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Review

Towards Digital Transformation of Agriculture for Sustainable Development in China: Experience and Lessons Learned

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Abstract: In the era of the digital economy, where digitization permeates all sectors of society, digital transformation in agriculture stands as a crucial solution for addressing the growing challenges in agricultural production. Amid the competition to enhance the resilience of sustainable food systems, China sets an exemplary model with its achievements in digital agricultural transformation, providing a blueprint for developing countries in Asia and the Pacific. Primarily based on statistical data and typical case studies, this paper presents analytical findings on how digital transformation of agriculture enhances the adoption of green agricultural practices and promotes inclusive development in China. In light of the intricate challenges faced by China's food system, the adoption of digitization emerges to facilitate the transformation from conventional agriculture to smart and sustainable practices. The pathways by which digital transformation of agriculture have the potential to address the over-application of chemical fertilizer and irrigation water, mitigation of carbon emissions, and the challenge of climate change and contribute to environmental sustainability of agriculture have been discussed. The implementation of digital transformation in sustainable agriculture—which enhances green practices and social inclusiveness by promoting digital literacy, reducing workload, creating job opportunities for low-skilled labor, and developing rural inclusive finance—has been completely explored. The challenges in digital transformation of agriculture are explained in this paper, which also provides evidence-based policy recommendations for its sustainable development applicable to developing countries.

Keywords: digital transformation; digital agriculture; sustainable development; China

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Academic Editor: Jianming Cai

Received: 7 March 2025
Revised: 2 April 2025
Accepted: 17 April 2025
Published: 21 April 2025

Citation: Wang, S.; Yang, Y.; Yin, H.; Zhao, J.; Wang, T.; Yang, X.; Ren, J.; Yin, C. Towards Digital Transformation of Agriculture for Sustainable Development in China: Experience and Lessons Learned. *Sustainability* **2025**, *17*, 3756. https://doi.org/10.3390/su17083756

1. Introduction

The sustainable development of agriculture faces numerous formidable challenges, necessitating digital responses that adhere to both short-term and long-term policy frameworks [1]. In addressing the immediate imperative of safeguarding national food security, the digital transformation of agriculture initiatives hold significant promise for China [2]. In the meantime, with the expansion and penetration of digital technologies and management, the broader goals of sustainable and environmentally friendly practices can be further achieved. Throughout this process, farmers are presented with the invaluable opportunity to enhance their digital literacy skills. This advancement not only serves to mitigate the vulnerability of farmers to poverty but also cultivates their resilience to various risks in the long term [3,4].

Asian and Pacific countries also encounter significant challenges in achieving sustainable development within their food system. The challenges faced in agriculture are multifaceted, arising from a combination of factors. These include a shortage of chemical fertilizers, which has been exacerbated by improper policy interventions (such as the fertilizer ban in Sri Lanka [5]), as well as disruptions caused by events like the Russia–Ukraine conflict [6]. Furthermore, other factors include persistent and prolonged droughts, driven by climate change [7] and further exacerbate by poor water management [8]. Another pressing issue is the upward trend in carbon emissions within the agricultural sector [9], which poses significant environmental concerns and contributes to climate change.

The digital transformation of agriculture can be regarded as one of the solutions to address the increasingly complex challenges faced by the global food system [10,11]. Digital technology and management can enhance crop yields and improve food supply [12,13], thereby reducing reliance on farmland [14]. Since 2020, COVID-19 has significantly accelerated the adoption of digitization across all sectors of society. The widespread application of digital services has made it easier for farmers to embrace the innovations brought about by the digital transformation of agriculture [15]. In practice, digital technology and management play a crucial role in helping farmers mitigate the adverse effects on food production and supply chains during COVID-19 pandemic [16,17], thereby making a significant contribution to national food security.

Developed countries, benefiting from their established leadership in industry and innovation, have advanced digital technology in agriculture and have successfully implemented digital agriculture on a national scale [13]. In contrast, developing countries face challenges in digital transformation due to their slower pace of innovation and the lack of advanced digital technology integrated with their food production systems [18].

China serves as a compelling example for Asian and Pacific developing countries in digital agriculture for several reasons: Effective management of green growth—China has excelled in addressing the challenges of green and sustainable agricultural growth, as shown in a comparative study with other major economies like Brazil, the EU-27, and the USA [19]. Farmer adoption of digital technology—Chinese farmers have demonstrated a high level of curiosity and willingness to adopt digital technology. A survey from Meng et al. [20] revealed that over 78% of farmers were willing to implement precision agriculture services, and over 69% were interested in purchasing digital facilities. Strategic national focus—digital transformation in agriculture is a key part of China's strategy to develop a 'digital China'. This approach aims to deeply integrate information technology with agricultural modernization [21]. China's approach leverages cutting-edge digital technologies and data analytics to revolutionize traditional farming practices, ensuring a comprehensive transformation of the agricultural sector [2,22]. At the macro level, the study by Liu and Liu [23] demonstrated that digital technology and management significantly enhance sustainable agriculture in China. At the farm level, empirical evidence demonstrates that digital transformation can positively impact environmental performance and sustainable innovation [24,25]. Alignment with UN SDGs—promoting sustainable agricultural development is crucial for China's attainment of the UN Sustainable Development Goals [26,27]. These factors collectively illustrate China's advanced position in digital transformation in agriculture, making it a model for other developing countries in the region.

In the context of agricultural development in China, the digital transformation of agriculture has become a key factor in enhancing agricultural productivity, optimizing resource allocation, and promoting sustainable development. In recent years, numerous studies have provided a comprehensive evaluation of agricultural development and the digital transformation of agriculture in China, focusing on the important role of digital technologies in improving agricultural efficiency, reducing resource waste, addressing climate change, and driving agricultural modernization. From a temporal perspective, the level of digital agriculture development has shown a steady upward trend in most provinces and regions [28]. Zhang et al. and Zhu et al. [29,30] used a multi-index comprehensive measurement method to categorize the agricultural modernization and digitalization levels of certain regions into three stages: slow increase, rapid stable increase, and high-level fluctuations. From a spatial perspective, due to the influence of various factors such as geography, economy, and agricultural structure, there are significant disparities in the development levels of agricultural digital economy across regions. The eastern regions are generally more developed in terms of agricultural digital economy, while the western regions lag behind. The development level of agricultural digital economy shows a gradual decrease from east to west [31,32].

In summary, the digital transformation of agriculture is steadily advancing across various regions of China, and it has already played a significant role in improving agricultural efficiency, promoting green development, and enhancing agricultural resilience. However, regional disparities remain a challenge, especially the gap in digital agricultural development between the eastern and western regions. In the future, the government needs to increase policy support and funding, improve farmers' digital skills, and strengthen infrastructure construction to bridge the digital divide and further deepen the digital transformation of agriculture. Furthermore, enhancing interregional cooperation and knowledge sharing will be crucial to ensuring that the digital transformation of agriculture better serves sustainable agricultural development across the country [33,34]. However, prior studies have not systematically explored the impact of digital transformation on agricultural sustainability, especially in addressing the intricate challenges that threaten the resilience of the food production system and the inclusive growth of agriculture in China [35–37]. In this paper, we systematically summarize the integration of digital transformation with the practical functional needs of agricultural productivity. Also, this study adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [38], strictly following its standardized process for literature retrieval, screening, quality assessment, and data analysis (see Supplementary Material).

1.1. Research Objectives

This paper aims to fill the gap by systematically analyzing how digital transformation in Chinese agriculture addresses multifaceted sustainability challenges while advancing both environmental and social objectives. Through a mixed-methods approach combining quantitative analysis of agricultural datasets and qualitative case studies, we (1) identify key pathways through which digital technologies mitigate overuse of agrochemical inputs, enhance water efficiency, and build climate resilience; (2) evaluate the role of digital literacy and inclusive policies in fostering equitable rural development; (3) derive evidence-based lessons for other developing economies in the Asia-Pacific region.

1.2. Research Contributions

By synthesizing China's successes and challenges in aligning technological innovation with sustainable development goals, this study contributes a holistic framework for understanding the synergies between digital transformation, green practices, and social inclusivity in agriculture. Our findings aim to inform policymakers and stakeholders in designing context-specific strategies to accelerate sustainable agricultural transitions globally. Specifically, this study (1) presents a framework that systematically analyzes the role of digital transformation in promoting green agriculture and social inclusivity, with a particular focus on its central role in addressing the multifaceted sustainability challenges faced by agriculture; (2) represents the first systematic exploration of how the digital transformation of agriculture in China addresses key environmental challenges, including the overuse of fertilizers, water inefficiency, carbon emissions, and climate change, while promoting green and sustainable agricultural development; (3) proposes a series of policy recommendations for developing countries, based on China's experience in digital agricultural transformation, aimed at helping them design sustainable agricultural transition pathways suited to their national contexts.

2. Major Challenges of Agriculture in China

As one of the largest agricultural countries globally, China grapples with multifaceted challenges in agricultural production. These challenges include cropland scarcity, the low educational attainment of rural labor, population aging, rural-to-urban migration leading to a loss of rural labor, escalating rural labor costs, water scarcity, non-point source pollution from chemical fertilizers, and the looming impacts of climate change. The challenges outlined significantly hamper the progress of agriculture towards achieving sustainable or green agricultural practices. It is imperative to recognize that the mere pursuit of agricultural development does not necessarily ensure sustainability or environmental friendliness. Hence, this section underscores the critical role of digital transformation of agriculture as a practical and strategic approach to addressing these challenges and fostering sustainable agricultural practices. By integrating digital technologies into agricultural management, such as precision farming, data-driven decision-making, and smart resource allocation, China can mitigate the adverse impacts of these challenges on agricultural sustainability and pave the way for a greener, more resilient food system.

2.1. Cropland Scarcity and National Food Security

Croplands constitute an essential natural resource within the realm of agriculture, playing a pivotal role in sustaining human livelihoods. However, the scarcity of croplands has emerged as a significant and pressing challenge within China. Despite accounting for approximately 8.2% of the world's total cropland area, China shoulders the responsibility of providing sustenance to around 18.2% of the global population The ratio of 8.2% to 18.2%, which equals 0.45, reflects the scarcity of China's cropland resources relative to its population burden, indicating that per capita arable land is only 45% of the global average. This disparity highlights the substantial challenges China faces in ensuring food security and optimizing the use of its arable land (Figure 1). Consequently, ensuring national food security has consistently taken precedence as a paramount objective within China's overarching national strategy. Digital technology and management can optimize the use of available land through precision agriculture techniques, which involve the use of technology to apply the right amount of inputs (water, fertilizers, and pesticides) at the right time and place. This can increase the productivity of the land without expanding the cropland area. The seventh meeting of the Standing Committee of the 14th National People's Congress of the People's Republic of China passed the Food Security Law of the People's Republic of China. The law implements a national food security strategy that prioritizes self-reliance, focuses on domestic production, ensures production capacity, allows for moderate imports, and is supported by technology. It adheres to the principles of "storing grain in the land and storing grain in technology", aiming to enhance the capacities for grain production, storage, circulation, and processing, while ensuring basic self-sufficiency in cereals and absolute security in staple food [39].

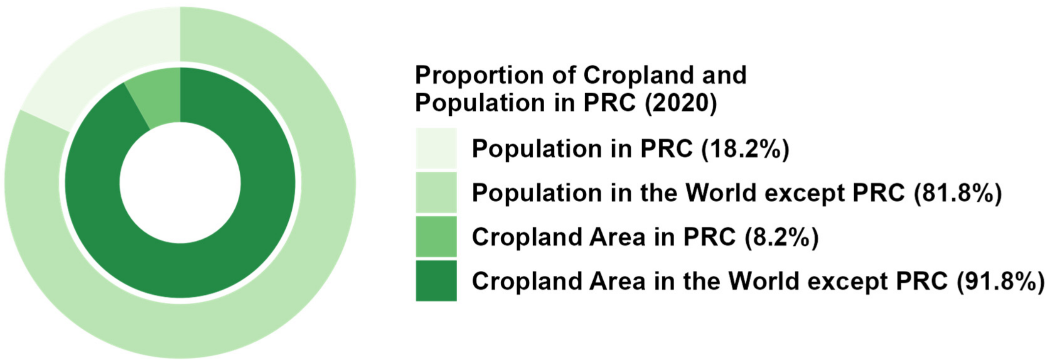

Figure 1. Comparison of cropland and population between China and world in 2020. Source: Data are from Food and Agriculture Organization Corporate Statistical Database [40].

2.2. Low Educational Level of Rural Labor

Based on the data from the third national agricultural census (Figure 2), it is evident that the educational attainment among rural laborers is notably modest. The census reveals that a substantial 91.8% of rural laborers have attained only junior high school education or even lower qualifications, with as many as 7.1% of rural laborers having never attended school. In contrast, a mere 1.2% of rural laborers hold a diploma degree. This significant gap in educational levels highlights a critical challenge for China as it strives to modernize its agricultural sector. The limited educational background of rural laborers may hinder their ability to adopt new technologies, techniques, and practices essential for the transition from traditional to modernized agriculture. This deficiency in human capital could potentially exert a profound impact on the pace and success of China's agricultural modernization efforts [41]. To address this challenge, the State Council of the People's Republic of China has actively implemented relevant policies, such as focusing on advancing the integration of urban and rural education and accelerating the reduction in educational disparities between urban and rural areas within counties. It has also comprehensively promoted the construction of urban–rural school communities, improved the incentive mechanisms for urban–rural school assistance, and ensured that rural schools receive counterpart support from urban schools [39].

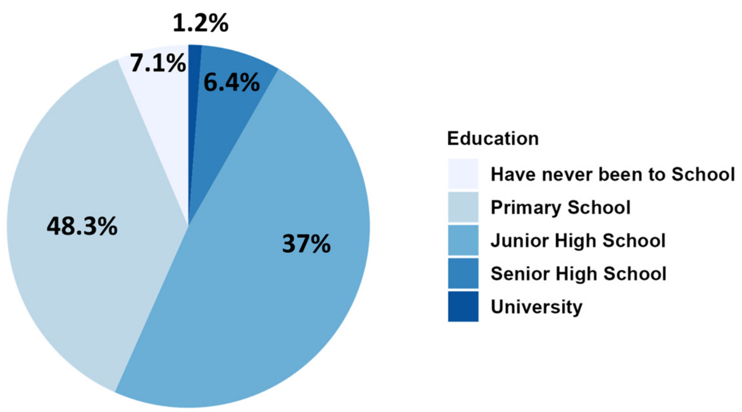

Figure 2. The structure of educational level of rural labor in China, 2016. Source: Data are from National Bureau of Statistics in China [42].

2.3. Aging Population

China's aging population is one of the most rapid increases globally, which is set to have profound implications, especially for rural development. By the end of 2023, the elderly population aged 60 and above in China had reached 297 million, accounting for 21.1% of the total population. Among them, the population aged 65 and above was 217 million, making up 15.4% of the total population [43]. As indicated by the World Population Prospects 2022 (Figure 3), the demographic landscape reveals a significant projection: the proportion of individuals aged 60 and above in China is anticipated to approach nearly one-third by 2040, and is forecasted to rise to approximately 50% by 2080. This means that half of China's population will be 60 years or older. This demographic shift can be attributed to the combined effects of increased life expectancy and declining fertility rates. However, the transformation also carries significant challenges for rural areas, where the effects of an aging population are even more pronounced.

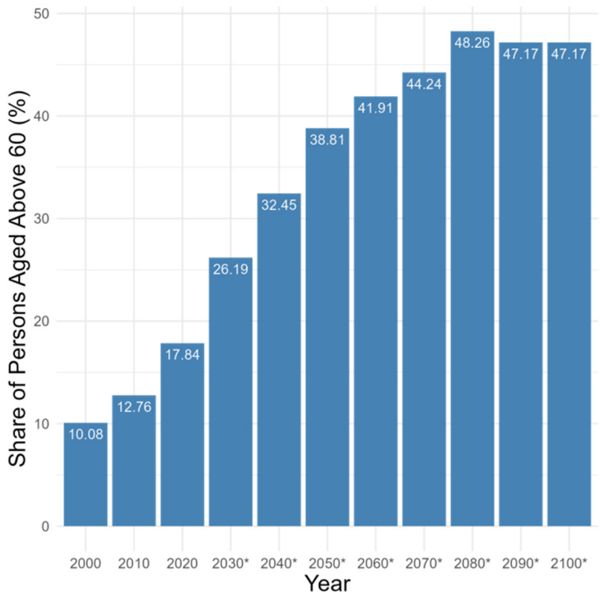

Figure 3. Share of population aged 60 and older in China from 2000 to 2020 with forecasts until 2100. Source: Data are from World Population Prospects (United Department of Economic and Social Affairs) [44]. Note: The asterisk * is the predictive value.

According to the Third National Agricultural Census [42], only 19% of rural laborers were under 36 years old, while 47% were aged 36–54 and 34% were over 54. This demographic imbalance poses significant challenges to the sustainability of agricultural production, particularly for labor-intensive practices, necessitating transformative solutions.

In rural regions, the aging population is particularly concerning due to the limited access to healthcare, social services, and economic opportunities. Rural communities are left with a shrinking and increasingly elderly workforce. Rural communities are left with a shrinking and increasingly elderly workforce [45]. The rapid aging of demographics poses significant challenges to both food security and agricultural sustainability. According to Ren et al. [46], survey data suggest that the aging of the rural population could result in a substantial reduction in agricultural output and labor productivity, estimated at 5% and 4%, respectively. Furthermore, this demographic shift is anticipated to lead to a 15% decline in farmers' incomes in China. In a complementary study, Liu et al. [47] empirically demonstrate the detrimental impact of an aging rural population on agricultural production and the resilience of agricultural systems in China. The No. 1 Document of the Central Committee in 2024 points out that improving the rural elderly care service system is an important way to achieve rural revitalization and common prosperity. It is an essential path to enhance the well-being of rural elderly people and promote social harmony in rural areas. Improving the rural elderly care service system involves enhancing rural public service infrastructure such as medical facilities and elderly care institutions, providing foundational support for elderly care in rural areas. It also emphasizes accelerating the establishment of a long-term care insurance system in rural areas, with priority given to meeting the basic elderly care service needs of the disabled, elderly, and empty-nest elderly [48]. Digital transformation can reduce the physical workload of farming, allowing older farmers to continue working with less strain. Automation and smart technologies can take over labor-intensive tasks, thus mitigating the impact of an aging rural population.

2.4. Loss of Rural Labor from Urbanization

The rapid growth and globalization of China's domestic economy have significantly expedited the process of urbanization. Meanwhile, the infrastructure and employment conditions in rural areas are relatively poor, which has led to a significant migration of young and energetic populations from rural areas to cities in search of better opportunities [49]. China's urbanization has been increasing year by year, rising from approximately 35% in 2001 to over 50% in 2011, meaning that in 2011, the urban population surpassed the rural population for the first time, and this gap has continued to widen over time (Figure 4). By 2021, the urbanization rate reached 65%. This change has brought profound consequences and impacts. Various regions in China are strengthening policy incentives to address the issue of rural labor migration. For example, Tai'an City in Shandong Province has implemented measures to better retain local residents and ensure the development of the rural economy. These measures include offering preferential policies such as land leasing and loans to individuals returning to their hometowns to start businesses, thus encouraging migrant workers to return and engage in entrepreneurial activities [50].

With the advancement of urbanization, the outflow of labor from rural areas has further accelerated the shift towards large-scale digital and mechanized operations in agriculture. Through the automation of various agricultural processes, digital transformation can reduce the reliance on manual labor. This helps retain some agricultural activities in rural areas, even as labor migrates to urban centers [51]. Furthermore, this transformation provides new opportunities for rural economic development, maintaining agricultural productivity and preventing agricultural decline caused by labor outflow.

2.5. Rise in Rural Labor Costs

Labor costs constitute a pivotal component within the agricultural sector. Drawing upon data sourced from the Rural Migrant Workers Monitoring and Survey Report (Figure 5), it becomes evident that monthly income for rural labor has experienced a remarkable surge, escalating from CNY 1690 in 2010 to CNY 4615 in 2022—a near-tripling of the initial figure. The substantial rise in labor expenses not only reduces the profitability of agricultural production but also increases the operational pressure on farmers [53]. The Ministry of Agriculture and Rural Affairs of China, in the "Guidelines for Digital Construction of Agricultural Modernization Demonstration Zones", has proposed advancing the digital upgrade of the entire agricultural industry chain to accelerate the intelligent transformation of agricultural production. The guidelines emphasize the accelerated deep application of modern information technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), blockchain, and 5G in the field of agricultural production [54]. Digital transformation in agriculture can lead to more efficient farming practices, effectively reducing labor costs. Specifically, agricultural digitalization enables production to move away from traditional labor-intensive methods. Smart irrigation systems can save water and reduce labor requirements, while precision application of fertilizers and pesticides can decrease their usage and associated costs. Furthermore, the application of digital technologies enhances the precision and sustainability of agricultural production, thereby improving overall production efficiency and economic benefits [55].

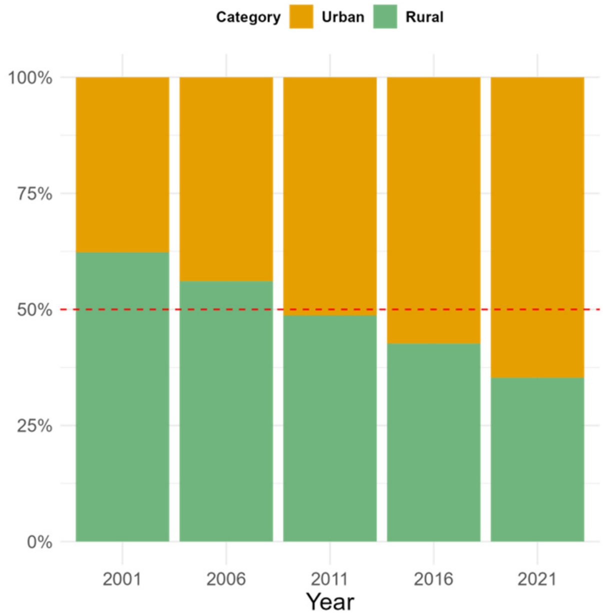

Figure 4. The change in urbanization rate of China from 2001 to 2021. Source: Data are from the 2001, 2006, 2011, 2016, and 2021 Statistical Bulletin of National Economic and Social Development, National Bureau of Statistics in China [52].

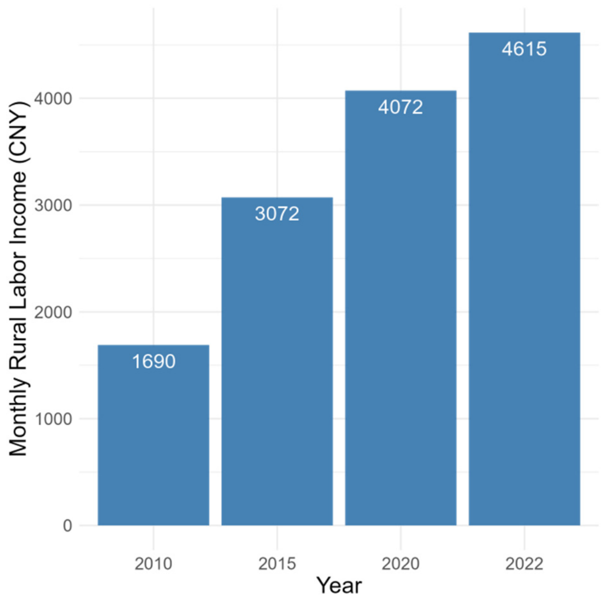

Figure 5. The change in monthly rural labor income of China from 2010 to 2022. Source: Data are from the 2010, 2015, 2020, and 2022 Rural Migrant Workers Monitoring and Survey Report, National Bureau of Statistics in China [56–59].

2.6. Scarcity of Water

Water plays a fundamental role in shaping agricultural production. When water becomes a scarce commodity, agricultural yields plummet, leading to elevated prices of essential food and fodder. This, in turn, poses a significant challenge to food security and affordability. China has an increasingly severe water scarcity issue, primarily magnified in its northern regions. The water scarcity conundrum in China is characterized by the dual woes of insufficient local water reservoirs and deteriorating water quality, stemming from the escalating pollution levels. China's water scarcity conundrum can be attributed to a triad of factors [60]. First, the uneven spatial distribution of water resources across the nation exacerbates the issue. Secondly, the rapid pace of economic expansion and urbanization, coupled with an ever-growing population, further intensifies the stress on available water resources. Lastly, a deficiency in effective water resource management compounds the challenges at hand. In light of these intricate factors, it is urgent that enhancing water resource management stands as a formidable and enduring task. Therefore, water-saving agriculture, characterized by highly efficient water management practices and enhanced food production, plays a pivotal role in advancing various SDGs related to water, land, and food security, not only within China but also on a global scale (Huang et al.) [61]. Digital systems can monitor and control water usage, ensuring that irrigation is efficient and water is conserved. The paper mentions the use of digital water and fertilizer integrated irrigation systems that significantly save water compared to traditional methods.

2.7. Non-Point Source Pollution from Chemical Fertilizers

Chemical fertilizers contribute to approximately 50% of the world's food production [62]. Thus, they are an essential agricultural input and make great contributions to China's national food security. However, due to the urgent pursual of crop yield increases, the overuse of chemical fertilizers is very serious in China. According to the statistics from FAOSTAT (Figure 6), the application of chemical fertilizers has increased dramatically since 2000 and reached the peak at around 2015.

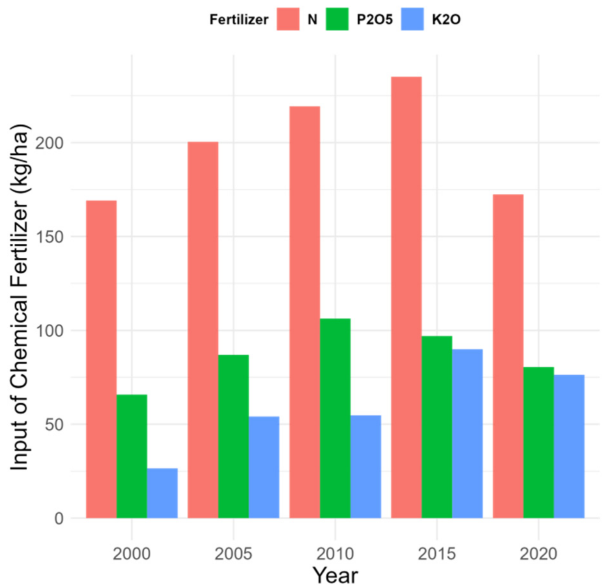

Figure 6. The chemical fertilizer application in China from 2000 to 2020. Source: Data are from the Food and Agriculture Organization Corporate Statistical Database [40].

Chemical fertilizers play a vital role in bolstering global food production, contributing to nearly 50% of the world's food supply [62]. Their significance as a fundamental agricultural input is especially pronounced in China, where they make substantial contributions to national food security. However, this indispensable role has been accompanied by a pressing issue—the rampant overuse of chemical fertilizers driven by the urgent pursuit of higher crop yields. The utilization of chemical fertilizers has witnessed an astonishing surge, particularly since 2000, as indicated by data from FAOSTAT (Figure 7). This upward trajectory peaked around 2015. Regrettably, this exponential increase in fertilizer application has not yielded proportionate gains in crop productivity. Rather, the excessive use of chemical fertilizers has led to counterproductive outcomes. An intricate interplay of factors, including precipitation and intense irrigation practices, contributes to a significant proportion of applied chemical fertilizers being washed away or leached, primarily due to rainfall and heavy irrigation [63]. As a result, pollutants infiltrate water bodies, contributing to the degradation of water quality, a phenomenon commonly referred to as non-point source pollution [64].

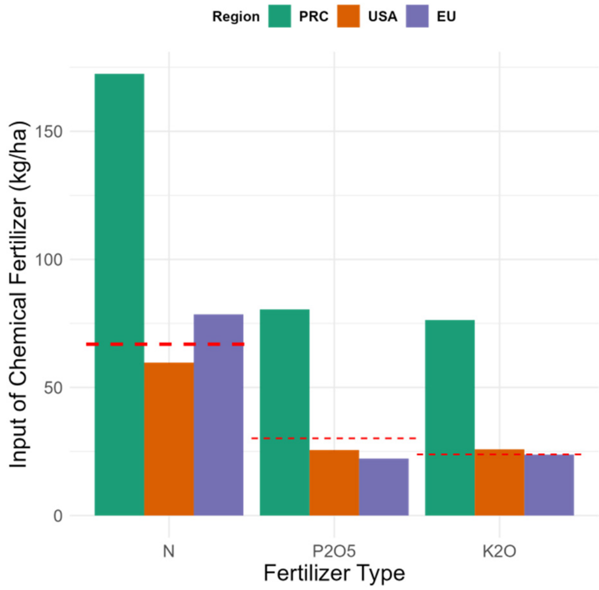

Figure 7. A comparison of the chemical fertilizer application in China with that of the USA and European Union (EU) in 2020. Note: The red dashed lines represent the global average level of chemical fertilizer usage. Source: Data are from the Food and Agriculture Organization Corporate Statistical Database [40].

In response to this circumstance, the Ministry of Agriculture in China introduced the 'Action Plan for Zero Growth in Chemical Fertilizer Usage' in 2015 [65], which has yielded remarkable outcomes. By 2020, there was a substantial reduction of approximately 27%, 17%, and 15% in the application of N, P2O5, and K2O fertilizers, respectively (Figure 7). However, despite these achievements, China's application of chemical fertilizers in 2020 continued to surpass the global average level, as well as the usage in the USA and EU (Figure 7).

Non-point source pollution from chemical fertilizers poses a significant threat to the global attainment of SDG 6: Clean Water and Sanitation, particularly in developing nations [66]. Digital soil mapping and nutrient recommendation systems can help reduce the over-application of chemical fertilizers, thus mitigating non-point source pollution. Precision agriculture can ensure that the correct amount of nutrients is applied, reducing runoff and environmental impact.

3. The Progress of Digital Transformation of Agriculture in China

3.1. The Understanding of Digital Transformation of Agriculture in China

The seamless fusion of cutting-edge information technology and agriculture has ushered in the third agricultural green revolution, known as the agricultural digital revolution. At the heart of this revolution lies the digital transformation of agriculture—a process that empowers farmers to make informed and intelligent production decisions. The significance of the digital transformation of agriculture was acknowledged in 2016. Since then, the

Chinese central government has consistently introduced annual policy plans to foster the advancement of digital transformation of agriculture.

Digital transformation of agriculture refers to the systematic integration of digital technologies and data-driven strategies to enhance the efficiency, productivity, and sustainability of agricultural practices. It incorporates artificial intelligence, 5G, robotics, the Internet of Things (IoT), big data, and cloud computing, which have introduced new opportunities for sustainable agriculture [23,67–70]. Furthermore, it encompasses both tangible 'hardware' equipment and intangible 'software' managerial arrangements aimed at optimizing agricultural processes [15,71]:

The tangible components of digital technology and management include the following:

- Hardware equipment: This involves the deployment of sensors and controllers for real-time data collection across various aspects of agricultural operations such as soil moisture, temperature, crop growth stages, and livestock health.
- Cloud-based systems: Digital transformation involves utilizing cloud-based platforms for storing and processing the vast amount of data collected from the field. These systems enable seamless data access and sharing among stakeholders involved in agricultural decision-making.
- Information and communication technologies (ICT): To facilitate real-time data transfer, ICT are employed to relay sensor data to the cloud-based systems efficiently [2,72–74]. This ensures timely access to critical information for informed decision-making.

The intangible aspects of digital technology and management include the following:

- Software systems: In the era of the digital economy, data have become a novel productivity factor [75]. Advanced data analysis techniques are now employed to derive actionable insights, promoting a sustainable agricultural food system [76]. Decision-making recommendations generated by these software systems assist farmers and agricultural stakeholders in optimizing resource allocation, crop management, and risk mitigation strategies.
- Mobile applications: Mobile applications serve as user-friendly interfaces for accessing and interacting with the digital system. Through these applications, farmers can monitor agricultural operations remotely, receive real-time alerts, and make informed decisions on-the-go using their smartphones.

3.2. Key Figures of Digital Transformation of Agriculture in China

In light of the intricate challenges faced by China's food system, the adoption of digitization emerges as a crucial approach to facilitate the transformation from conventional agriculture to smart and sustainable practices.

Despite the initial achievements of digital transformation of agriculture in China, it still faces challenges such as weak innovation capabilities in critical core technologies, high costs of technology research, development, and dissemination, as well as a shortage of versatile talents. These issues have led to a relatively slow progression in the development of smart agriculture. The national level of digital management in agriculture has grown from 18.6% in 2018 to 25.4% in 2021 (Figure 8a, the definition and measurement of the adoption rate of digitization are available on the Modern Agriculture Platform [77]). When broken down by distinct agricultural sectors, the level of digitization in livestock production stands at 34%, while for facility cultivation, field cultivation, and aquaculture, the levels are 25.3%, 21.8%, and 16.6%, respectively (Figure 8b). Considering different crop types, among them, the levels of digitization are relatively higher for cotton, wheat, and rice, at 36.3%, 39.6%, and 37.7%, respectively. However, the level of digitization in maize is relatively lower at 26.9% (Figure 8c).

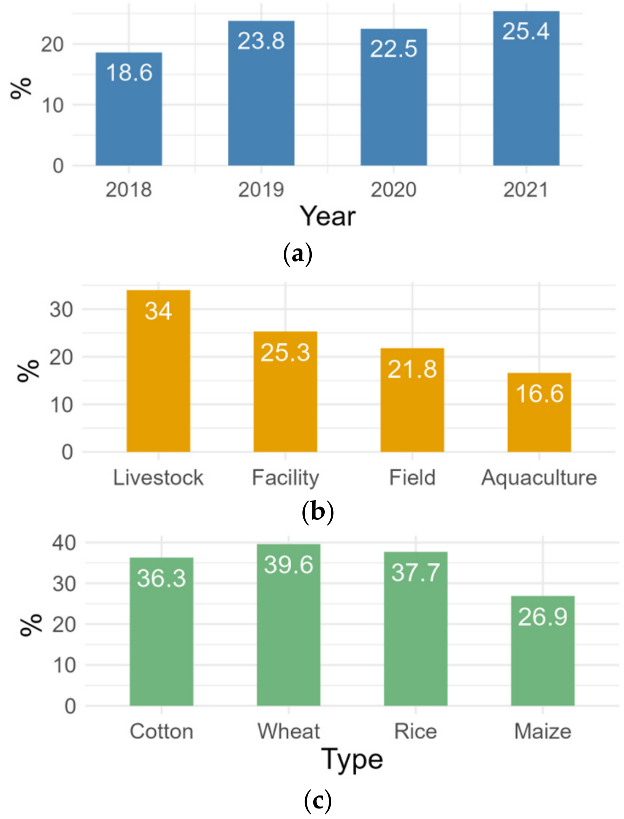

Figure 8. The level of digitization in agriculture in China. (**a**) presents the results of the annual national assessment of digitization in agriculture spanning the years 2018 to 2021. In (**b**,**c**), the level of digitization management in agriculture is further dissected and presented based on distinct agricultural sectors and crop types in 2021, respectively. Source: Data are from Ministry of Agriculture and Rural Affairs, China [78–82].

In recent years, propelled by the pressing need for the transformation and modernization of traditional agriculture, coupled with robust backing from pertinent policies, the realm of digital transformation of agriculture in China has undergone rapid expansion. As per the estimation from Askci Consulting Institute [83], the potential Chinese market size of digital agriculture was estimated at CNY 74.3 billion in 2022, with expectations to reach CNY 82.6 billion (Figure 9). The outlook for future development in the food system is exceedingly promising, with a vast expanse of opportunities on the horizon.

3.3. Comparison of China's Agricultural Digital Transformation with That of Other Countries

With the increasing recognition of the advantages of agricultural digital transformation, countries around the world, particularly China, are accelerating their efforts to advance digital transformation in agriculture [68]. Developed nations, such as EU and USA, are actively promoting the application of 5G technology in agricultural and rural areas [84]. In developing countries, such as Tanzania, the agricultural sector has introduced digital platforms, including mobile applications, extension service call centers, digital fertilizer subsidy distribution, and payment systems (DFSDS), to improve the production and living standards of rural farmers [85]. Specifically, by the end of 2021, the broadband coverage rate in administrative villages in China reached 100%, with fiber optic and 4G network coverage exceeding 99%, achieving near "same-speed same-network" conditions for rural and urban areas [86]. However, according to the 14th Broadband Deployment Report released by the US.

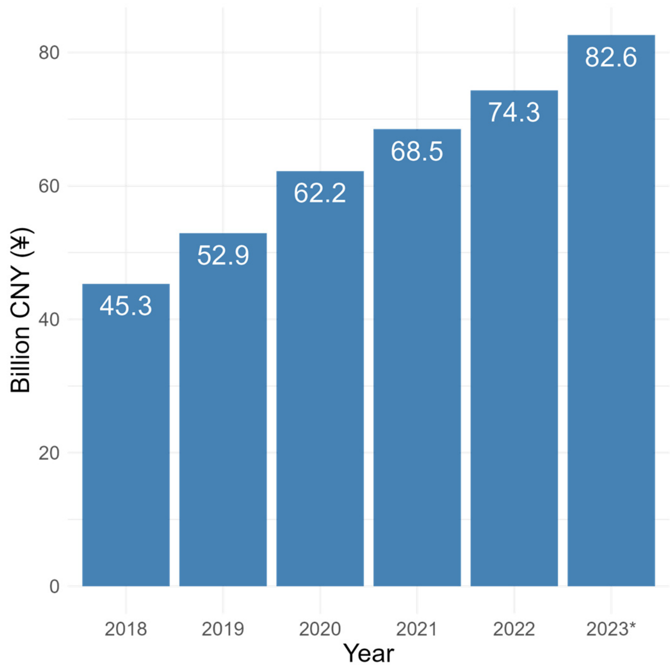

Figure 9. The potential Chinese market size of digital agriculture. Source: Data are from Askci Consulting Institute [83]. Note: The asterisk * is the predictive value.

Federal Communications Commission in 2023, about 17% of residents in rural areas and 21% of residents in tribal areas in the US lack access to broadband internet [87]. In terms of precision agriculture technologies, compared to developing countries such as China, major grain-producing regions in Europe, the US, and Australia possess larger farms and more expansive land areas, where precision agriculture technologies are relatively more advanced, and farmers typically rely on commercial models to maximize profits [68].

Nevertheless, China's efforts and progress in agricultural digital transformation, especially in terms of infrastructure development and network coverage, have provided valuable experiences and examples for many developing countries. There are still some gaps between China and developed countries in terms of agricultural digital transformation. Particularly, China lags behind the US, Europe, and other developed countries in high-end agricultural technologies, the widespread adoption of precision agriculture applications, and the maturity of commercialization models.

4. Relationship Between Digital Transformation and Sustainable and Environmentally Friendly Practices

4.1. Chemical Fertilizer Reduction by Digital Transformation

Digital transformation, through the implementation of intelligent and precise agricultural practices, has the potential to reduce the overuse of chemical fertilizers and alleviate environmental burdens [88]. The Chinese government has acknowledged the pressing need to address the substantial consumption of chemical fertilizers through digital strategies. China has established digital soil census platform, and national farmland construction comprehensive monitoring and supervision platform, which can provide specific, expert-based fertilizer recommendations. The integration of digital technology and soil testing and formulated fertilization can be helpful for chemical fertilizer reduction [70,89]. On a national scale, He et al. [90] have introduced an innovative approach to nutrient recommendations known as the Nutrient Expert (NE). This approach is aimed at enhancing the yields of major crops such as maize, wheat, and rice, all while optimizing fertilizer usage through the integration of nutrient stewardship principles, which entail applying the correct source of nutrients at the appropriate rate, time, and location. He et al. [90] also evaluated the widespread impact of these nutrient management strategies on both crop productivity and the environmental footprint of cropping systems. By harnessing the capabilities of digital management and precision agriculture techniques, their recommended treatment yielded a remarkable increase of 4.4% in grain production and resulted in a 5.8% higher profitability in comparison to the prevailing practices of local farmers. Notably, their NE approach necessitated a reduction of 29.0% in nitrogen-based fertilizer application, demonstrating its efficacy in resource optimization.

Based on survey data collected from 622 apple farmers residing in key apple-producing regions within Shaanxi Province, China, Mao et al. [91] conducted an analysis concerning the influence of digital transformation on the reduction in farmers' fertilizer usage, as well as the underlying mechanisms involved. The findings of their study reveal that the implementation of digital transformation has the capacity to curtail both the cost and amount of chemical fertilizer application. This reduction is achieved by motivating farmers to embrace green fertilization techniques, which serve as alternatives to conventional chemical fertilizers. Furthermore, the adoption of digital management practices contributes to a decrease in fertilizer-related expenses and quantities by enhancing farmers' awareness regarding the ecological and economic advantages associated with reduced fertilizer usage. Moreover, through heterogeneity analysis, it has been determined that the impact of digital management on fertilizer reduction is more pronounced among farmers possessing a higher level of digital literacy, in contrast to their counterparts with lower digital literacy levels.

4.2. Water Saving by Digital Transformation

In recent years, the Ministry of Agriculture and Rural Affairs, China has formulated guidelines for advancing water-saving practices in farmland, developed implementation plans for integrated water and fertilizer management, consistently allocated resources for drought-resistant agricultural demonstration and promotion projects, and facilitated the construction of efficient and water-saving irrigation systems. These efforts have led to significant achievements in promoting water-saving agriculture in China. With the assistance of digital transformation, the total agricultural water consumption and its proportion to the national water usage have both decreased [92]. Simultaneously, agricultural water efficiency and productivity have increased, effectively enhancing the utilization efficiency of agricultural water resources [92]. These accomplishments have played a crucial role in ensuring national food and food security.

In the Kiwi fruit base located in Huangshi Village, Xixia County, Henan Province, China, a network of 12 sets of digital water and fertilizer integrated irrigation equipment is interconnected through the IoT [93]. Huangshi Village is renowned for its 226 hectares of various kiwi fruit plantations and stands as a prominent specialized kiwi fruit village. Irrigation water management has consistently been a pivotal aspect of the village's agricultural development. In 2020, Huangshi Village established the kiwi fruit cooperative, and in collaboration with the Japanese company Nishiki, they jointly established a digital kiwi fruit base. This base is equipped with digital water and fertilizer integrated irrigation systems, employing online data collection and operation to achieve efficiency in water conservation, fertilization, and soil nurturing, thus ensuring scientifically precise and efficient water application.

In the past, local farmers used flooding irrigation, which led to uneven water distribution in the fields. Later, they switched to sprinkler irrigation, which was prone to root rot and had low efficiency. Now, with digital irrigation, the process is simplified, and irrigation is uniform, delivering water and nutrients directly to the roots. The key point is that the limited water resources are being fully utilized. According to local survey [93], when compared to traditional sprinkler irrigation, digital irrigation has increased irrigation efficiency by over tenfold, saving more than 225 tons of water per hectare, and completing irrigation for 0.4 hectares of orchards in just three hours. Because of advanced technology and scientific management, the kiwi fruit base has achieved an 80% rate of high-quality fruit, selling at prices CNY 2 to 4 higher per kg compared to regular fruit.

The government of China has played a crucial role in promoting the adoption of digital irrigation, primarily through two strategic approaches. Firstly, the government provides financial subsidies to incentivize farmers to embrace digital irrigation technologies. For instance, in Shaanxi province, farmers are eligible to receive subsidies ranging from CNY 0.02 to CNY 0.05 for each m3 of water saved, based on water consumption and irrigated area [94].

Secondly, the adoption of digital irrigation is further encouraged through the establishment of water rights trading systems across the country. In the realm of agricultural irrigation, local government and water administration offices evaluate individual farmers' water quotas. This process facilitates the clear delineation of individual water rights, confirmed through contractual agreements [95]. Leveraging the capabilities of digitization, the application of digital irrigation proves instrumental in achieving tangible water savings.

Analogous to carbon emission trading initiatives [96], the conserved water becomes a tradable commodity in future transactions. The enduring institutional framework established by water rights trading systems serves as a catalyst for the sustained adoption of digital irrigation. Consequently, farmers stand to benefit by mitigating operational costs and, in some cases, even realizing profits through participation in this innovative water conservation model. This multifaceted approach not only aligns with the government's environmental goals but also propels the food system towards a more sustainable and technologically advanced future.

4.3. Agricultural Carbon Emission Mitigation by Digital Transformation

Amid the escalating global climate change and the imminent approach of carbon peak targets, industries across the board need to join forces to comprehensively achieve carbon reduction. Agriculture, as a significant carbon emission source [97,98], should play a crucial role in the process of achieving goals of carbon peak and carbon neutrality in China.

According to the research conducted by Jin et al. [99], China's agricultural carbon emissions have been on the rise, increasing from 249 million tons in 1961 to 870 million tons in 2018. The joint publication "OECD-FAO Agricultural Outlook 2022–2031" by the OECD and the Food and Agriculture Organization of the United Nations [100] forecasts a 6% increase in direct greenhouse gas emissions from agriculture over the next decade. It is evident that the transition away from high-carbon agricultural production methods is becoming increasingly urgent [101,102].

As a modernized agricultural production approach, digital transformation undoubtedly holds the key to driving carbon reduction in agriculture. In such agricultural production models, stakeholders in agricultural production can utilize digital technologies to promote precision farming, simultaneously enhancing agricultural efficiency and reducing carbon emissions [103–105]. This, in turn, contributes to the realization of goals of carbon peak and carbon neutrality in China. Consequently, the synergistic achievement of intelligent and low-carbon agriculture has become an imminent problem in need of resolution.

In Chengdu City, Sichuan Province, China, under the digital management model, precise monitoring of soil fertility is achieved through remote sensing technology and a ground and underground data collection system. This system guides farmers to apply precise fertilization techniques based on soil testing formulas, thereby avoiding excessive use of chemical fertilizers. Through field sensor devices, the model continuously monitors and analyzes pest and disease situations, providing guidance to farmers for using drones to manage pests and diseases [106]. This approach enables timely and accurate pesticide application, also preventing overuse [107]. The direct carbon emission reductions per hectare are estimated at 116 kg and 121 kg for wheat and rice cultivation, respectively [107]. Assuming an approximate cropping area of 13,300 acres and one season/year for both wheat and rice, the annual total carbon emission reduction for grain cultivation through digital management model in Chengdu City is estimated to be approximately 3166 tons [107].

In the low-carbon and digital rice fields of Jiashan County, China, the technical team from the Rice Cultivation Technology Research and Development Center of the China National Rice Research Institute conducted on-site yield measurements of hybrid rice cultivation. On the east side of the low-carbon and intelligent rice fields, a display screen provides real-time updates on data such as daily carbon emissions, irrigation water usage, fertilizer application, and the quality of water discharged from the rice paddies. After calculation, from planting in June to harvesting in December, compared to traditional cultivation methods, the unit carbon emissions in the low-carbon and intelligent rice fields have reduced by over 20%, cumulative irrigation water usage has decreased by 30%, fertilizer application has dropped by 15%, and nitrogen and phosphorus content in the drained water from the rice fields has decreased by 30% to 40% [108].

Through the integrated innovation of agronomy, agricultural machinery, agricultural techniques, and digital transformation in these low-carbon intelligent fields has achieved a transition from relying on traditional practices to relying on data-driven decisions. Determining when to irrigate, when and where to fertilize, where to apply pesticides, and which ones to use are no longer based solely on experience but are guided by digital system instructions. These changes have significantly reduced carbon emissions without compromising crop yields.

Leveraging the digital model of low-carbon plant operations proposed by the China National Rice Research Institute, and utilizing Alibaba cloud computing, IoT, and other digital technologies, the low-carbon and digital rice fields have constructed a digital twin platform specifically for low-carbon rice paddies [108]. The IoT enables farmers to effectively manage larger farming areas [23,109]. This platform integrates three intelligent control systems: precise irrigation and drainage, unmanned agricultural machinery, and eco-friendly pest control. It also incorporates three online automatic detection systems for water, air, and soil conditions. These collectively guide rice cultivation efforts, ultimately resulting in reduced carbon emissions.

4.4. Inclusion of Smallholder Farming Within Large-Scale Production Systems by Digital Transformation

Smallholder marginal farmers in China encounter challenges in accessing agricultural digitization primarily from two key perspectives. Firstly, individuals engaged in agricultural production in rural China, particularly those belonging to disadvantaged groups such as the elderly and women with relatively low educational levels, face hurdles in adapting to digital transformation. Their limited awareness and proficiency in manipulating digital equipment hinder their integration into digital agricultural practices. Secondly, smallholder marginal farmers struggle with the initial costs associated with agricultural digitization. Unlike conventional agricultural machines such as tractors and harvesters, which are well established and stable, the ever-evolving technologies in digital agriculture contribute to the short life cycle of digital equipment [110]. Hence, these concerns can be described as the 'digital divide', where smallholder farmers risk becoming less competitive than large-scale farmers in the context of digital transformation [111].

Taking the digital transformation of cotton production in China as example [112], the life expectancy for digital equipment—including smart agriculture systems, agricultural IoT systems, and drones—is set at merely three years. In contrast, conventional agricultural machines typically have a life cycle ranging between 10 and 15 years [113]. Moreover, the costs associated with implementing digital transformation are economically burdensome for smallholder marginal farmers, while large-scale farming operations can share these costs more efficiently. To mitigate the challenge of significant initial investments in digital equipment and achieve economies of scale with lower average costs, outsourcing emerges as a viable option.

Outsourcing, grounded in the specialization and separability of agricultural production stages, enables smallholder marginal farmers to hire others in completing specific aspects or the entirety of their production practices [114]. In China, a well-established outsourcing model known as the Modern Agriculture Platform, jointly established by Sinochem Holdings and Syngenta Group China, has demonstrated successful operations. According to survey data from 2021 [77], outsourcing outperforms individual farming in green practices, technological innovation, and environmental conservation (Figure 10 and Table 1). This superior performance is attributed, in part, to the integration of agricultural digitization within the outsourcing framework.

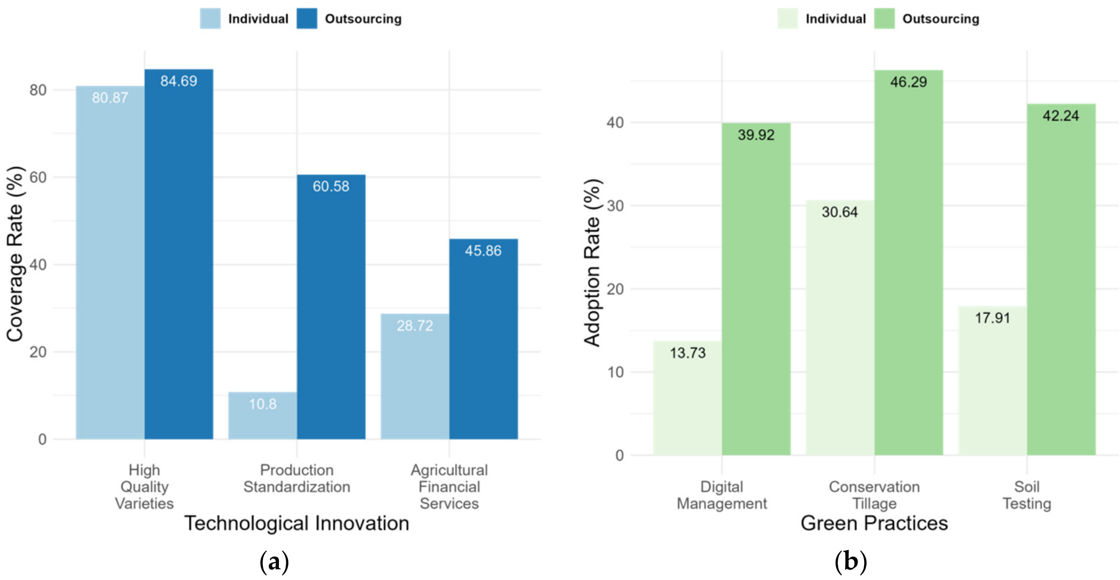

Figure 10. Comparison of green practices (**a**) and technological innovation (**b**) between outsourcing and individual farming in China. Note: Data are from Modern Agriculture Platform [77].

Table 1. Comparison of environmentally friendly performance between outsourcing and individual farming in China.

Performance Indicator	Outsourcing	Individual
Water Consumption	98.02	61.42
Chemical Fertilizer Application	22.51	14.44
Pesticide Application	6.98	5.4
Carbon Intensity	422.23	503.9

Note: Water consumption is determined by dividing crop yield by water used (kg/ton); chemical fertilizer application is calculated by dividing crop yield by chemical fertilizer used (kg/kg); pesticide application is measured by dividing crop yield by pesticide used (kg/mL); and carbon intensity is evaluated by dividing carbon emission in crop production by crop yield (kg CO_2 eq./kg). Data are from Modern Agriculture Platform [77].

5. How the Implementation of Digital Transformation in Sustainable Agriculture Contributes to Both Green and Social Inclusiveness in China

The digital transformation of agriculture has made a significant contribution to promoting social inclusiveness. It not only provides new opportunities to increase farmers' incomes but is gradually becoming a new driving force for income growth [115]. At the same time, the implementation of agricultural digital transformation requires farmers to possess a high level of digital literacy. Therefore, training in digital literacy is crucial for enhancing farmers' skills and competence. Additionally, agricultural digital transformation helps liberate farmers from strenuous physical labor, facilitating the transition of traditional labor-intensive farmers into highly skilled agricultural technicians [116].

The digital transformation also contributes to the creation of job opportunities for low-skilled labor. By introducing new technologies and innovative agricultural management practices, many low-skilled farmers can participate in more flexible and technical work, improving their employment capabilities and income levels. At the same time, digital transformation promotes the development of rural inclusive finance. With the help of digital platforms, farmers can more easily access financial services and support, including microloans and insurance, thereby improving their production conditions and quality of life. This transformation not only promotes the green and sustainable development of agriculture but also strengthens farmers' sense of participation and belonging in society and the economy.

5.1. Promotion of Digital Literacy from Digital Transformation

At present, digital devices, represented by smartphones, have become widely popular in rural areas in China. From a practical perspective, the key to enhancing the digital literacy of farmers lies in improving their awareness, willingness, and capabilities. Gong et al. [117] employed a field survey methodology to gather data directly from farmers in China. Their empirical findings convincingly demonstrate that farmers' digital literacy positively influences green production efficiency within the food system. This underscores the importance of digital skills in enhancing sustainable agricultural practices. Similarly, Du et al. [118] conducted an empirical analysis in China, revealing that efforts to enhance farmers' digital literacy have a tangible impact on increasing agricultural income. Improving the digital literacy of farmers, thereby harnessing digital technology to better contribute to rural revitalization, holds promising prospects [119].

5.2. Reduction in Workload from Digital Transformation

The reduction in workload in agriculture has emerged as a crucial consensus in fostering green and social inclusiveness [120]. Drawing from the theory of work–family balance, Wang et al. [121] discovered that the adoption of agricultural mechanization markedly diminishes workload burdens, allowing rural families in China to allocate more time to childcare responsibilities. The advent of digital transformation represents a pivotal advancement in agricultural production, serving as a driving force in alleviating workload burdens.

In China, cotton cultivation is recognized as a labor-intensive and high-workload endeavor, with the amount of labor input for cotton being 3.5 and 3 times that required for wheat and corn, respectively [122]. Consequently, researchers are highly motivated to explore methods for reducing the workload associated with cotton cultivation, aiming to achieve dual objectives of cost savings and social responsibility. The Cotton Research Institute of the Chinese Academy of Agricultural Sciences has independently developed a range of cutting-edge smart agriculture technologies, including automatic monitoring of crop growth and soil conditions, decision-making management, and intelligent control of water and fertilizer. This technology encompasses three main components: crop management decision-making techniques, hardware equipment, and software platforms. Utilizing this smart agriculture technology, farmers can remotely monitor crop growth, manage irrigation, and apply fertilizers without leaving their premises. This aids in promoting sensible water and fertilizer management and facilitating remote intelligent control [123].

This technology has been applied in greenhouse facilities in various provinces such as Shandong, Jiangxi, and Henan provinces. As a result, real-time monitoring of environmental conditions and crop growth, integrated water and fertilizer management, automated functions like curtain rolling and ventilation, and automatic shading net deployment have been achieved in orchards and greenhouses. Operations that previously required manual intervention or traditional methods have been automated through digital technology and management, reducing workload and ensuring production safety. Estimates suggest potential savings of labor usage are CNY 10,000 to 20,000 per greenhouse per year [123].

5.3. Creation of Job Opportunities for Low-Skilled Labor Through Digital Transformation

With the rapid expansion of the digital economy, the disruptive effects of digitization are expected to disproportionately affect low-skilled workers, potentially exacerbating existing inequalities [124]. Conversely, high-skilled workers stand to benefit from increased employment opportunities and accelerated wage growth. This trend of widening inequality is not unique to China but is observable globally. However, initiatives such as the implementation of digital transformation in the agricultural sector in China acknowledge this issue and aim to mitigate disparities by creating new job opportunities in digital transformation for low-skilled labor. These efforts represent a proactive approach to addressing the challenges posed by digitization and its potential impact on employment dynamics.

In China, a group of agricultural technology companies proposes a novel approach that integrates traditional monitoring conducted by low-skilled labor with digital specialized troubleshooting. This innovative mode of operation aims to synergize the advantages of manual oversight with the precision and efficiency afforded by digital technologies. The Jingxi Rice Smart Farm, located in the western suburbs of Beijing, was completed and put into operation in 2022, covering a total area of 27 hectares. The farm integrates cutting-edge agricultural information technologies such as the Internet of Things, big data, artificial intelligence, and unmanned driving. It constructs a digital farm with smart machinery at its core and digital intelligent control [125]. This rice paddy has undergone significant transformations, featuring an intelligent control center, a smart machinery depot, and digital equipment scattered throughout the fields. It includes a precise crop planting system based on IoT technology [126]. Specific components comprise the farmland monitoring system, an digital irrigation system for rice paddies, and a complementary green and efficient precision cultivation digital model. These systems collectively achieve digital transformation for rice. Spanning 27 hectares of rice cultivation, the Jingxi Rice Smart Farm requires only one person for daily management, without any specialized agricultural skills. The smart machinery does not rely on skilled machine operators, resulting in an average labor cost reduction of CNY 9450 per hectare annually.

From the standpoint of social inclusiveness, digital transformation holds the potential to empower women and girls, a demographic often labeled as low-skilled labor, thus contributing to the advancement of gender equality (SDG 5). In regions of China that are geographically isolated and suffer from labor shortages, women and girls frequently constitute the primary workforce in agricultural operations [127]. Implementation of digital management methodologies can lead to significant improvements in operational efficiency and resource accessibility, concurrently promoting the family status for women and girls [128].

5.4. Development of Rural Inclusive Finance from Digital Transformation

The rapid development of the internet and information technology has propelled the growth of digital finance, reducing the reliance of traditional finance on physical branch networks. The acquisition of data literacy through digital transformation of agriculture is reshaping farmers' payment habits. Data show that as of June 2022, the number of online payment users in rural areas of China reached 227 million, accounting for 77.5% of rural internet users [129]. The scenarios for online payment in rural areas are continuously enriching, making it more convenient to use. Through activities such as mobile payments, mobile financial management, and microloans conducted on smartphones, digital finance has expanded the coverage of financial services, lowered service costs, and advanced financial inclusiveness. In addition to covering traditional life service sectors such as transportation, healthcare, retail, education, and public utilities payments, it has also been extensively applied in rural characteristic industries and agricultural product procurement. Innovative agricultural service models have been introduced to enhance the convenience of payment in rural areas, driving the usage among rural internet users. In summary, digital inclusive finance plays a pivotal role in facilitating access to financial resources for rural households, thereby fostering increased investments in productive endeavors [130]. Empirical analysis conducted by Fu et al. [131] demonstrated a substantial positive impact of digital inclusive finance on the enhancement of productive investments among rural households.

While digital finance enhances rural financial inclusivity, its potential risks necessitate careful consideration. Over-reliance on digital platforms may expose farmers to cybersecurity threats, such as data breaches or phishing scams, particularly in regions with limited digital literacy. For instance, simplified access to microloans through mobile apps could lead to over-indebtedness among vulnerable households lacking financial management skills. Additionally, the digital divide—uneven access to reliable internet and smartphones—may exacerbate regional inequalities, as marginalized communities risk exclusion from these advancements. These challenges highlight the importance of integrating safeguards into digital finance frameworks. Financial literacy programs, transparent loan terms, and robust cybersecurity protocols are critical to ensuring that digital tools empower rather than exploit rural populations. By addressing these risks, policymakers can harness the benefits of digital finance while fostering resilient and equitable rural development [132,133].

6. Provision of Evidence-Based Policy Recommendations

In light of the successful practices and experiences observed in China, Asian and Pacific countries can stand to gain valuable insights from the advancement of digital transformation of sustainable agriculture. Meanwhile, evidence-based policy recommendations have emerged to address the challenges and lessons in China [134,135]. These recommendations offer valuable guidance for Asian and Pacific countries seeking to strategically position themselves to enhance their food systems and adopt efficient digital management practices.

6.1. Improvement of Agricultural Digital Infrastructure

In the practical application and dissemination of digital technology and management, the construction of novel agricultural infrastructure undoubtedly forms the fundamental material foundation and guarantee. However, the present scenario reveals a significant digital infrastructure disparity persisting between urban and rural regions in China [136], impeding the progression of green and socially inclusive digital transformation. Therefore, emphasizing government investment becomes paramount as part of fostering digital public infrastructure and digital public goods [137], thereby accelerating the progress of rural digital infrastructure development [138]. The 5G network has achieved coverage in key towns and some key administrative villages, with the internet penetration rate in rural areas exceeding 60%. The digital economy in rural areas is accelerating, the informatization level of agricultural production is steadily improving, and the online retail sales of agricultural products have surpassed CNY 430 billion. The rural digital governance system continues to improve, information services benefiting the public are being further deepened, farmers' digital literacy and skills have been effectively enhanced, and the pilot construction of digital villages has shown initial results [139]. In recent developments, the Ministry of Agricultural and Rural Affairs in China has issued guidelines aimed at facilitating the integration of private capital into investments in agricultural digital infrastructure [140]. This initiative is geared towards alleviating the strain on public finances while simultaneously stimulating private sector involvement. A commonly employed strategy to attract private investment in such endeavors is through Public–Private Partnerships (PPP) [141]. By leveraging insights gained from successful projection management and risk control practices within PPP frameworks, the future development of agricultural digital infrastructure promises to be robust and dynamic.

6.2. Construction of Large Agricultural Databases and Platforms

The advantages of digital agricultural technologies in promoting high-quality agricultural development rely heavily on thorough exploration of data resources. The establishment of databases serves as a crucial asset for optimizing data storage and management [142], and platforms facilitate data sharing, thereby enhancing efficiency, productivity, and sustainability within the agricultural sector [143,144]. Drawing upon existing frameworks such as the knowledge-sharing mechanism for advancing digital agriculture promoted by China [145], it becomes evident that Asian and Pacific countries stand to gain valuable insights from successful experiences in database and platform construction.

6.3. Promotion of Digital Agricultural Technologies

While China has made significant strides in digital management and agricultural technologies, achieving notable success in chemical fertilizer reduction, water conservation, and carbon emission mitigation, a notable gap persists when compared to developed countries. To bridge this gap, it is imperative to intensify efforts in technological innovation and research within the digital agriculture domain. There is a pressing need for increased investment in digital agricultural technologies. This investment imperative spans both governmental initiatives, in the interest of national food security and social responsibility supported by public financing [69], and the attraction of private capital through innovative projects characterized by a 'high-risk, high-return' paradigm [146]. In 2020, the comprehensive mechanization level of major crop planting and harvesting in Henan Province reached over 85%, with wheat machine planting and harvesting rates stabilizing at over 98%, and mechanical land preparation achieving full coverage of arable land [147]. In 2023, Guangdong Province clearly proposed that no less than 6% of provincial fiscal funds would be allocated to digital agriculture. The provincial Department of Agriculture and Rural Affairs will also collaborate with the Provincial Meteorological Bureau to explore a new "Agriculture + Meteorology" model through information and data sharing, helping agricultural production shift from "relying on the weather" to "weather-based management", ensuring more reliable food production and strengthening food security [148].

6.4. Establishment of Policy Evaluation Mechanism

In the application of digital agricultural technologies, the real-time feedback analysis of application effects through a policy evaluation mechanism, along with swift and effective adjustments to address practical issues, is crucial for ensuring the sustained and efficient implementation of digital agricultural development. The implementation of agricultural digitization, led by the government [15], underscores a critical need for robust policy evaluation. Nevertheless, there exists an imperative demand for thorough evaluations in this aspect. For sustaining green agricultural development in China, the government proposed quantitative indicators in assessment. Specifically, by 2025, it is expected that the utilization rate of chemical fertilizer and pesticide should reach 43%, the effective utilization coefficient of irrigation should reach 0.57, the level of soil quality should reach 4.58, and so on [149]. Meanwhile, the intelligent rice production in western Beijing has significantly improved both yield and quality. In previous years, the yield was approximately 5250 kg/ha, but in 2022, the estimated yield would reach 6750 to 7125 kg per ha, representing an average increase of about 30% in yield per ha [150]. For the inclusive development of agriculture in China, agricultural digitization can reduce the poverty, improve human well-being, and mitigate inequalities in rural areas [2]. The digital transformation could play important role for achieving these goals, and its role and contribution should be identified in advance.

6.5. Safeguard of Cybersecurity

The adaptation of digital transformation relies on internet-enabled sensors in agricultural production, which involve concerns about privacy protection and cybersecurity [151]. For digital companies in the food system, the risk of cyber attacks should be identified and controlled in advance [111]. Attacks targeting digital facilities and precision agriculture devices represent a significant threat to agricultural productivity. These attacks have the potential to not only damage yields but also, if executed on a large scale, to impose a substantial risk of regional food delivery or even national food security [152]. However, in China, most farmers are not aware of this problem [111], which is one of the key reasons the government pays close attention to it. The establishment of safeguards to protect the connectivity in digital transformation is of utmost urgency. A comprehensive regulatory framework must be developed to address this critical need and fill the existing gap.

7. Conclusions

This paper analyzes digital transformation of agriculture for sustainable and systematic development in China. To begin with, the major challenges of agriculture in China were raised: cropland scarcity and national food security, low educational level of rural labor, aging population, loss of rural labor force from urbanization, rise in rural labor costs, scarcity of water, non-point source pollution from chemical fertilizers, and climate change.

In light of the intricate challenges faced by China's food system, the adoption of digitization emerges as a crucial approach to facilitate the transformation from conventional agriculture to smart and sustainable practices. Digital transformation of agriculture is a process that empowers farmers to make informed and intelligent production decisions. The application of digital technology and management has been expanded dramatically in China, and it has great market potential.

In addition, the pathways by which digital transformation have potential to address over-application of chemical fertilizer and irrigation water, the mitigation of carbon emissions, the challenge of climate change, and contribute to the environmental sustainability of agriculture have been discussed. Farmers' experience usually causes the overuse of chemical fertilizer. With the help of integrated digital technology, soil testing, and formulated fertilization, the recommended fertilizer can achieve the significant chemical fertilizer reduction without the sacrifice of crop yield. Instead of flood irrigation with great water waste, digital water-saving techniques can deliver water to the root in a way that avoids water evaporation. In addition, digital transformation can achieve the smart agricultural production chain with precision control, thereby reducing production input and mitigating carbon emissions. Moreover, developing more precise and efficient digital management tools can enhance the food system's capacity to respond to extreme weather, safeguarding agricultural production and aiding farmers in achieving bountiful harvests. The implementation of digital transformation for sustainable agriculture contributes to both green and social inclusiveness. The implementation of digital transformation can promote farmers' digital literacy and reduce workload, and increase farmers' incomes.

From an environmental perspective, this study highlights how digital transformation directly reduces agricultural pollution and enhances resource efficiency. Precision technologies curtail chemical runoff and water waste, tackling China's pressing issues of non-point source pollution and water scarcity. Smart monitoring systems further lower carbon footprints by optimizing input use and energy consumption. These advancements align agricultural practices with global climate goals and ecological preservation. To amplify these benefits, policymakers should invest in green digital infrastructure (e.g., solar-powered IoT sensors, AI-driven resource systems) and establish regulatory frameworks incentivizing eco-friendly technology adoption. Cross-sector collaborations to develop climate-resilient digital solutions are equally vital to sustain environmental gains amid escalating climate risks.

In general, digital transformation of agriculture in China can achieve sustainable and environmentally friendly practices, and it has contributed to both green and social inclusiveness. Policy recommendations have been put forth to sustain long-term development, encompassing improvements in agricultural digital infrastructure, the establishment of large agricultural databases and platforms, the promotion of digital agricultural technologies, the implementation of a policy evaluation mechanism, and ensuring cybersecurity safeguards.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17083756/su17083756/s1, File S1: The PRISMA procedure for literature retrieval.

Author Contributions: Conceptualization, S.W. and C.Y.; methodology, S.W.; validation, H.Y., T.W. and J.Z.; formal analysis, S.W.; investigation, S.W.; resources, S.W.; data curation, Y.Y.; writing—original draft preparation, S.W.; writing—review and editing, H.Y., X.Y. and J.R.; visualization, S.W.; supervision, C.Y.; project administration, X.Y. and J.R.; funding acquisition, S.W. and C.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Major Program of the National Fund of Philosophy and Social Science of China (18ZDA048); Chinese Academy of Agricultural Sciences Science and Technology Innovation Project (CAAS-ZDRW202419); Jinan University Enterprise Development Research Institute 2023 Annual Research Project (QF20230902); Guangdong Province College Students' Innovation and Entrepreneurship Training Program Supported Project (S202410559033); and the Special Funds for Cultivation of Guangdong College Students'Scientific and Technological Innovation ("Climbing Program"Special Funds).

Data Availability Statement: No new data were created.

Conflicts of Interest: The authors declare no conflicts of interest.

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