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Review

Role of AI and IoT in Advancing Renewable Energy Use in Agriculture

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Abstract: This paper discusses how integrating renewable energy, AI, and IoT becomes important in promoting climate-smart agriculture. Due to the changing climate, rise in energy costs, and ensuring food security, agriculture faces unprecedented challenges; therefore, development toward innovative technologies is emerging for its sustainability and efficiency. This review synthesizes existing literature systematically to identify how AI and IoT could optimize resource management, increase productivity, and reduce greenhouse gas emissions within an agricultural context. Key findings pointed to the importance of managing resources sustainably, the scalability of technologies, and, finally, policy interventions to ensure technology adoption. The paper further outlines trends in the global adoption of renewable energy and smart agriculture solutions, indicating areas of commonality and difference and emphasizing the need for focused policies and capacity-building initiatives that will help, particularly in the developing world, the benefits of such innovations. Eventually, this research covers some gaps in understanding how AI, IoT, and renewable energy could jointly contribute to driving towards a greener and more resilient agriculture sector.

Keywords: climate-smart agriculture (CSA); renewable energy; artificial intelligence (AI); internet of things (IoT); sustainable resource management; agricultural productivity

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1. Introduction

While agriculture aims to feed over 7.9 billion people currently and 9.6 billion by the year 2050, the demand for food is expected to rise by at least 60%, and the agriculture sector faces a crisis in terms of sustainability [1,2]. Agriculture uses almost 30% of all consumed energy globally [3]. The current global agricultural sector faces serious challenges portrayed by the rise in demand for sustainable food production, increase in energy costs, and climate change impacts [4,5]. Conventional farming has traditionally depended on fossil fuels as its energy source [6]. Agriculture is now poised to transition to cleaner and more effective energy sources. Climate change threatens agricultural productivity with rising temperatures, erratic rain patterns, and extreme weather events that disrupt food systems [7]. In this context, there is a need for an approach to agriculture that is important, imperative, sustainable, and energy efficient. Renewable energies such as solar, wind, and bioenergy offer immense opportunities to improve energy efficiency in agricultural processes [8]. This shift addresses environmental concerns, reduces operational costs, and increases productivity. With the introduction of advanced technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), integrating renewable energy into precision farming techniques is becoming increasingly feasible, offering innovative solutions to modern agricultural demands [8–10].

Recent developments in smart farming systems have made it possible to utilize resources optimally with the help of renewable-powered precision technologies. These will achieve precision farming through data-driven decisions on optimizing the use of resources, such as water and fertilizer, whose processes are driven by renewable energy sources to power the tools needed for monitoring and automation. A prime example is soil monitoring sensors powered by solar energy [11], while renewable energy sources also power autonomous machinery or smart irrigation systems [12]. In addition, bioenergy, derived from agricultural waste, presents a circular solution that powers operations and reduces waste management costs [13]. These inventions, which link technology with renewable energy, are transforming farming and making it more sustainable, efficient, and cost-effective. However, it is important to note that introducing these systems remains uneven across regions due to varying local policies, infrastructure, and economic conditions [14]. Global trends include a push toward carbon neutrality and an increasing need for climate resilience [15], making the urgency of adopting energy-efficient renewable systems across agriculture quite prominent. Agriculture alone contributes greatly to the various global sources of greenhouse gas emissions [16]. Hence, improving energy efficiency through renewables does much to help lower emissions and eventually prepare farms to cope with climate-related challenges [17,18]. Despite such barriers, issues of finance, technical limitations, and supportive infrastructure are still lacking, and wide diffusion is impeded [19]. It is very important to consider these barriers if agriculture is to be compatible with global sustainability goals, such as targets included in the Paris Agreement or the United Nations' Sustainable Development Goals [20]. This, therefore, underlines the need for a transition to renewable energy within the agriculture sector since agriculture is one of the sectors that contribute to climate change. Agriculture alone accounts for about 12% of the total greenhouse gas emissions, especially because of livestock, land-use change, and energy use [21]. Improvement in energy efficiency through renewable energy decreases these emissions and helps farmers adapt to climate risks like droughts and floods by powering resilient and data-driven systems [22]. Accordingly, agricultural renewable energy is a significant factor in formulating mitigation and adaptation strategies to counter the impacts of climate change.

This paper combines, within a model of circular economy, renewable energy, AI/IoT technologies, and agriculture sustainability, to outline how advanced technologies can transform agriculture in such a way as to ensure economic and environmental sustainability. Indeed, the framework is pegged holistically on key factors, including sustainable resource management, technology adoption, policy interventions, global value chains, and the circular economy.

2. Materials and Methods

2.1. Conceptual Framework

The results and discussion section synthesizes existing literature on climate-smart agriculture, renewable energy integration, and the transformative role of AI and IoT in enhancing efficiency and sustainability. The developed conceptual framework gives an overall picture of how these elements intersect and impact different agricultural contexts at the intersection of economic and policy-related challenges, shaping their adoption and effectiveness.

AI- and IoT-based solutions, in the shape of smart irrigation, real-time monitoring of data, and efficient energy use systems, form important solutions in managing agricultural resources towards more sustainable uses. Such technologies enable the optimal use of water, energy, and land, which will be of high importance for regions in which these are scarcer or very sensitive to changes in climate. Examples include intelligent renewable energy-powered irrigation systems that ensure water use efficiency based on real-time data to reduce waste and enhance productivity [23–25]. Research in this area is vital since it directly affects the balance between environmental sustainability and the increasing requirements for agricultural productivity. Hence, resource optimization without loss in output forms the core of achieving climate-smart agriculture.

In addition, AI, IoT, and renewable energy technologies introduce major transformations in agricultural processes. The application of technologies allows for precise observation and optimization of farming activity, helps to save energy, and causes less environmental degradation. This is a very important development, as scaling up those technologies makes them affordable and accessible, especially for small and medium-sized farms, which generally possess fewer financial resources and less technical capacity than bigger farms. Some of the key technologies involved are precision agriculture and IoT-enabled energy systems that contribute to going green by reducing dependence on non-renewable energy sources [23,26,27]. Research in this area, therefore, examines how such innovative interventions can be scaled up and adapted to diverse agricultural contexts so that resource-constrained regions can benefit from recent advances in farming technology.

On the other hand, policy and economic factors have become critical in deducing how renewable energy and smart technologies will be integrated into agriculture. Government initiatives like subsidies on renewable energy or investments in smart agricultural practices are hugely encouraging to farmers. Economic barriers involve the hefty upfront costs of AI and IoT systems and inadequate infrastructure; these may further hamper the potentiality for adoption, especially in developing regions [28–30]. It calls for research into these policy interventions to identify strategies promoting broader implementations of renewable energy in agriculture and how economic incentives can be suitably designed to surmount infrastructural barriers. It also identifies government and institutional support as key drivers in changing the course of agriculture toward sustainability in general. One relevant case that may be brought into focus is the Netafim project in Israel. This project incorporates an advanced drip irrigation system with IoT sensors, which monitor the moisture, temperature, and humidity levels in the soil in real time [31]. The integration of AI and IoT has, therefore, allowed the precision irrigation to save a further 50% more water than conventional methods can, while raising crop yields by a little over 20% [32]. Another example is the Smart AgriHubs project in Europe, knitting together IoT and renewable energy solutions, such as solar-powered irrigation, for developing farmers' competencies in sustainable and efficient resource management, reduced GHG emissions, and so on [33].

It is studied because all these elements interact to create an agricultural sector that is perceived to become more sustainable and efficient. Understanding the interlinkages of resource management, technology adoption, and policy interventions gives an in-depth insight into how agriculture can evolve to meet the challenges thrown by the need to enhance productivity while reducing environmental impacts. These aspects will then form the backbone of the discussion, guiding the analysis of how renewable energy and smart technologies effectively integrate into farming practices across diverse agricultural systems.

This conceptual framework, as shown in Figure 1, outlines the interlinked factors that will influence the adoption of climate-smart agriculture through AI and IoT with renewable energy. It contains, at the top, climate-smart agriculture and renewable energy integration, supported by three important pillars, namely: sustainable resource management for optimization of water, energy, and land use; adoption of technologies regarding scalability and accessibility in AI and IoT solutions for agriculture; and finally, policy interventions and economic barriers as a study of how government policies and economic incentives further or dampen the adoption of these kinds of innovations. It also explains how all these factors lead to environmental impact and productivity gains by stating that the components should help reduce greenhouse gas (GHG) emissions while improving efficiency and ensuring more sustainable farming practices.

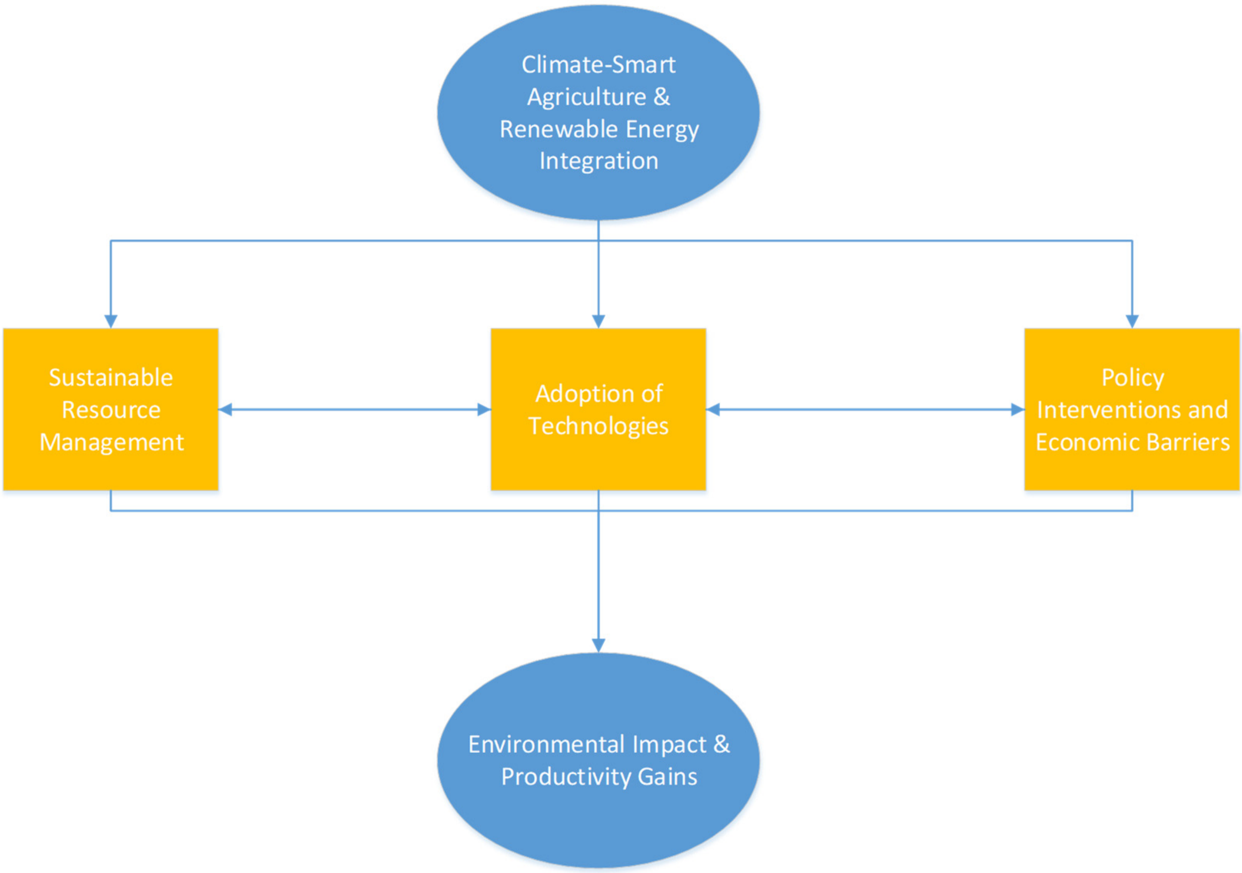

Figure 1. Conceptual framework.

2.2. Information Gathering

Literature was searched in two major academic databases, Clarivate Web of Science (WoS) and Scopus, which are relevant to our study. The search was based on a pre-defined keyword string that captured key themes related to renewable energy, agriculture, and technological adoption. The search string was: ("renewable energy" OR "clean energy" OR "solar energy" OR "wind energy" OR "bioenergy") AND ("agriculture" OR "farming" OR "precision farming" OR "agricultural technology") AND ("energy efficiency" OR "sustainability" OR "smart irrigation" OR "IoT" OR "AI") AND ("barriers" OR "adoption" OR "policy" OR "regional differences"). The search was completed on 9 September 2024. No time limitation was applied to the literature search to ensure that this review encompasses a wide and historical perspective of renewable energy, agriculture, and the adoption of AI and IoT technologies. This allows the inclusion of foundational studies, emerging trends, and a full spectrum of research developments over time.

As shown in Figure 2, first of all, through the WoS database, we retrieved 744 records. Then, by applying a filter, excluding book chapters and conference papers, the amount became 699 articles. After removing one irrelevant article on religion, it reached 698 articles. On the other hand, the Scopus database returned an initial sum of 786 records. This was reduced to 572 articles once book chapters and conference papers had been excluded, and then three arts and humanities articles were removed, bringing the number to 569. After that, we removed the duplicates between the two databases, resulting in a total of 1015 unique articles to be analyzed.

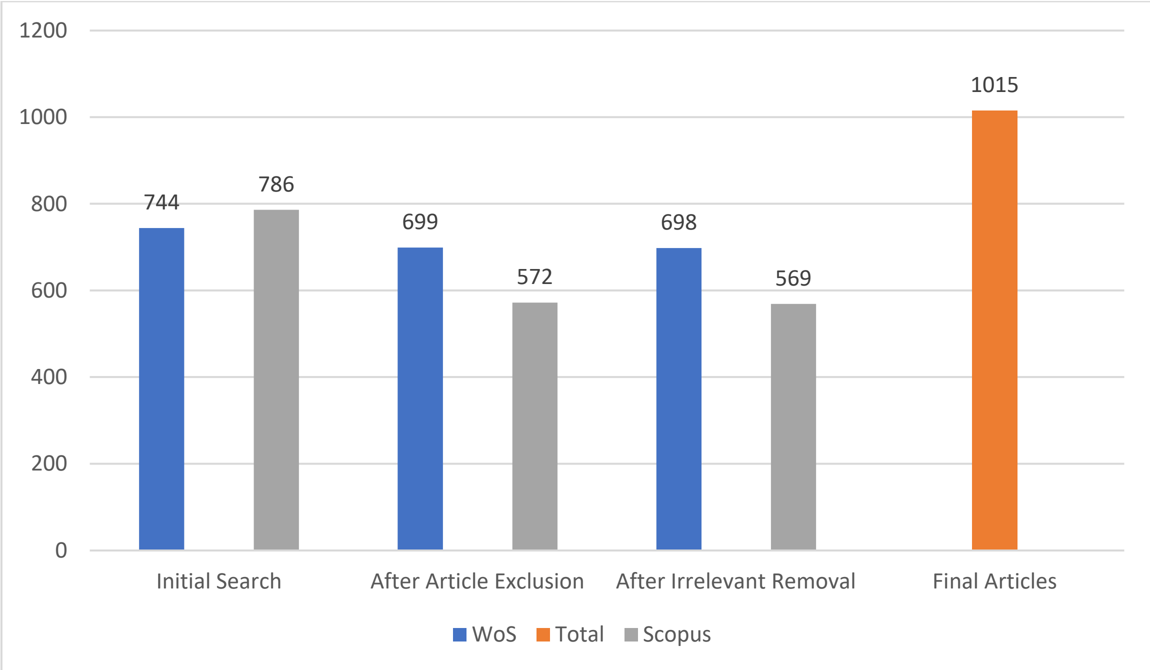

Figure 2. Process of article selection.

3. Results and Discussion

Agriculture faces growing pressures to improve sustainability and reduce environmental impacts in the face of new global challenges such as climate change, ever-rising energy costs, and food insecurity. In response to these pressures, countries are adopting several approaches, such as mainstreaming renewable energy and sustainable farming techniques and developing and formulating climate-smart agricultural policies [34–36]. This chapter explores key academic literature on interactions between renewable energy and agriculture in the context of policy incentives' efficiency, consumption patterns, and various forms of environmental certification frameworks.

3.1. Resource Efficiency and Optimization

AI, IoT, and renewable energy are coming together to revolutionize the farm sector, particularly in resource management such as water and energy [37]. In light of the growing challenges of climate change, energy cost hikes, and increasing demands for sustainable farming, these technologies enable operation efficiency, reduction of waste, and environmental sustainability. At the core of this transformation is the role of renewable energy that, coupled with AI and IoT, makes it more energy efficient, cost effective, and ecologically viable [38,39]. Among the biggest challenges in agricultural sectors, which is gaining unprecedented importance due to increasing water shortages and high energy consumption, is water management because of ineffective irrigation systems [40,41]. The traditional irrigation approach wastes water resources and depends extensively on energy systems powered by fossil fuels. These disadvantages are being tackled by renewable energy, along with IoT and AI technologies, thus offering more efficient and, at the same time, eco-friendly ways of managing liquid resources [42–44]. IoT-based smart water metering, for example, utilizes sensors to monitor basic environmental parameters: soil moisture, weather conditions, and crop water demand. In turn, farmers have the data in real time to decide upon an optimal time and manner of water application [45,46]. IoT-based smart water metering systems become game-changers once integrated with renewable energy sources, such as solar or wind. For example, where water availability is scarce, as in the State of Rajasthan, India, researchers have already seen how integrating solar-powered pumps with IoT sensors enables irrigation to be managed much more efficiently [47]. IoT sensors monitor the degree of soil moisture and the weather in real time. This system eventually pumps the water only when required, optimizing its usage [48]. Operating these pumps with renewable energy sources, like solar power, reduces farmers' reliance on the grid or fossil fuels, drastically lowering energy costs and greenhouse gas emissions. The connectivity ensures efficiency in water use and stabilizes energy consumption, as these would meet fluctuating agricultural demands while supporting sustainable farming. Scaling this up, the intelligent fusion of IoT and renewable energy can ensure that water wastage reduction is as high as 71.8% [49]. In this respect, renewable energy-driven irrigation systems hold great potential for addressing the dual challenges of water waste and energy overuse. These renewable energy irrigation systems offer off-grid solutions, enabling farms in remote or energy-insecure areas to function independently of fossil fuel-based grids [50]. A common example of such systems is wind-powered irrigation, which converts natural wind energy into useful potential for water pumping at reduced energy cost with minimum environmental impacts on the sustainable management of water [51,52].

Energy use in agriculture represents one of the largest operational costs and environmental degraders. Conventionally, agricultural operations rely heavily on non-renewable energy sources, such as diesel-powered machinery and grid electricity from fossil fuels [53]. However, with the heightened use of renewable energy technologies such as solar and wind power and the integration of AI systems, farms are fine-tuning their energy use and greatly reducing dependency on non-renewable resources [54]. Artificial intelligence-powered systems prove much handier in predicting energy demand and fine-tuning farm activities with periods of high renewable energy availability [55–58]. For example, some AI algorithms can analyze weather patterns and predict the best intervals for using solar or wind energy in different farming activities [59]. When solar or wind energy production is at its peak, the AI system can automatically adjust energy-intensive tasks, such as irrigation, heating, or greenhouse ventilation, to fully take advantage of renewable energy sources. This is handy for those areas where the solar and wind energies are not perpetual [60–62]. This will ensure effective energy use and reduce dependency on fossil fuels, reducing energy costs and carbon emissions. A common example is the application of AI-powered energy management systems in greenhouse farming. Such greenhouses connect renewable energy sources, including solar panels and wind turbines, that power automatic climate control mechanisms comprising smart glass technologies and ventilation fans. While continuously monitoring, AI algorithms automatically adjust internally for energy use again; this time, they follow real-time environmental data [60,63]. Soon, integrating renewable energy with AI will go a long way toward achieving better energy efficiency within greenhouses, reducing dependence on grid electricity, and enhancing overall sustainability and productivity. Renewable energy systems have also increasingly become viable in off-grid locations, providing agricultural operations with uninterruptable power without the need for conventional fuel sources [64,65]. Such is important in developing regions where consistent grid power access remains limited. This again creates opportunities to make farms independent by off-grid renewable energy solutions where the dependency on fossil fuels is reduced using solar or wind potential, hence promoting long-term sustainability [66,67].

3.2. Environmental Sustainability and Emission Reductions

The rapid integration of AI, IoT, and renewable energy technologies is happening in ways that will offer agriculture new pathways to reduce GHG emissions. Agriculture conventionally caused high amounts of GHG emissions through conventional methods of energy usage for irrigation and fertilization and various machinery-related operations powered by fossil fuels. Agriculture is among the major contributors to GHG emissions, accounting for a share of about 10–12% of the total [68–70]. However, integrating AI and IoT with renewable energy sources pushes forward a more efficient and environmentally sustainable model for modern agriculture. AI systems have revolutionized agriculture with energy management through real-time analytics supported by predictive capability. Integrated with renewable energy sources like solar and wind, AI algorithms create an opportunity to manage energy consumption much more efficiently to reduce dependence on fossil fuels and decrease GHG emissions [71]. The most important use of AI is in forecasting energy demand. By analyzing historical data in concert with real-time data gathered by IoT devices, the AI system can anticipate when energy demands will peak, allowing it to adjust farming operations accordingly. For example, AI can predict optimal irrigation timing according to weather patterns, soil moisture levels, and projected renewable energy generation [72,73]. Consequently, farmers could perform energy-intensive work pumping water or operating machinery only during peak solar or wind energy periods [74,75]. Further, ensuring that renewable energy is utilized efficiently reduces the consumption of grid electricity or fossil fuels on farms [76].

IoT sensors also identify the best time and optimal fertilization level in precision farming, reducing the carbon footprint related to resource overapplication [77]. AI can identify specific areas in the field that require more or less water or nutrients, enabling farmers to target such areas with greater efficiency, saving energy and lowering emissions [78–80]. The real role of AI and IoT for GHG reduction comes when these technologies are integrated into renewable energy systems. While renewable energy sources, such as solar and wind, are increasingly used in agriculture, their intermittent nature requires intelligent management systems that make their use efficient. This is where AI and IoT come in [81,82]. AI systems can further utilize renewable energy by predicting peaks and accordingly scheduling farm operations. Predicting high solar output may recommend the time for scheduling irrigation or heating greenhouses [83]. Moreover, IoT sensors can provide real-time information on energy produced by renewable sources to seamlessly switch farms between solar, wind, or grid power [84,85]. The achieved degree of precision limits reliance on only non-renewable energy and maximizes reliance on renewable energy. Waste-to-energy management systems in livestock farming, where animal manure is converted to biogas, have also seen the application of AI and IoT [86,87]. In that respect, IoT sensors will track waste decomposition processes, while AI systems optimize conditions for biogas production to ensure efficient waste energy conversion. The biogas produced can power farming activities, creating a closed-loop system that reduces GHG emissions and energy costs [88–91]. However, carbon sequestration is also an increasingly important approach to reducing net GHG emissions in farming, and its development is similarly abetted by AI and IoT technologies. Satellite images and soil data will provide the basis upon which AI highlights the potential of sites where carbon sequestration can go to full effect, either through reforestation or regenerative farming methods. These methods improve the health of the soil and increase plant biomass, both of which are crucial to sequestering more carbon in the soil [92,93]. IoT-enabled monitoring systems provide real-time information on soil conditions, enabling farmers to know how operational their carbon sequestration strategy is. This ensures that sequestration practices work as they should and that real-time insight can be derived for future sustainability initiatives [94,95]. For example, the Common Agricultural Policy of the European Union (EU) incentivizes climate-friendly farming by subsidizing those farmers who adopt sustainable agriculture, integrating renewable energy systems. It invests a significant amount of funds in precision farming and green energy adoption, motivating farmers across the various EU members to adopt renewable-powered systems and efficient resource management technologies to reduce their carbon footprint [96,97]. Another major initiative is the Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) scheme in India, whereby farmers are incentivized for the installation of solar-powered irrigation mechanisms. The KUSUM program subsidizes both solar pumps and grid-connected projects using solar energy on agricultural lands with an objective to reduce operational costs, apart from inducing sustainable usages of water. This policy has made solar irrigation accessible, especially to areas suffering from energy shortages and high fuel costs [98–100].

In light of this, integrated AI, IoT, and renewable energy in agriculture could significantly reduce GHG emissions because of the optimization of energy use, improvement of efficiency in the use of resources, and promotion of carbon sequestration efforts. AI can provide predictive insight, while IoT offers real-time monitoring capabilities that enable farmers to make informed decisions based on actual conditions, in tandem with the availability of renewable energy supply, to further reduce their dependence on fossil fuel emissions and ensure environmental sustainability. As these technologies advance, their role will continue to play an increasingly complementary contribution towards global GHG reduction goals; hence, agriculture is one of the important sectors in taming this monster called climate change.

3.3. Open-Source Platforms and Scalability in Developing Regions

Renewable energy and agricultural digital technologies are opening new vistas for tackling food insecurity, climate change, and resource scarcity [101]. However, if such innovations are to be useful at the global level, particularly in developing regions, they need to be moderately priced and scalable [102]. Indeed, the combination of open-source platforms and scalable renewable energy solutions has produced critical tools that quicken the pace of adopting sustainable farming worldwide, particularly in resource-poor countries [103,104]. Open-source platforms democratize advanced technologies and best practices, completely changing the agricultural landscape. Conventionally, access to cutting-edge agricultural technologies such as AI, IoT, and renewable energy systems is normally denied to many because of the high costs of proprietary software and hardware [105]. Open-source platforms remove this barrier by providing farmers and agricultural businesses with free or low-cost tools to manage resources, optimize productivity, and reduce environmental impact [106,107].

Another great advantage of open-source platforms is that they are flexible and adaptable [108]. Farmers from various regions can customize and adapt such platforms according to their particular needs, whether these relate to managing soil, conducting crop rotation, using water, or even integrating renewable energy [109,110]. An example could be open-source software for farm management systems that enables users to input information regarding local weather conditions, soil type, and crop type to get specific irrigation and fertilization recommendations, such as IrrigaSys or CropSight. These platforms grant real-time insights into farm operations through AI and IoT, allowing for more precise and sustainable decision making [111,112]. Open-source platforms allow more collaboration and knowledge sharing among farmers, researchers, and tech developers [113]. Communities of practice can develop around these platforms, enabling the sharing of insights and innovations in how farming practices can become more sustainable and productive. Collaboration, in turn, accelerates the pace at which scalable solutions can be created for diverse environmental and socio-economic contexts [114]. Scalability of agricultural technologies remains one of the most important challenges in developing regions. While highly developed countries show significant progress in adopting renewable energy and digital technologies, developing countries face high upfront costs, a lack of infrastructure, and limited technical expertise as the main barriers [115,116]. However, open-source platforms and scalable renewable energy systems offer a pathway out of these challenges [117,118].

High upfront costs remain one of the biggest barriers to entry in adopting renewable energy and digital technologies in agriculture. Most farmers in developing regions suffer from a scarcity of capital, which makes investment in AI, IoT, or renewable-powered systems prohibitively expensive [119]. Initiatives such as micro-financing schemes or subsidized loans, intended to reduce high upfront costs, do demonstrate promise in support given to farmers to overcome such a financial barrier [120]. Another challenge lies in inadequate infrastructure. The majority of rural areas lack consistent electricity, high-speed internet, and efficient transport systems—all of which are particularly important in the successful deployment of smart agricultural technologies [121,122]. Innovations like solar-powered IoT systems and offline-capable software alleviate this by allowing farmers to access technology without continuous internet or grid power [123]. The adoption of smart technologies and renewable energy is further constrained by farmer training and technical expertise. Even with the available technology, many farmers have limited digital literacy and specialized knowledge that prevent their effective use [124,125]. This has stimulated capacity-building programs for farmers, especially in partnership with local governments, NGOs, and private companies. For instance, the Digital Green program in India applies video-based training on the basic skills and knowledge required by farmers to use digital farming tools [126,127]. In addition, open-source platforms are contributing highly to training and adaptability since farmers can share insights and learn from each other through online communities and forums [128,129].

Scalable solutions are important in regions such as sub-Saharan Africa, South Asia, and Latin America, where smallholder farmers form the backbone of the agricultural sector [130,131]. Improving their livelihood is directly related to improved food security. Renewable energy systems are used mostly to power farming operations off-grid, from irrigation to storage and processing, particularly solar and wind power. This adds much to their scalability in combination with open-source platforms that enable farmers to monitor and optimize their energy use [132–134]. A case in point is that solar-powered irrigation systems can be scaled up or down depending on the size of the farm, meaning that even the most reasoned sections for farming can be irrigated by solar power, from the smallest-scale farmers up to even mid-sized agricultural enterprises [135–138]. This system could be integrated with open-source software solutions for real-time water and energy use. This will allow farmers to maximize resources while minimizing operations costs. Therefore, adopting renewable energies will become more affordable and viable in regions with limited access to traditional power grids [139]. In addition, an open-source platform would contribute to local farmers' easier training and education in digital technologies and renewable energy systems [140]. It can thus host tutorials, guidelines, and case studies that have depicted how other farmers in similar contextual settings can implement scalable and sustainable solutions [141,142]. This is, in fact, a critical knowledge transfer if the benefits of improved agricultural technologies are to reach the most vulnerable populations, especially those with very limited access to formal education and agricultural extension services. Due to their effectiveness, these open-source platforms are quite economical, especially in developing regions [143]. Unlike proprietary technologies, which normally have high licensing fees and require specialized training [144], open-source platforms usually come free and can thus be changed to suit local needs [145]. This makes them particularly attractive to smallholder farmers and agricultural cooperatives operating on tight budgets [146,147].

In this respect, open-source platforms lower such entry barriers so farmers can use advanced technology applications without bearing the financial burden [148]. For instance, it could be an open-source farm management system where farmers can keep track of growth, soil health, and water resource management without paying expensive licenses in software technologies. In this vein, open-source hardware solutions can include low-cost IoT sensors that track weather conditions, soil moisture, and energy consumption, further reducing the cost of operation while increasing resource efficiency [149,150]. Besides the cost savings via open-source platforms, the solutions are also cheaper to maintain. Farmers can leverage global communities of users and developers who can support, troubleshoot issues, and update the software. This collaborative ecosystem reduces dependency on expensive technical support services and ensures the technology remains functional and current [151]. It is about scalability and developing resilience in agricultural systems, not just scaling up in size. In developing regions where climate change threatens food security, scalable renewable energy solutions and open-source platforms support farmers in adapting to shifting environmental conditions [152]. With real-time data on weather patterns, soil conditions, and crop health, technologies put farmers in a better position to make informed decisions that reduce the risks related to climate-related disruptions [153,154]. For example, scalable solar-powered irrigation systems with open-source data analytics provide farmers in drought-prone areas with ways to optimize water application and allow crops to receive adequate moisture, even in low water availability. In areas where freak weather events strike frequently, IoT sensors and AI-driven predictive models enable farmers to prepare for oncoming storms, floods, or heatwaves, reducing crop losses and stabilizing food production [155–158].

Advanced technologies like large-scale renewable energy access and open-source platforms make agriculture more accessible and affordable to smallholders in developing regions. These technologies will discover the pathway to more sustainable, efficient, and resilient agricultural practices through AI, IoT, and renewable energy. Emerging challenges of climate change, resource scarcity, and food insecurity continue to push the farm sector globally. It is, therefore, necessary to look toward open-source platforms and scalable solutions to ensure that the benefits of innovation reach all corners of the world, particularly those who need it most [159,160].

3.4. Commonalities and Discrepancies in Global Adoption

Global adoption of renewable energy technologies, AI, and IoT in agriculture has been promising but with considerable challenges. While many regions are making fast moves towards implementing these innovations in the pursuit of sustainability, reduced environmental impact, and improved productivity, the pace and scale of such adoptions differ greatly across various countries. Determining the common drivers and barriers to wider implementation will be important for ensuring global sustainability in agriculture [161]. Some significant drivers of renewable energy, AI, and IoT adoption in agriculture worldwide include resource efficiency, environmental sustainability, and resilience in the face of climate change [162]. Farmers also feel that integrating advanced technologies is key to solving these challenges, irrespective of location. With the standard reliability of farming practices lowered by climate change and resource scarcity [163], countries are increasingly adopting renewable energy systems for farming, such as solar-powered irrigation, putting artificial intelligence into drive with predictive analytics to optimize available resources while minimizing the negative impacts of climate variability. Renewable energy technologies help farms decrease their dependence on fossil fuels. At the same time, AI and IoT systems increase the accuracy of the usage of resources, from smart water management to energy optimization [164–166]. Most driving policies and incentives also play a significant role in governments worldwide. Many governments give farmers subsidies, tax breaks, and loans to incentivize them to invest in renewable energy and AI-driven solutions [167]. For example, the Common Agricultural Policy of the EU provides financial support to farmers to implement sustainable environmental practices [168–170]. Similarly, other countries like India and China have rolled out plans to promote solar-powered irrigation systems and smart farming technologies in wider efforts that may help increase food security and reduce greenhouse gas emissions [171,172]. Knowledge sharing and collaboration amongst these actors will also facilitate technology uptake. It also called for cooperation between governments, academic institutions, technology companies, and farmer associations to develop open-source platforms, training, and pilot projects to ease farmers' adoption of renewable energy and digital solutions [173–175]. For instance, the Food and Agriculture Organization (FAO) has facilitated knowledge transfer across countries to disseminate best practices for using renewable energy and digitalizing agriculture [176]. With these shared drivers, vast differences prevail in the pace and size of this adoption across different regions, especially between developed and developing countries. Economic disparity, access to capital, and infrastructure gaps are some reasons that have been barriers to wider diffusion in some regions. In many developing areas, the high initial investment costs of AI, IoT, and renewable energy technologies are still unaffordable [177,178]. While large numbers of smallholder farmers make up most of the agricultural workforce, generally in sub-Saharan Africa and Southeast Asia, they are usually not in a good financial position to invest in these innovations, though they stand to benefit most [179,180]. Farmers in developed countries have better access to credit, subsidies, and government support, which allows them to easily adopt these technologies [181,182]. Moreover, extensive infrastructure challenges persist in most developing regions [183]. The implementation of digital agriculture solutions is hampered in rural areas by the absence of reliable internet, electricity, and transport systems [184,185]. The IoT systems function with continuous data transmission at their core, while AI thrives on predictive models to function, requiring stable internet connectivity [186]. These are often opposed to developed regions, where abundant infrastructure forms the basis for providing AI, IoT, and renewable energy technologies [187]. The gap in technological literacy and skills may be another factor. In the areas where educational and training resources are scarcer, farmers may be unable to grasp or control advanced digital systems [188]. A greater divide can be found in developing nations offering more limited formal digital agriculture education [189]. Contrarily, most developed regions usually offer wide training programs, workshops, and technical support that help farmers adapt to and operate systems of AI, IoT, and renewable energy more effectively [190].

Notwithstanding the discussed challenges, success stories highlight how regions, particularly those in the developing world, overcome barriers to adopting renewable energy and digital technologies into agriculture. Incentivizing solar-powered irrigation through India's KUSUM scheme has played an important role in reducing diesel pumps. The government of India supports the scaling up of the adoption of renewable energy sources in agriculture through financial incentives and technical support policies that open up better energy access with reduced GHG emissions [191]. On the other hand, companies like M-KOPA and SunCulture provide Kenyan farmers with solar-powered irrigation systems at reasonable costs, connected to IoT platforms for remote water usage and energy consumption monitoring. These solutions improve the efficiency of resources and productivity while reducing operational costs [192–194]. The use of renewable energy, AI, and IoT in agriculture worldwide is a key foundational building block of the emergent sustainable and resilient food system. While common drivers, such as adaptation to climate change and government support in the regions toward these technologies, large disparities in economic money, infrastructure, and skill levels remain obstacles to wide realization. Further international collaboration, investment in infrastructure, and a focused training program will be required to ensure that each country can fully utilize the potential of renewable energy and digital technologies in agriculture [195].

4. Conclusions

Integrating renewable energy, AI, and IoT in agriculture is a vital starting point toward realizing long-term sustainability, efficient use of resources, and resilience to most unforeseen global challenges. At the rate at which temperature rises unpredictably, and resources are in high shortage, agriculture needs to shift away from traditional farming. The convergence of these high-level technologies provides a pathway to more viable farming. It acts as a model for how the agricultural sector may lead to environmental conservation and economic resilience. Throughout this paper, we have dwelled on the critical roles that AI and IoT play in enhancing the adoption and effectiveness of renewable energy within agriculture. These technologies will enable farmers to make informed resource-use decisions with real-time data gathering and predictive analytics at their beck and call. Smart irrigation systems powered by renewable energy and monitored with IoT sensors will drastically reduce water waste, energy consumption, and GHG emissions. AI-powered analytics further optimize these operations to ensure the deployment of resources only when and where needed, in line with peak demand. Such precision will mean that farms increase their productivity and contribute to a reduction in carbon footprint, thereby being key contributors towards global climate goals. Renewable energy in agriculture has enormous environmental benefits. All these irrigation systems powered by solar or wind and AI-based energy management have obvious advantages in reducing dependence on fossil fuels. These systems bring about quite sizeable operational costs and emission reductions and contribute to energy sustainability in the long term. Moreover, agricultural waste to bioenergy solutions creates some form of a circular economy model of transforming waste into energy and further low environmental impact. This circular approach not only cuts down on emissions but also ensures waste-to-value conversion and adds value to resources, thereby reinforcing the sustainability of the agricultural sector. However, their spread globally is not distributed evenly. There is a huge difference between the developed and developing regions of the world. This is where developed nations have been able to go a long way in integrating renewable energy, AI, and IoT into their agricultural functions. In contrast, economic, infrastructural, and technological barriers create barriers that are a little hard to cross for many developing nations. Some limitations to wider dissemination include high initial costs, inadequate infrastructure, and limited technological literacy. On the other hand, there are some promising examples of scale-up from countries like India and Kenya, which successfully scaled up solar-powered irrigation systems and IoT solutions that are more affordable to improve resource management and agriculture productivity. The success of these initiatives proves that renewable energy and smart agriculture technologies can be adapted to various contexts, even those in resource-poor regions. In this vein, open-source platforms hold great flexibility and are costless. Such platforms help provide farmers in developing areas with the ability to access tools for the optimization of their farming operations without incurring the significant financial burden brought by proprietary technologies. Knowledge sharing and adapting these platforms to local conditions may ensure better yields, waste reduction, and environmental sustainability for smallholder farmers by realizing the benefits of AI, IoT, and renewable energy.

Making regions at par and reaching the benefits of such technologies is not mere wishful thinking but an urgent need for which several steps are required. These steps involve international cooperation and much-needed investments in renewable energy infrastructures. Such will be achieved through the collaboration of governments, development agencies, and private sector players in providing farmers with financial and technical support, especially in regions where such technologies have not been reached. Subsidies, grants, and soft loans would ensure small and medium-sized farms access to renewable energy and smart agriculture solutions by lowering the entry barriers. Secondly, education and training for capacity building are quite crucial. Farmers have to know and manage both the AI, IoT, and renewable energy systems themselves. Training programs delivered through partnerships between governments, universities, and technology providers can ensure farmers know how to optimize their use of the technologies. Further, developing local technical support networks will help sustain the long-term use of such systems, hence their continued benefits. Lastly, policy frameworks should be targeted to address the global sustainability agenda. Governments should create enabling environments that ensure farmers tap renewable energy sources and smart farming technologies. Policies on renewable energy, innovation incentives, and policies that favor the circular economy could help transform agriculture into a sustainable and more resilient sector.

Integrating AI with IoT and renewable energy will be a great opportunity for agriculture to take up today's challenges and secure its future. That sets up a clear pathway to cut greenhouse gas emissions, advance resource efficiency, and boost productivity in agriculture while aligning it with global climate targets. However, most will realize their full potential through concerted efforts to address particular barriers, particularly in the developing world. The international community has a key role in fostering collaboration, investing in infrastructure, and building capacity to make agriculture a leading pillar in the transition to a low-carbon future. As these two continue to evolve rapidly, the contribution they will make to the future of food systems will increase. This would place agriculture at the forefront of the global battle against climate change and resource depletion.

Future research could further refine how AI and IoT solutions could be enhanced for small-scale farms, where resource limitations and scale demand tailored methods to ensure these new technologies function. Another key area of exploration might be investigating the role of open-source platforms in ramping up access and affordability, especially within developing regions. Such open-source platforms could be optimized for knowledge sharing with the aim of reducing financial and technical barriers to digital and renewable energy solutions. Predictive models can be created using AI on the use of renewable energy under various agricultural conditions along with field experiments involving sensor data in order to enhance knowledge on the impact of IoT-enabled precision farming on crop yield and resource conservation. Practical data related to the cost-effectiveness of integrating AI and IoT with renewable energy would be provided by life-cycle assessments (LCA) or economic modeling. Further policy intervention studies, such as the EU's Common Agricultural Policy or India's KUSUM scheme, could be instructive in terms of how government support has helped accelerate adoption—a road map of best practices that other regions might consider. Last but not least, considering that one of the acute difficulties the farmers face refers to the limited technical capacity, further research might be directed at elaborating effective training programs that would provide farmers with relevant skills for applying and maintaining these very technologies.

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