adaptability, reduce GHG emissions, and ensure national food security [26]. It combines the three components of economy, society, and environment by working together to address climate change-related threats to food security and sustainable agricultural development [9].

The specific objectives of CSA are mainly reflected in three aspects: sustainably improving the production efficiencies of agricultural systems which can support farmers' income, ensure food security, and enhance the ability of agricultural systems to adapt to climate change; reducing or eliminating the GHG emissions of agricultural systems as far as possible; enhancing the carbon sequestration capacities. Finally, the tripartite win-win goals of production increase, stress resistance, and GHG emission reduction in the agricultural systems are achieved [3,9]. Even though CSA aims to achieve all three objectives, not every practice used in every location can result in three victories. In order to arrive at locally acceptable solutions, CSA needs to consider all three goals at local to global scales from short-term and long-term perspectives. The relative importance of each goal will vary according to the location and situation. The priority of realizing the three objectives of CSA should be focused on, and the balance between the three needs to be found [3].

3. Recent Advancements of CSA in Different Countries

3.1. CSA in Developing Countries

For developing countries, agriculture is the main economic source of many countries. Climate change threatens the agricultural production and food security in developing countries in complex ways. Consequently, increasing agricultural production efficiency, guaranteeing food security, and fostering economic growth should be given top priority while setting CSA development goals in these developing nations. At the same time, the GHG emission reduction in agricultural systems should be gradually realized through the investment of additional funds [3]. Under the CSA idea, the developing countries have given corresponding solutions according to the situation of different regions (Table 1).

Maharashtra in India is a significant climate risk region. The biggest issue with agricultural production in Maharashtra is the lack of irrigation water during dry seasons. Therefore, the drought can be solved through irrigation water management technologies, such as well digging, pipe well, rainwater collection, drip irrigation, and other groundwater extraction methods. Combining with nutrient management methods, such as farmyard manure, earthworm compost, straw residue incorporation, the sprinkler irrigation and other micro irrigation technologies can improve the utilization efficiency of water and fertilizer and agricultural productivity, and reduce the total amount of agricultural water and fertilizers and GHG emissions [27–29].

Using excellent rice varieties, optimizing sowing and harvest dates, reducing chemical fertilizers, and modifying irrigation plans in the Mekong Delta of Vietnam have all helped farmers to increase crop yields, cut down production costs, and ensure food security [30–32]. In Nepal, farmers adopt management measures, such as no tillage, crop rotation and straw returning to the field, which can improve soil biological activity, water use efficiency, and soil physical properties [33]. The improved soil can increase the tiller number, plant height, and grain yield of wheat, and also reduce erosion. In Pakistan, local cotton farmers adopt the CSA idea, and use bed seeders and lasers to level the land. Through using the measures of indirect water use and drainage management, such as less tillage and fallow, improved varieties resistant to drought and waterlogging, the local cotton qualities are improved, and the GHG emissions are indirectly slowed down [34].

Table 1. Adaptation measures for CSA in different countries.

Country	Representative Countries	Major Difficulties	Adaptation Measures for CSA
Developing countries	Maharashtra of India in Asia	• Significant climate risks; • Lack of irrigation water; • GHG emissions.	• Irrigation water management technologies, such as well digging, pipe well, rainwater collection, drip irrigation, and other groundwater extraction methods; • Combined with nutrient management methods, such as farmyard manure, earthworm compost, and straw residue incorporation.
	Mekong Delta of Vietnam in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Using excellent rice varieties; • Optimizing sowing and harvest dates; • Reducing chemical fertilizers; • Modifying irrigation plans.
	Nepal in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Adopting management measures, such as no tillage, crop rotation, and straw returning to the field; • Improving soil biological activity, water use efficiency, and soil physical properties.
	Pakistan in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Use bed seeders and lasers to level the land; • Through using the measures of indirect water use and drainage management, less tillage and fallow, and improved varieties resistant to drought and waterlogging.
	Zambia in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Protective agricultural measures, such as organic mulching of surface crops in farmlands, rotation of legumes and cereals, and improved crop varieties.
	Malawi in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Adopting the continuous agroforestry intercropping of two main fertilizer species; • Agroforestry complex system.
	Namibia in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Collecting nutrient rich earthworm compost leachate; • Carrying out hydroponic cultivation; • Planting mushrooms along the coast of the Namib Desert; • Gathering fog water.
Developed countries	California in the United States	• Flexibility of agricultural system; • GHG emissions; • Production efficiency.	• Upgrading underground water pumps; • Installing drip irrigation or micro sprinkler irrigation systems; • Formulation and implementation of policies.
	France in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Paying attention to the service functions of agricultural ecosystems; • Developing precision agriculture.
	Switzerland in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Recycling the waste generated by the farm itself to the biogas plant for free; • Production of renewable energy.
	Netherlands in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Adopting the LED horticultural technology; • Increase the viability of horticulture.
	Cyprus in Asia	• Impacts of climate change on agricultural development; • GHG emissions.	• Using agricultural robots to spray pesticides on crops; • Strengthening crop protection and production; • Reducing the use of pesticides; • Improving the sustainability of the agricultural environment.

In Africa, in order to solve the two expanding and connected concerns of food security and climate change, some significant agricultural reforms are required [26]. For example, in Zambia of Southcentral Africa, protective agricultural measures, such as the organic mulching of surface crops in farmland, rotation of legumes and cereals, and improved crop varieties are used [35]. These actions in Zambia have the potential to boost soil fertility and carbon fixation capabilities, greatly raising grain yields on average, and efficiently guarantee local food securities. Moreover, Malawi in Africa has adopted the continuous agroforestry intercropping of two main fertilizer species, and the orderly agroforestry fallow of planting fast-growing leguminous trees or shrubs, as well as the agroforestry complex system [36,37]. These measures in Malawi increase the amount of soil nitrogen fixation, improve the level of soil nutrients, and significantly slow down the emission of GHG, such as CO_2 and N_2O [35]. The farmers in Namibia have increased additional income by collecting nutrient rich earthworm compost leachate, carrying out hydroponic cultivation, and planting mushrooms along the coast of the Namib Desert. In order to save irrigation water, they also gathered fog water to use as irrigation water for the agricultural production in coastal desert areas, or they mixed seawater with fog water to precisely drip-irrigate crop roots [38]. Through these additional measures, Namibia has alleviated the crisis of food shortage and enhanced its adaptability to climate change.

3.2. CSA in Developed Countries

For developed countries, they have developed agriculture, high economic efficiency agricultural products, relatively rich per capita land resources, and perfect mechanized and intensive production. As a result, the CSA's development objectives in these developed nations are primarily focused on lowering GHG emissions and improving agricultural capacity to adapt to climate change. At the same time, they need to integrate high and new technologies, pay attention to the formulation and implementation of policies, enhance the flexibility of the agricultural system, and reduce GHG emissions while improving production efficiency [39]. California in the United States, one of the most productive and resource-rich agricultural regions in the world, places a greater emphasis on the sustainable management of water resources and the reduction of GHG emissions in order to achieve CSA [40]. Through a series of laws and regulations, as well as pertinent agricultural technical measures of the public research system, the California government has obtained the goal of reducing GHG emissions.

For example, the latest methane law requires the dairy industry to reduce methane emissions by 40% before 2030 [41]. The government of California views increasing agricultural water use efficiency as a strategy for resolving the water resources issue, in terms of water resources management. The local government helps farmers to overcome the high investment cost, reduce GHG emissions, and adapt to water restrictions by upgrading underground water pumps and installing drip irrigation or micro sprinkler irrigation systems to improve water storage and recovery capacity [42,43]. However, in Europe, where agriculture is developed, people pay more attention to the impacts of climate change on agricultural development [44]. Therefore, European countries mainly give play to the service functions of agricultural ecosystems. The integration of satellite data in agricultural models, combining remote sensing with agricultural models to develop precision agriculture, was applied in France. We can make better decisions in facing uncertain weather, managing our time more effectively, saving money on investments, and possibly cutting GHG emissions if we use technologies to better adapt to climate change [11]. In response to the GHG emission plan, Switzerland recycles the waste generated by the farm itself to the biogas plant for free, reduces GHG emissions through the production of renewable energy, and provides the farm with high-quality fertilizers and feed additives improved by the biogas plant [45]. The Netherlands has increased the viability of horticulture through LED horticulture technology, making it less vulnerable to climate change. Compared with traditional lighting, this LED technology reduces the heat load and energy use, improves the light distribution, and has a positive impact on the growth of gardening [39]. Cyprus uses agricultural robots to spray pesticides on crops, strengthening crop protection and production, reducing the use of pesticides and improving the sustainability of agricultural environments [46].

The aforementioned nations have carried out a series of practices centered on the CSA's development goals in response to various regional conditions, as well as independently verified the CSA's implementation to varying degrees. The above results show that CSA is well implemented in various countries. Some nations have been successful in achieving their objectives by diminishing GHG emissions, increasing income and production, enhancing climate change adaptability, and improving agricultural practices (Table 1).

4. Challenges in CSA

4.1. Shortage of Agricultural Water Resources

Water security is the basis of food security. At present, the shortage of agricultural water resources has become a rigid constraint on global food security and sustainable development of CSA. The global water demand is expected to rise by 55% [47]. The current water shortage is rapidly growing and impacts agricultural water consumers worldwide [48]. A study showed that water shortage in agriculture reduced the yield and protein of sweet corn in Turkey. Moreover, the fresh ear yield, marketable ear number, leaf area index, and the concentration of Fe, Zn, and Cu in kernels reduced with the increase of water deficiency [49]. A study indicated that arid Northwest China in 2010 had a medium and low risk of agricultural water resource shortages [50]. The risk of agricultural water resource shortages was predicted to increase significantly in 2030, to a medium-high risk level. Zhang et al. [51] revealed the grain yield and water use efficiency decreased with rainfall shortage in the Loess Plateau, which was a typical dryland agricultural region in China. In addition, some coal-mined areas are often associated with hostile environmental conditions where the scarcity of water and key nutrient resources negatively affect plant growth and development. A study indicated the combination application of water, nitrogen, and phosphorus promoted the ecological restoration of coal-mined areas under arid environmental conditions [52].

Assessment of agricultural water resources is critical for planning and management over a long period of time. For example, in South Korea, the agriculture in irrigated areas is easily affected by water shortage due to seasonal changes in rainfall and water quality [53,54]. In recent years, due to the shortage of water resources and its uneven distribution at spatiotemporal scales caused by climate variability, such as drought and heat waves, the available agricultural water resources were in decline [55]. Therefore, estimating the supply and demand of agricultural water resources under climatic warming was becoming more and more important for the development of CSA.

4.2. Climate Variability and Climate Change

Climate change caused by human activities poses challenges to global food production and sustainable development of CSA. How to actively respond to climate change, improve agricultural productivity, and reduce GHG emissions in a more sustainable way is a common topic faced by the international community [9]. Climate variability and climate change have changed the distributions of light, heat, water, and other agricultural climate resources. Climate variability has a destructive impact on smallholder agriculture, resulting in a reduction in crop yield, income, and food insecurity [56]. A questionnaire from Ghana showed that climate variability greatly affected subsistence agriculture, and caused 58% families to experience food anxiety, while 62% of families could not acquire the amount and quality of food they liked [57]. Direct impacts of climate change on agriculture include the increased average temperatures, prolonged growing season length, increased number of hot days and hot nights, more variable precipitation patterns, and elevated CO_2 concentrations [58]. It is estimated that these direct effects of climate change on crop production will continue to change in space and time in the world, especially in developing countries where food crops are the mainstay [59]. It is generally acceptable that the predicted yield in some regions will increase, while the predicted yield in other regions will decrease [60]. For example, Long et al. [61] predicted the wheat yield in the Yellow River Basin of China, and found an average reduction of 0.19% during 2020–2050 compared with the baseline period (1975–2005), with a large spatial variation in wheat yield. Daloz et al. [62] revealed the direct impact of climate change on wheat yields in the Indo-Gangetic Plain. They reported that the increase in average and maximum temperature, as well as precipitation in the growing season led to the 1–8% loss of wheat yield.

However, unforeseen climate variability and environmental variables are increasing year by year and continue to threaten food security in some areas [2]. If GHG continue to be released at the current rate, it is projected that many countries will easily suffer from extreme climatic conditions, including persistent drought, severity drought, and daily maximum rainfall, posing a threat to food security [63]. In addition, changes in temperature and precipitation caused by climate change may strongly alter regional climates, leading to potential shifts in crop distribution [64]. Combined with income growth, climate change can change the specific nutrients, carbohydrates, and proteins, and so on. Therefore, for low-income countries, how to obtain various nutritional food sources is crucial for the improvement of sustainable nutrition security under climate change [65].

4.3. Agricultural GHG Emissions

Agricultural GHG emissions further expand challenges to the sustainable development of CSA. The fossil fuel use, land use change, and deforestation have led to significant increases in anthropogenic GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) has stressed the influences of GHG emissions on climate change [1]. GHG emissions have resulted in ecosystem imbalance [66]. Agricultural ecosystem is the second largest source of global anthropogenic GHG emissions, accounting for 56% of the total non-CO_2 emissions [67]. Seven nations—Argentina, Australia, Brazil, Canada, Chile, China, India, and the United States—are estimated to be responsible for more than half of the world's total soil emissions and 49% of the world's total agricultural emissions [68]. Statistics from South Korea show that the agricultural sector accounts for nearly 3.4% of the total GHG emissions in Korea, of which 58% comes from crop planting [69]. Agricultural practices can, not only produce the GHG emissions, but also emerge the nitrogen and water footprints [70,71]. Although agriculture is a primary source of GHG emissions, it also has significant potential to reduce them. This requires us to not only improve agricultural production efficiency and ensure food security, but also to reduce agricultural GHG emissions. Some technologies can effectively reduce agricultural GHG emissions by controlling GHG emissions (such as clean energy alternative technology, renewable energy technology, and new energy technology), increasing GHG absorption (such as carbon fixation technology), adapting to climate change (such as cultivating new crop varieties and adjusting agricultural production structure), etc.

4.4. Information Resource Integration

In the production, management, transportation, and sales of CSA, product information and data support are indispensable. Therefore, maintaining the security of information and data is key to promoting the smooth development of CSA. However, from the perspective of the development process of CSA, there are some problems in the information and security of CSA, such as low standardization, incomplete data collection and sorting, and lack of accuracy and effectiveness in agricultural data collection. Real-time sharing of information technology resources is currently difficult to obtain, and the CSA information security issue is acute. The basic security of agricultural information has become a major issue in the long-term development of CSA. In addition, CSA will also face the problem of overloaded agricultural information. If false information cannot be correctly identified, it will affect the long-term development of CSA.

5. Future Directions of CSA

5.1. Using Advanced Internet Technology to Ensure Agricultural Information Security

5.1.1. Application of Remote Sensing Techniques

Remote sensing technology is widely used in various fields because of its fast, macro, real-time, dynamic, large-area observation, and easy economic access. The characteristics in physics of the globe's surface can be detected and monitored using remote sensing, which gathers data from satellites or unmanned aerial vehicles. The three most common properties of remote sensing data are the spatial resolution, spectral resolution, and temporal resolution [72]. Spatial resolution is the pixel size of an image, which affects the ability to detect objects through imagery. Spectral resolution is the spectral sampling interval, size and quantity, which affects the ability of the sensor to detect targets in the electromagnetic region. The temporal resolution is the frequency of acquired data. With the continuous improvement of temporal, space, and spectral resolutions of remote sensing observation, and the improvement of remote sensing inversion algorithms and products, remote sensing has become an important means and has wide prospective applications in regional-scale CSA [20,73].

For decades, image-based remote sensing has been used for precise crop management. However, hyperspectral images have brought about a vast improvement in the identification and differentiation of crop nutrients, diseases, and canopy structures [74]. In addition, images, general reflectometry, and three-dimensional (3D) mapping of crop spectral dynamics have provided insight into agricultural productivity [75]. For example, the China Agriculture Remote Sensing Monitoring System has been in operation since 1998, which was initially developed by the Remote Sensing Application Center in the Ministry of Agriculture of China [76]. This system can monitor crop growth, planting area, yield, and agricultural disaster information for staple crops in China, including wheat, corn, rice, soybean, cotton, canola, and sugarcane. By combining the abundance of information of rice mixed components calculated with the spectral index, Yuan et al. [77] distinguished the spectral difference between rice and background. Multispectral, hyperspectral, and thermal imaging sensors also provide convenient conditions for crop stress studies [78–80]. Fertilizer and pesticide management in the field can be further enhanced by combining a wireless sensor network on the ground with a remotely operated aerial vehicle [81].

At present, there are some contradictions in spatiotemporal resolution of remote sensing observation data. The data with high spatial resolution has a low temporal resolution, which makes it difficult to capture the dynamic changes of crops during the vigorous growth period. The data with high temporal resolution has a low spatial resolution, so mixed pixels will appear in data fusion. These bottlenecks of remote sensing inversion accuracy need to be improved. In the future, the fusion of multi-source remote sensing data is an important development direction for the sustainable development of CSA. By fusing data from multiple sources with varying spatial and temporal resolutions, it is possible to obtain more exact and precise dynamic changes in the crop growth light of the growing abundance of remote sensing data.

5.1.2. Application of Internet of Things

Internet of things (IoT) is a cosmos of interconnected computing devices, sensors, and machines connected to the internet. Each device has a unique identity and the ability to implement remote sensing and monitoring [82]. In the agricultural field, the IoT is mainly used to collect data through different types of sensors, including environmental and crop parameters, such as temperature, humidity, pH value, leaf color, etc. Numerous aspects of the IoT implementation in agricultural sectors have been examined, including evaluating IoT applications [83] and developing IoT architectures for food control [84], to checking the integration of the IoT and agriculture UAV in smart agriculture [85,86].

The future development of the IoT for CSA needs to be strengthened in the following several aspects: Firstly, the IoT system must have a high adaptability and be customizable to local circumstances considering the great difference in farmers' demands. Secondly, the

IoT deployment must be efficient and configured in each system. The network connection and farm infrastructure must be reliable, and adequate human and economic resources must be arranged. Lastly, the IoT in CSA farming must be safe. This is because data is often valuable to farmers and is considered a trade secret. As a result, the sensor network of the IoT must have a security strategy that is in sync with cloud database and prospective calculation networks that are actually in use [87].

5.1.3. Application of Artificial Intelligence

Artificial intelligence application is another direction of CSA in the future. Artificial intelligence (AI) uses a digital computer or other controlled machines to simulate, extend, and expand human intelligence, perceive the surrounding environment, and acquire relevant knowledge. AI has already demonstrated its great advantages in many fields [25]. The latest advances in computer hardware and big data have created space for the application of AI in agriculture. At present, AI is being used in many fields of agriculture, and can analyze and integrate data from different agricultural fields to realize plant recognition, weed prediction, crop yield prediction, GHG emissions forecasting, climate prediction, pest control, crop planting risk assessment, etc. [24,88]. In particular, AI can improve crop yield, not only by accurately forecasting the optimum sowing and harvesting date, and monitoring crop health, but also by decreasing the agricultural input costs, such as fertilizers, chemicals, and irrigation. Accordingly, agricultural risks can be minimized by solving problems, such as insufficient precipitation, weed growth, and disaster losses.

However, many algorithms in the AI model are extremely dependent on the amount and accuracy of the data. The more data, the more accurate the prediction and judgment made by building AI models. In the future, the collection and analysis of data from different sources, such as soil, climate, diseases, and pests should be strengthened through AI technologies. By predicting various factors that affect crop yield, and assessing the health status of crops and the occurrence probability of diseases and pests, the high quality and quantity of crops are ensured. In addition, the extensive application of the deep learning method is another direction of AI technologies, because it expands the machine learning method by increasing the depth of the model. The main characteristic of deep learning is to process the original data to improve the accuracy and classification. The accuracy of plant identification, fruit counting, and crop yield prediction can be improved by using deep learning technology.

5.2. Improvement of Cropping Patterns and Management Techniques

Rice-wheat rotation and rice-potato-sesame cropping are examples of multiple cropping patterns, crop diversification practices, and no-till agriculture that can increase agricultural productivity and reduce GHG emissions [75,89], and introducing suitable dryland crops to reduce the submergence period in the annual planting cycle [90]. Combining inorganic fertilizers with organic improvers is a common practice to improve soil quality and crop productivity, especially for low fertility soils [91]. For example, as a soil additive, biochar is considered as a good synergist, because it has great potential in fixing carbon, repairing soil, and improving soil quality and crop productivity [92]. Adding biochar can change the release of soil nutrients and C/N cycle in soil, thus affecting GHG emissions from farmland [93]. Some soil protection practices aimed at reducing CO_2 emissions are recommended, such as using crop residues, improving nitrogen utilization efficiency, and reducing planting [94]. Applying crop residues can increase soil organic carbon, which can enhance crop yield [95]. These practical measures can further conserve water, improve soil structure, strengthen the element cycle, improve the increase of agricultural productivity, and reduce GHG emissions. It is important to note that carbon sequestration and carbon loss from soil in different agricultural systems vary greatly. In addition, the cultivation technology of conservation agriculture has been widely used in agricultural production with its unique ecological protection role, and is regarded as an important sustainable agricultural technology. The development of CSA in the future will carry the sustainable development of agriculture forward and achieve the multiple goals of food security, climate adaptation, and GHG emission reduction. Improvement of cropping patterns and management techniques contributes to the realization of CSA in the future.

5.3. Carrying out "Internet + Weather" Service and Improving the Quality of Agricultural Service

At present, agriculture has developed towards mechanization and industrialization. In the process of future development, it is bound to put forward higher requirements for meteorological services. Internet technology should be used to effectively combine meteorological services with farmers' needs. The technology platform is used to closely combine growers, transport households, service institutions, and consumers to form a vertical meteorological service system for agriculture. In the future, carrying out "internet + weather" service and improving the quality of agricultural service, and the combination of human-computer interaction, comprehensive meteorological observation and other automatic weather stations can better meet the needs of rural and agricultural construction, improving the ability of weather forecasting, monitoring and early warning, and realizing the goals of CSA.

5.4. Agricultural Weather Index-Based Insurance

Agrometeorological indicators used as the trigger mechanisms in agricultural insurance, known as agricultural weather index-based insurance, can lessen or eliminate the negative effects of natural risks on agricultural output. If it exceeds the predetermined standard, the insurer will be responsible for compensation. There is no need to analyze and calculate the loss from door to door because it is unrelated to the actual situation with regard to crop damage following the catastrophe. Agricultural weather index-based insurance applies the concept of financial instruments to the risk management of natural disasters, and attracts social funds to participate in the dispersion of agricultural natural risks, providing a new way for the risk transfer of agricultural producers. It is simple to settle claims and easy to promote, overcoming the adverse selection and moral hazard of traditional insurance, and reducing the operating cost [96].

With the development of weather index-based insurance products for a variety of weather circumstances, many developing nations have started to bring weather index-based insurance into the market of agricultural insurance. Since the beginning of the 21st century, the agricultural weather index-based insurance products in developing countries have gradually appeared in India, Ethiopia, Mongolia, Africa, Central Asia, and other places [97–101]. At least dozens of weather index-based insurance plans are piloted in developing countries. For example, smallholder farmers have the willingness to pay for flood insurance as a climate change adaptation strategy in Northern Bangladesh [102]. Despite the fact that the demonstration work has produced positive outcomes by and large, and given the relatively limited exploratory time and experience, it is impossible to achieve long-term and sustainable developments. In the future, the agricultural weather index-based insurance is considered as an important development direction of CSA. In order to meet the needs of stabilizing agricultural production, ensuring food security, and realization of CSA goals, further studies on the evaluation methods and indicator systems of agricultural weather index-based insurance, as well as the cause, process, and mechanism of related disasters should be strengthened.

6. Conclusions

This paper reviews the recent advancements, challenges, and future directions of CSA. The recent advancements of CSA in representative developing and developed countries are introduced in detail. However, the problems and challenges in CSA are still existing, such as shortage of agricultural water resources, climate variability and climate change, agricultural GHG emissions, and information resource integration. In the future, using advanced internet technology to ensure agricultural information security, improvement of cropping patterns and management techniques, carrying out "internet + weather" service and improving the quality of agricultural services, and conducting agricultural weather index-based insurance are considered as the main development direction of CSA.

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