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REVIEW ANALYSIS ON ENHANCING AGRICULTURAL PRODUCTIVITY AND REDUCING GREENHOUSE GAS EMISSIONS THROUGH RENEWABLE ENERGY, AI AND IOT

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ABSTRACT

Climate change jeopardizes agricultural output due to increasing temperatures, unpredictable precipitation patterns, and catastrophic weather phenomena that affect food systems. In this setting, a strategy to agriculture that is significant, essential, sustainable, and energy-efficient is required. Renewable energy sources, including solar, wind, and bioenergy, present significant opportunity to enhance energy efficiency in agricultural practices. This transition mitigates environmental issues, lowers operating expenses, and enhances productivity. The advent of sophisticated technologies, like the Internet of Things (IoT) and artificial intelligence (AI), is rendering the integration of renewable energy with precision farming practices increasingly viable, providing unique answers to contemporary agricultural challenges. Globally, there are compelling instances of AI enhancing traditional agricultural and energy methods, optimizing resource utilization, and ultimately fostering a better environment. A notable advance is AI-driven precision agriculture. This method integrates sustainable agricultural methods with advanced predictive analytics. Technologies like smart irrigation systems and bioenergy generation from agricultural waste promote environmental sustainability and economic resilience. Notwithstanding these advantages, adoption is inconsistent among areas owing to financial, infrastructural, and technical limitations, especially in poorer nations. Successful projects in nations like India and Kenya illustrate that cost-effective and scalable solutions may surmount these obstacles. Open-source platforms augment accessibility by lowering expenses and facilitating information exchange among farmers. Future research should concentrate on creating economical AI and IoT solutions for smallholder farmers, assessing the impact of open-source platforms on technology distribution, and enhancing predictive models for renewable energy management in agriculture.

Keywords: *Enhancing, Agricultural, Productivity, Reducing, Greenhouse, Gas, Emissions Renewable Energy, AI, Iot*

INTRODUCTION

Agriculture seeks to nourish about 7.9 billion individuals now and 9.6 billion by 2050, with food consumption projected to increase by at least 60%, while the industry confronts a sustainability dilemma. Agriculture accounts for over 30% of world energy use. The global agricultural business currently confronts significant problems, including heightened demand for sustainable food production, rising energy prices, and the effects of climate change. Conventional agriculture has always relied on fossil fuels as its energy source. Agriculture is now prepared to shift to greener and more efficient energy sources[1]. Climate change jeopardizes agricultural output due to increasing temperatures, unpredictable precipitation patterns, and extreme weather events that undermine food systems. In this setting, a strategy to agriculture that is significant, essential, sustainable, and energy-efficient is required. Renewable energy sources, including solar, wind, and bioenergy, present significant opportunity to enhance energy efficiency in agricultural practices. This transition mitigates environmental issues, lowers operating expenses, and enhances productivity. The advent of sophisticated technologies, like the Internet of Things (IoT) and artificial intelligence (AI), is rendering the integration of renewable energy with precision farming practices increasingly viable, providing unique answers to contemporary agricultural challenges.

The Food and Agriculture Organization of the United Nations (FAO) has emphasized that fulfilling the heightened demand necessitates a significant enhancement in food production. The assistant editor overseeing the evaluation and approval of this work for publication was Zhengmao Li, addressing the environmental consequences of conventional agriculture, including elevated greenhouse gas (GHG) emissions, water shortages, and land degradation. This worldwide dilemma has prompted the pursuit of creative and sustainable approaches to local food production that are efficient and minimize environmental carbon emissions. Conventional food supply networks are sometimes lengthy, intricate, and very vulnerable to interruption. The worldwide system is strongly dependent on the transportation of food across extensive distances, leading to a substantial carbon footprint due to emissions produced by shipping and trucks[2].

AI in Agriculture and Energy Transition

Artificial intelligence (AI) is revolutionizing agriculture and energy by enhancing production while also promoting environmental stewardship. Globally, there are compelling instances of AI enhancing traditional agricultural and energy methods, optimizing resource utilization, and ultimately fostering a better environment. A notable advance is AI-driven precision agriculture. This methodology integrates sustainable agricultural methods with advanced predictive analytics. By tracking critical variables like soil vitality and crop development in real-time, farmers can make more informed decisions that boost productivity and minimize waste. Machine learning models evaluate data from satellites and sensors to optimize irrigation and fertilizer application. Some studies have indicated a 15% increase in resource efficiency, indicating that high-tech agriculture can be sustainable. In addition to enhancing yields, these AI systems contribute to the conservation of land for future generations. They can mitigate soil deterioration and modify agricultural practices to accommodate fluctuating weather conditions. In drought-prone regions, AI techniques are essential for managing limited water supplies while sustaining strong agricultural output. Consider AquaIntelligence, for instance. Established in 2019, this firm focuses on pioneering water management solutions, employing technology to track water consumption and recommend enhancements.

This method not only aids farms but also assists urban areas in reducing trash, which is vital in regions where every drop is significant. In the realm of energy, AI is also revolutionary, particularly in optimizing the utilization and distribution of electricity. Companies such as GreenTech Innovations lead in developing technologies that automate monitoring and enhance the utilization of renewable energy. These advanced technologies can evaluate data in real-time and discover methods to enhance energy distribution, leading to a significant 30% decrease in energy use across diverse environments. This not only reduces expenses but also facilitates the reduction of carbon emissions by promoting the utilization of solar and wind energy. Artificial intelligence is transforming decision-making in agriculture. Predictive analytics allows farmers to forecast ideal planting periods and detect possible pest problems, empowering them to intervene before concerns intensify.

Components of IoT in Agriculture: Sensors, Drones, and Connectivity

The Internet of Things (IoT) in agriculture signifies a revolutionary change in the generation, transmission, and utilization of farming data. Central to IoT systems are intelligent sensors that collect real-time data on soil moisture, temperature, humidity, pH, and nutrient concentrations. These sensors, integrated across fields or affixed to agricultural machines, provide localized and continuous observation of agro-ecological conditions. Their capacity to perceive nuanced environmental alterations facilitates early alerts and prompt responses, enhancing both yield and sustainability results. Drones are a crucial element of the agricultural IoT framework. Drones, outfitted with multispectral, thermal, or LiDAR sensors, conduct high-resolution airborne surveys of fields, acquiring visual and spectral data that is difficult to discern from the ground. These pictures facilitate the assessment of plant health, identification of insect infestations, monitoring of irrigation efficiency, and evaluation of crop coverage with superior precision compared to manual scouting methods. Drones are particularly advantageous in isolated or rugged terrains, providing extensive surveillance capabilities across vast expanses. Connectivity infrastructure constitutes the foundation of IoT networks. Wireless technologies, including LPWAN (Low Power Wide Area Networks), Zigbee, and cellular networks, are employed to convey data from far farms to cloud-based systems or local edge servers. In regions with restricted internet availability, satellite IoT and mesh networks have surfaced as feasible alternatives. The dependability and latency of these communication routes significantly influence the efficacy of IoT systems, especially in time-critical processes like as irrigation management or disease response.[3]

IoT-AI Integration Architecture in Smart Farming

The amalgamation of IoT and AI in agriculture yields a complex architecture aimed at enabling real-time data collection, sophisticated analysis, and informed decision-making. The foundation of this architecture consists of the perception layer, which includes IoT-enabled devices such as soil sensors, weather stations, drones, and intelligent machinery. These components function as the principal data collecting instruments, producing detailed, high-frequency environmental and operating data.

The subsequent layer is the network layer, which facilitates communication between scattered sensors and centralized or edge computer resources. This layer guarantees safe and efficient data transfer using protocols like MQTT or CoAP, tailored for low-power, low-bandwidth settings typical in rural agricultural areas. It also include gateways and routers that enable data transmission from field devices to cloud infrastructure.

The processing layer contains artificial intelligence engines, analytical modules, and machine learning models. This is the stage when raw data is converted into predicted insights or control signals. Cloud computing systems offer scalable resources for extensive data analysis, whereas edge computing nodes allow localized AI processing to reduce latency in time-sensitive applications such as irrigation automation or illness notifications. AI models are generally encapsulated utilizing platforms such as Docker to facilitate modularity and expedite upgrades.[4]

Toward Global Collaboration and Governance

Artificial intelligence (AI) is set to significantly influence sustainable practices in the agriculture and energy sectors, merging technological advancements with a dedication to environmental preservation. As these domains progress concurrently, we anticipate a confluence of artificial intelligence, data analytics, and renewable energy technologies to propel future sustainable growth. Agriculture is seeing a transition towards novel agricultural methods that utilize data to improve production and ecological balance. Advancements in AI promise enhanced agricultural practices that employ high-resolution satellite imaging, predictive analytics, and sensor technologies. These instruments will assist farmers in optimizing their water and fertilizer utilization while reducing energy consumption.

Through the automation of several decision-making processes, AI empowers farmers to swiftly adjust to fluctuating weather, soil conditions, and insect pressures, ultimately resulting in enhanced crop yields with reduced resource use. Emerging agricultural technology firms are developing AI-driven systems that combine machine vision, robotics, and cloud-based analytics for immediate crop assessments and precise treatments. These advancements not only improve efficiency but also further global sustainability objectives by decreasing agricultural emissions and mitigating environmental consequences. The expanding AI agricultural sector underscores its capacity to serve as a pivotal force in advancing climate-smart farming methods globally. Nonetheless, actualizing the whole potential of AI in agriculture and energy transitions poses considerable hurdles. Substantial initial expenses, insufficient digital infrastructure, and restricted data accessibility may impede mainstream adoption, especially in developing nations.[5]

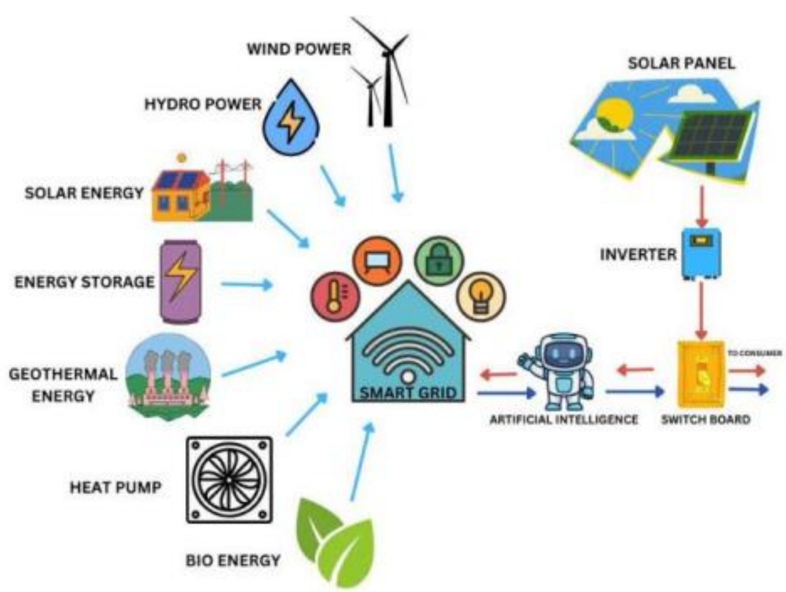

Figure 1. AI-powered potential of the industry for renewable energy and material development

Benefits: Efficiency, Monitoring, and Real-Time Insights

The amalgamation of AI and IoT in agriculture has several advantages that rectify enduring inefficiencies and knowledge deficiencies in farming systems. A primary benefit is resource efficiency. Precision irrigation systems, guided by soil moisture sensors and meteorological predictions, optimize water use by supplying moisture exclusively when and where it is required. Likewise, AI-assisted fertilization regimens guarantee the application of nutrients in appropriate quantities, minimizing environmental runoff and enhancing crop absorption. A notable advantage is ongoing surveillance. IoT-enabled devices deliver a continuous flow of data on soil conditions, equipment status, and crop growth. This enables farmers to identify problems promptly—such as defective irrigation systems or bug invasions—before they develop into more significant challenges. Ongoing monitoring facilitates adherence to traceability and sustainability criteria, which are progressively mandated in international markets. Real-time insights enhance decision-making by facilitating adaptive reactions to unexpected factors such as weather variations, input price changes, or disease outbreaks. AI systems evaluate real-time data streams to produce alerts and recommendations, assisting farmers in taking prompt action. Predictive algorithms can alert to an impending fungus epidemic, enabling preventive spraying and perhaps preserving a full crop cycle.

REVIEW LITERATURE

Riccardo Bertoglio et. al. (2021) The utilization of digital technology in agriculture can enhance conventional techniques to accommodate climate change, decrease Greenhouse Gas (GHG) emissions, and foster sustainable intensification for food security. Certain authors contend that we are undergoing a Digital Agricultural Revolution (DAR) that will enhance sustainable agricultural practices. This study seeks to identify evidence of the current DAR process and elucidate its origins, significance, and future trajectory. We employed bibliometric analytic methods to conduct an impartial and repeatable review of the scientific literature. We acquired 4,995 papers by querying the Web of Science database from 2012 to 2019, and we examined the dataset to address three particular research questions: i) what is the range of DAR-related terminology? ii) What are the principal articles, as well as the most prominent publications, institutions, and nations?What are the primary research streams and developing topics? Through the aggregation of authors' keywords from publications, we discerned five primary study domains: Climate-Smart Agriculture (CSA), Site-Specific Management (SSM), Remote Sensing (RS), Internet of Things (IoT), and Artificial Intelligence (AI). We conducted an analysis of pertinent review papers to offer a comprehensive overview of each issue, highlighting the principal accomplishments and current problems. Ultimately, we presented the popular subjects over the last three years (2017, 2018, 2019).[7]

Mangirdas Morkūnas et al. (2024) This study examines the significance of combining renewable energy, artificial intelligence, and the Internet of Things in advancing climate-smart agriculture. In light of the shifting climate, escalating energy expenses, and the necessity for food security, agriculture has unparalleled problems; thus, advancements in novel technologies are being pursued for its sustainability and efficiency. This study rigorously synthesizes available material to ascertain how AI and IoT might enhance resource management, boost production, and diminish greenhouse gas emissions in agriculture. Critical results emphasized the necessity of sustainable resource management, the scalability of technologies, and, ultimately, policy interventions to facilitate technological uptake. The document delineates trends in the worldwide implementation of renewable energy and smart agriculture solutions, highlighting similarities and disparities while underscoring the necessity for targeted policies and capacity-building initiatives to enhance the advantages of these innovations, especially in developing nations. This research addresses gaps in understanding how AI, IoT, and renewable energy may collaboratively enhance a sustainable and resilient agricultural economy.[6]

Hongyun Zheng et al. (2024) This study examines material published from 2013 to 2023 to thoroughly comprehend the implications of implementing climate-smart agriculture (CSA) practices. The literature is classified into three categories according to the dimensions of climate-smart agriculture: (a) sustainably enhancing agricultural productivity and income; (b) adapting to and strengthening the resilience of individuals and agrifood systems against climate change; and (c) mitigating or, when feasible, preventing greenhouse gas emissions. The review indicates that the use of CSA techniques frequently enhances agricultural output and revenue levels. This growth is seen in enhanced crop yields and productivity, elevated revenue and profitability, and improved technological and resource use efficiency. Furthermore, the implementation of CSA methods enhances the resilience of farmers and agrifood systems by fostering food consumption, nutritional variety, and food security, while also alleviating production risks and vulnerabilities. Implementing CSA methods is ecologically viable since it lowers greenhouse gas emissions and enhances soil quality. An integrated method including several CSA activities presents an enhanced pathway to develop agrifood systems resilient to climate change.[8]

Dalhatu Muhammed et al. (2024) The Artificial Intelligence of Things (AIoT), which integrates the Internet of Things (IoT) with Artificial Intelligence (AI), is becoming increasingly significant in smart agriculture (SA). The AIoT has been used in several areas, including agriculture, for purposes such as crop yield estimation, soil and water conservation, pest and disease detection, and supply chain management. Although several studies exist on AIoT applications in healthcare, smart cities, manufacturing, and transportation, South Africa now represents a minimal portion of the documented study. This study offers a thorough examination of the current literature on AIoT and Federated Learning (FL) for Situational Awareness (SA). It highlights existing and prospective difficulties and offers research guidance for future investments in both academia and industry.[9]

Hammad Shahab et al. (2024) The United Nations' Sustainable Development Goals (SDGs) aim to foster an agricultural sector capable of driving transformation at both local and global levels. IoT-based agricultural management systems are substantially aiding farmers in sustainably increasing food production, hence contributing to the attainment of these Sustainable Development Goals (SDGs). By 2050, the global population is projected to attain 9.7 billion, requiring a 60% enhancement in food production efficiency and security to satisfy the escalating wants of the populace. Smart farming, driven by the Internet of Things (IoT) and employing artificial intelligence (AI) with machine learning (ML) algorithms, is emerging as a feasible and sustainable approach to enhance agricultural output while minimizing environmental effect. This thorough overview article summarizes the latest research and development projects in IoT-based smart farming and their potential impact on the agriculture industry. The paper provides a comprehensive review of the capabilities of machines that facilitate smart farming, encompassing sensing, reasoning and learning, communication, task planning and execution, and systems integration. The study illustrates the application of robots and unmanned aerial vehicles (UAVs) in several agricultural settings, highlighting their potential to enhance production and reduce environmental impact. The research continues by emphasizing the importance of employing wireless communication LoraWan technology in the development of smart systems that facilitate sustainable agricultural management.[10]

Ajit Singh Rathor et al. (2024) The significant rise in the human population severely burdens food resources. Agriculturalists require fertile land and natural minerals for conventional farming, and the production process is rather prolonged. Vertical farming (VF), a soil-less agricultural practice, necessitates little land use and significantly less water compared to traditional soil-based farming techniques. Contemporary technologies such as hydroponics, aeroponics, and aquaponics suggest a potential future for vertical farming in urban regions where agricultural land is both costly and limited. VF has challenges in concurrently monitoring several indicators, providing nutritional guidance, and diagnosing plant conditions. These difficulties can be addressed by the use of contemporary technological breakthroughs, including artificial intelligence (AI)-based control methodologies such as machine learning (ML), deep learning (DL), the internet of things (IoT), image processing, and computer vision. This article provides a comprehensive review of machine learning and Internet of Things applications in value chain systems. The focal areas are disease detection, crop production forecasting, nutritional assessment, and irrigation management. The computer vision technology is examined for predicting agricultural yield and illnesses through the categorization of various crop picture collections. This paper also demonstrates ML and IoT-based VF solutions that can enhance product quality and output in the long run. The paper delineates the assessment and evaluation of the knowledge-based VF system, highlighting the potential results, advantages, and limits of machine learning and the Internet of Things inside the VF system.[11]

OBJECTIVES OF THE STUDY

1. To study on AI in Agriculture and Energy Transition
2. To study on IoT-AI Integration Architecture in Smart Farming

RESEARCH METHOD

The findings and discussion part consolidates current research on climate-smart agriculture, renewable energy integration, and the revolutionary impact of AI and IoT on improving efficiency and sustainability. The established conceptual framework provides a comprehensive overview of the intersection and influence of these factors within various agricultural contexts, particularly concerning economic and policy-related difficulties, hence determining their acceptance and efficacy. [12]

AI- and IoT-driven technologies, including smart irrigation, real-time data monitoring, and efficient energy utilization systems, are crucial for managing agricultural resources sustainably. These technologies facilitate the efficient utilization of water, energy, and land, which will be crucial for areas where these resources are limited or highly susceptible to climatic variations. Examples encompass clever irrigation systems driven by renewable energy that optimize water usage through real-time data, therefore minimizing waste and improving production. Research in this domain is essential as it directly influences the equilibrium between environmental sustainability and the escalating demands for agricultural output. Thus, optimizing resources without compromising productivity is fundamental to attaining climate-smart agriculture.

Furthermore, artificial intelligence, the Internet of Things, and renewable energy technologies instigate significant modifications in agricultural practices. The utilization of technology facilitates accurate monitoring and enhancement of agricultural practices, conserves energy, and reduces environmental harm. This advancement is significant, as the scale of these technologies renders them inexpensive and accessible, particularly for small and medium-sized farms, which often have less financial resources and technical expertise compared to larger farms. Key technologies include precision agriculture and IoT-enabled energy systems, which facilitate sustainability by diminishing reliance on nonrenewable energy sources. This research investigates the scalability and adaptability of novel solutions across various agricultural contexts, enabling resource-limited countries to use recent advancements in farming technology. Conversely, policy and economic issues have become essential in determining the integration of renewable energy and smart technology into agriculture. Government measures such as incentives for renewable energy and investments in advanced farming methods significantly motivate farmers. Economic constraints encompass the substantial initial expenses of AI and IoT systems and insufficient infrastructure, which may further impede adoption, particularly in developing areas. This necessitates study into these policy interventions to uncover techniques that facilitate the wider use of renewable energy in agriculture and how economic incentives may be effectively structured to overcome infrastructure obstacles. It also recognizes governmental and institutional assistance as essential factors in steering agriculture towards sustainability overall. A pertinent instance to consider is the Netafim project in Israel. This project integrates a sophisticated drip irrigation system equipped with IoT sensors that continuously monitor soil moisture, temperature, and humidity levels in real time. The amalgamation of AI and IoT has consequently enabled precision irrigation to conserve an additional 50% more water compared to traditional approaches, while enhancing agricultural yields by slightly over 20%. The Smart AgriHubs initiative in Europe integrates IoT and renewable energy technologies, including solar-powered irrigation, to enhance farmers' skills in sustainable and effective resource management and to decrease greenhouse gas emissions.[13]

This is examined due to the interaction of various aspects, which fosters a more sustainable and efficient agriculture industry. Comprehending the connections between resource management, technological adoption, and policy interventions provides profound insight into how agriculture may adapt to the difficulties of increasing output while minimizing environmental consequences. These elements will be the foundation of the discourse, directing the examination of the appropriate integration of renewable energy and smart technology into agricultural operations across various farming systems.

This conceptual framework, illustrated in Figure 2, delineates the interconnected aspects that will affect the adoption of climate-smart agriculture utilizing AI and IoT in conjunction with renewable energy. It encompasses, at its apex, the integration of climate-smart agriculture and renewable energy, underpinned by three critical pillars: sustainable resource management aimed at optimizing water, energy, and land utilization; the adoption of scalable and accessible technologies in AI and IoT for agriculture; and, lastly, an examination of policy interventions and economic barriers that influence the adoption of such innovations through government policies and economic incentives. This elucidates how these aspects contribute to environmental effect and productivity enhancements by asserting that the components should mitigate greenhouse gas (GHG) emissions while augmenting efficiency and promoting more sustainable agricultural practices.

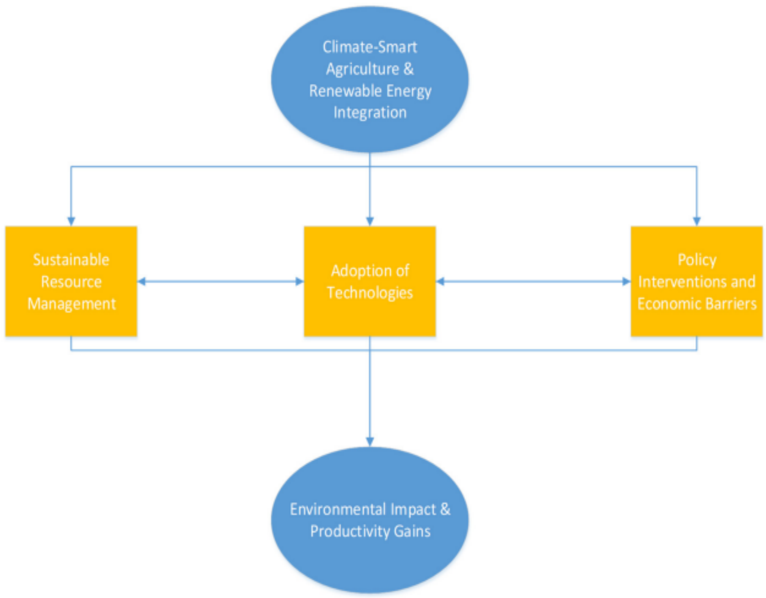

Figure 1. Conceptual framework

Information Gathering

Literature was examined in two main academic databases, Clarivate Web of Science (WoS) and Scopus, pertinent to our research. The search utilized a predetermined keyword string that encompassed essential subjects pertaining to renewable energy, agriculture, and technology adoption. The search query 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 hunt concluded on 9 September 2024. No temporal constraints were imposed on the literature search to guarantee that this study includes a comprehensive and historical perspective on renewable energy, agriculture, and the integration of AI and IoT technologies. This facilitates the incorporation of basic studies, developing trends, and a comprehensive range of research advancements across time.[14]

Initially, as seen in Figure 3, we obtained 744 records from the WoS database. Subsequently, by using a filter to exclude book chapters and conference papers, the total was reduced to 699 articles. Upon the removal of one extraneous item pertaining to religion, the total count reached 698 articles. Conversely, the Scopus database yielded an initial total of 786 entries. The total was lowered to 572 articles after excluding book chapters and conference papers, followed by the removal of three articles from the arts and humanities, resulting in a final count of 569. Subsequently, we eliminated the duplicates across the two databases, yielding a total of 1015 unique articles for analysis.

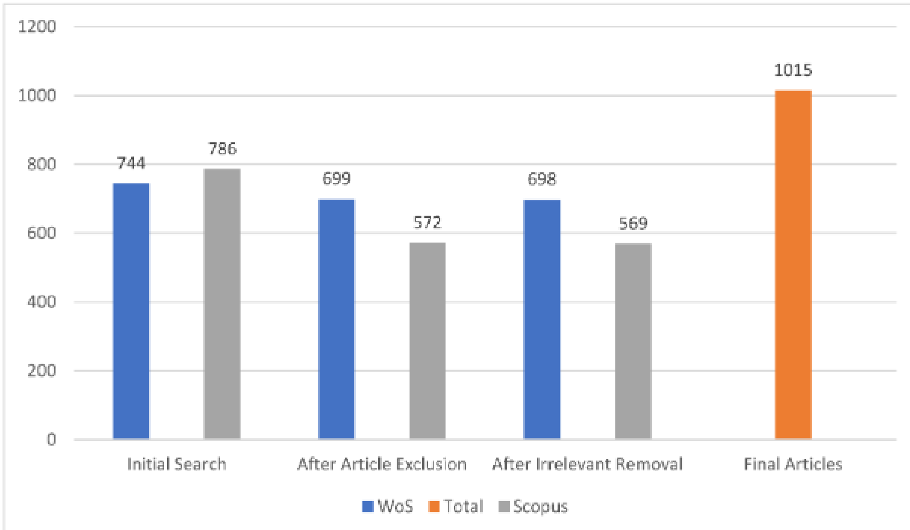

Figure 3. Process of article selection.

RESULT AND DISCUSSION

Agriculture confronts increasing demands to enhance sustainability and mitigate environmental effects amid emerging global issues, including climate change, escalating energy expenses, and food poverty. In response to these challenges, nations are implementing several strategies, including the integration of renewable energy, the adoption of sustainable agriculture practices, and the formulation of climate-smart agricultural policy. This chapter examines significant scholarly literature about the interactions between renewable energy and agriculture, focusing on the efficacy of governmental incentives, consumption behaviors, and diverse environmental certification schemes.[15]

Resource Efficiency and Optimization

Artificial Intelligence, the Internet of Things, and renewable energy are converging to transform the agricultural industry, especially in resource management, including water and energy. Given the escalating issues posed by climate change, rising energy costs, and heightened expectations for sustainable agriculture, these solutions facilitate operational efficiency, waste reduction, and environmental sustainability. The transition fundamentally hinges on the integration of renewable energy, which, in conjunction with AI and IoT, enhances energy efficiency, cost-effectiveness, and ecological sustainability. One of the foremost difficulties in the agricultural industry, which is becoming increasingly significant owing to escalating water constraints and elevated energy use, is water management resulting from inefficient irrigation systems. The conventional irrigation method squanders water resources and relies heavily on fossil fuel-powered electricity systems. Renewable energy, in conjunction with IoT and AI technology, is addressing these shortcomings by providing more effective and environmentally sustainable methods for managing liquid resources. IoT-enabled smart water metering employs sensors to assess fundamental environmental parameters: soil moisture, meteorological conditions, and agricultural water requirements. Consequently, farmers possess real-time data to choose the most advantageous timing and method for water application. IoT-based smart water metering systems transform significantly when coupled with renewable energy sources, such as solar or wind. In regions with limited water resources, such as Rajasthan, India, researchers have observed that the integration of solar-powered pumps with IoT sensors significantly enhances irrigation management efficiency. IoT sensors assess soil moisture levels and meteorological conditions in real time. This method activates the water pump just when necessary, hence maximizing its utilization. Utilizing renewable energy sources, such as solar power, to operate these pumps diminishes farmers' dependence on the grid or fossil fuels, significantly reducing energy expenses and greenhouse gas emissions. The link guarantees efficient water utilization and stabilizes energy usage, addressing variable agricultural demands while promoting sustainable farming practices. By amplifying this approach, the strategic integration of IoT and renewable energy may achieve a water wastage reduction of up to 71.8%. In this regard, irrigation systems powered by renewable energy has significant promise for mitigating the combined issues of water waste and excessive energy use. These renewable energy irrigation systems provide off-grid alternatives, allowing farms in distant or energy-insecure regions to operate independently of fossil fuel-based grids. An illustrative instance of such systems is wind-powered irrigation, which transforms natural wind energy into effective potential for water pumping, hence lowering energy expenses and minimizing environmental consequences in the sustainable management of water.[16]

Energy use in agriculture constitutes a significant portion of operating expenses and contributes to environmental degradation. Agricultural operations often depend significantly on non-renewable energy sources, including diesel-powered machinery and grid electricity derived from fossil fuels. Nevertheless, the increased utilization of renewable energy technologies, like solar and wind power, alongside the incorporation of AI systems, enables farms to optimize their energy consumption and significantly diminish reliance on non-renewable resources. Artificial intelligence-driven systems are significantly more effective in forecasting energy consumption and optimizing agricultural operations during periods of high renewable energy availability. Certain AI algorithms can assess meteorological patterns and forecast optimal periods for utilizing solar or wind energy in various agricultural operations. During peak solar or wind energy output, the AI system may autonomously modify energy-intensive operations, such as irrigation, heating, or greenhouse ventilation, to optimize the utilization of renewable energy sources. This is useful for regions where solar and wind energy are not consistently available. This will guarantee efficient energy use and diminish reliance on fossil fuels, hence lowering energy expenses and carbon emissions. An illustrative instance is the utilization of AI-driven energy management systems in greenhouse agriculture. These greenhouses include renewable energy sources, such as solar panels and wind turbines, which energize automated climate control systems that include smart glass technology and ventilation fans.[17] AI algorithms continually monitor and autonomously recalibrate for energy use based on real-time environmental data. Integrating renewable energy with AI would significantly improve energy efficiency in greenhouses, decrease reliance on grid electricity, and enhance overall sustainability and productivity. Renewable energy solutions have increasingly shown feasible in off-grid areas, supplying agricultural operations with uninterrupted electricity without reliance on traditional fuel sources. This is crucial in developing countries where reliable grid power availability is still restricted. This fosters prospects for farm independence through off-grid renewable energy solutions, so diminishing reliance on fossil fuels by harnessing solar or wind potential, thus advancing long-term sustainability.

Environmental Sustainability and Emission Reductions

The swift amalgamation of AI, IoT, and renewable energy technologies is occurring in manners that will provide agriculture with novel avenues to diminish GHG emissions. Agriculture traditionally generates significant greenhouse gas emissions due to typical energy use for irrigation, fertilizing, and different mechanical activities reliant on fossil fuels. Agriculture constitutes a significant source of greenhouse gas emissions, representing around 10–12% of the total. Integrating AI and IoT with renewable energy sources advances a more efficient and ecologically friendly paradigm for contemporary agriculture. AI technologies have transformed agriculture by enhancing energy management via real-time analytics bolstered by predictive capabilities. By integrating renewable energy sources such as solar and wind, AI algorithms facilitate the effective management of energy use, therefore diminishing reliance on fossil fuels and reducing greenhouse gas emissions. The primary use of AI lies in predicting energy consumption. By examining historical data with real-time information collected from IoT devices, the AI system can predict peak energy usage, enabling adjustments to agricultural operations accordingly. For instance, AI can forecast ideal irrigation schedules based on meteorological trends, soil moisture content, and anticipated renewable energy production. As a result, farmers might engage in energy-intensive tasks such as pumping water or operating machinery just during peak solar or wind energy periods. Moreover, optimizing the utilization of renewable energy diminishes the reliance on grid electricity or fossil fuels in agricultural operations.[18]

IoT sensors determine the correct timing and fertilization levels in precision agriculture, hence minimizing the carbon footprint associated with excessive resource use. AI can pinpoint particular regions in the field that need varying levels of water or nutrients, allowing farmers to address these areas more efficiently, therefore conserving energy and reducing emissions. The true function of AI and IoT in reducing greenhouse gas emissions is realized when these technologies are incorporated into renewable energy systems. Although renewable energy sources like solar and wind are widely utilized in agriculture, their intermittent characteristics necessitate sophisticated management systems to optimize their efficiency. This is the intersection between AI and IoT. AI systems can optimize renewable energy utilization by forecasting peak demand and strategically arranging agricultural operations. Forecasting elevated sun output may suggest optimal timing for irrigation or greenhouse heating. Furthermore, IoT sensors may deliver real-time data on energy generated by renewable sources, facilitating the smooth transition of farms between solar, wind, or grid electricity. [19] The attained level of accuracy restricts dependence only on non-renewable energy and enhances dependence on renewable energy. In livestock farming, waste-to-energy management systems that turn animal excrement into biogas have included AI and IoT technologies. In this context, IoT sensors will monitor waste breakdown processes, while AI systems will enhance conditions for biogas production to assure effective waste energy conversion. The generated biogas may fuel agricultural operations, establishing a closed-loop system that diminishes greenhouse gas emissions and energy expenses. Carbon sequestration is an increasingly vital method for diminishing net greenhouse gas emissions in agriculture, and its advancement is similarly facilitated by artificial intelligence and Internet of Things technology. Satellite imagery and soil data will serve as the foundation for AI to identify places where carbon sequestration may be maximized, either through reforestation or regenerative agricultural practices. These strategies enhance soil health and augment plant biomass, both of which are essential for sequestering more carbon in the soil. IoT-enabled monitoring devices deliver real-time data on soil conditions, allowing farmers to assess the effectiveness of their carbon sequestration strategies. This guarantees the efficacy of sequestration procedures and facilitates real-time insights for forthcoming sustainability projects. The European Union's Common Agricultural Policy incentivizes environmentally sustainable farming by providing subsidies to farmers that use sustainable agricultural practices and include renewable energy systems. It allocates substantial resources to precision agriculture and the adoption of green energy, encouraging farmers throughout the EU to implement renewable-powered systems and efficient resource management technology to minimize their carbon impact. The Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) plan in India incentivizes farmers to adopt solar-powered irrigation systems. The KUSUM initiative subsidizes solar pumps and grid-connected solar energy plants on agricultural areas to minimize operational costs and promote sustainable water consumption. This approach has rendered solar irrigation attainable, particularly in regions experiencing energy deficits and elevated fuel expenses.

Consequently, the integration of AI, IoT, and renewable energy in agriculture has the potential to substantially diminish GHG emissions through the optimization of energy use, enhancement of resource efficiency, and advancement of carbon sequestration initiatives. Artificial intelligence can deliver predictive insights, whereas the Internet of Things facilitates real-time monitoring, empowering farmers to make informed decisions based on actual conditions. This, combined with the availability of renewable energy sources, further diminishes their reliance on fossil fuel emissions and promotes environmental sustainability. As these technologies progress, they will progressively complement global greenhouse gas reduction objectives; hence, agriculture is a crucial sector in combating climate change.[20]

Open-Source Platforms and Scalability in Developing Regions

Renewable energy and digital agriculture technology are creating new opportunities to address food hunger, climate change, and resource shortages. Nonetheless, for these inventions to be beneficial globally, especially in poor areas, they must be affordably priced and scalable. The integration of open-source platforms with scalable renewable energy solutions has generated essential tools that accelerate the global adoption of sustainable agriculture, especially in resource-limited nations. Open-source platforms democratize sophisticated technology and optimal practices, fundamentally transforming the agricultural sector. Access to advanced agricultural technology, including AI, IoT, and renewable energy systems, is typically restricted for many due to the prohibitive prices of proprietary software and hardware. Open-source platforms eliminate this obstacle by offering farmers and agricultural enterprises complimentary or affordable tools to manage resources, enhance production, and mitigate environmental effect.

A significant benefit of open-source platforms is their flexibility and adaptability. Agriculturalists from diverse areas may tailor and modify these platforms to suit their specific requirements, whether pertaining to soil management, crop rotation, water utilization, or the incorporation of renewable energy. An illustration may include open-source software for agricultural management systems that allows users to enter data on local weather conditions, soil composition, and crop variety to receive tailored irrigation and fertilization suggestions, such as IrrigaSys or CropSight. These technologies provide real-time insights into agricultural operations using AI and IoT, facilitating more accurate and sustainable decision-making. Open-source platforms facilitate enhanced collaboration and knowledge dissemination among farmers, academics, and technology developers. Communities of practice may emerge around these platforms, facilitating the exchange of ideas and innovations to enhance the sustainability and productivity of farming methods. Collaboration expedites the development of scalable solutions for various environmental and socio-economic circumstances. The scalability of agricultural technology constitutes a significant barrier in emerging countries. Developed nations exhibit substantial advancements in the adoption of renewable energy and digital technology, but emerging nations encounter considerable initial expenses, inadequate infrastructure, and restricted technical proficiency as primary obstacles. Nonetheless, open-source platforms and scalable renewable energy systems provide a solution to these difficulties.[21]

Significant initial expenditures continue to be a major obstacle to the adoption of renewable energy and digital technology in agriculture. Farmers in developing countries frequently have a lack of finance, rendering investments in AI, IoT, or renewable energy systems too costly. Micro-financing programs and subsidized loans, designed to alleviate substantial upfront expenses, show potential in assisting farmers to surmount this financial obstacle. A further difficulty resides in insufficient infrastructure. Most rural regions are deficient in reliable energy, high-speed internet, and effective transportation infrastructure, all of which are crucial for the successful implementation of smart agriculture technology. Innovations like as solar-powered IoT devices and offline-capable software mitigate this issue by enabling farmers to utilize technology without the necessity of constant internet or grid electricity. The use of smart technology and renewable energy is also limited by the training and technical proficiency of farmers. Despite the available technologies, most farmers possess inadequate digital literacy and specialized skills, hindering their efficient utilization. This has prompted the development of capacity-building initiatives for farmers, particularly in collaboration with local governments, NGOs, and commercial enterprises. The Digital Green initiative in India utilizes video-based training to provide the skills and information necessary for farmers to effectively utilize digital agricultural instruments. Moreover, open-source systems significantly enhance training and flexibility, since farmers may exchange insights and learn collaboratively through online groups and forums.[22]

Scalable solutions are crucial in areas like sub-Saharan Africa, South Asia, and Latin America, where smallholder farmers constitute the foundation of the agricultural industry. Enhancing their livelihood is closely correlated with augmented food security. Renewable energy systems predominantly supply electricity to off-grid agricultural activities, encompassing irrigation, storage, and processing, with a special emphasis on solar and wind energy. This significantly enhances its scalability when combined with open-source tools that allow farmers to monitor and improve their energy consumption. Solar-powered irrigation systems may be adjusted in scale according to the size of the farm, allowing even the most marginal farming areas to utilize solar energy for irrigation, from smallholder farmers to mid-sized agricultural companies. This system may be combined with open-source software solutions for real-time monitoring of water and energy use. This will enable farmers to optimize resources while reducing operational expenses. Consequently, the adoption of renewable energy sources will become more economical and feasible in areas with restricted access to conventional power systems. Furthermore, an open-source platform would facilitate the training and instruction of local farmers in digital technologies and renewable energy systems. It may therefore accommodate lectures, recommendations, and case studies illustrating how other farmers in analogous contexts might adopt scalable and sustainable solutions. This is a vital knowledge transfer to ensure that the advantages of enhanced agricultural technology reach the most disadvantaged communities, particularly those with minimal access to formal education and agricultural extension services. Owing to their efficacy, these open-source systems are notably cost-effective, particularly in underdeveloped areas. In contrast to proprietary technologies, which typically entail substantial licensing costs and necessitate specialized training, open-source platforms are generally available at no cost and may be modified to accommodate local requirements. This renders them especially appealing to smallholder farmers and agricultural cooperatives functioning under constrained budgets.

Commonalities and Discrepancies in Global Adoption

The worldwide use of renewable energy technology, artificial intelligence, and the Internet of Things in agriculture has shown promise, however it faces significant obstacles. Although several regions are rapidly advancing towards the implementation of these technologies for sustainability, less environmental impact, and enhanced production, the speed and extent of such adoptions vary significantly among different countries. Identifying the prevalent facilitators and obstacles to broader adoption will be crucial for achieving global sustainability in agriculture. Key factors influencing the global use of renewable energy, artificial intelligence, and the Internet of Things in agriculture encompass resource efficiency, environmental sustainability, and resistance to climate change.[23]

Farmers believe that the integration of sophisticated technology is essential for addressing these difficulties, regardless of location. As the reliability of agricultural practices diminishes due to climate change and resource scarcity, nations are progressively implementing renewable energy systems in agriculture, such as solar-powered irrigation, and employing artificial intelligence with predictive analytics to optimize resource utilization while mitigating the adverse effects of climate variability. Renewable energy solutions assist agricultural operations in reducing their reliance on fossil fuels. Simultaneously, AI and IoT technologies enhance the precision of resource utilization, including smart water management and energy efficiency. Numerous driving laws and incentives significantly influence governments around. Numerous countries provide farms with subsidies, tax incentives, and loans to encourage investment in renewable energy and AI-driven solutions. The EU's Common Agricultural Policy offers financial assistance to farmers for the adoption of sustainable environmental practices. Likewise, nations such as India and China have implemented initiatives to advance solar-powered irrigation systems and smart agricultural technology as part of broader strategies aimed at enhancing food security and mitigating greenhouse gas emissions. The exchange of knowledge and collaboration among these entities will help promote technological adoption. It also advocated for collaboration among governments, academic institutions, technology firms, and agricultural groups to create open-source platforms, training programs, and pilot projects to facilitate farmers' adoption of renewable energy and digital solutions. The Food and Agriculture Organization (FAO) has enabled the transmission of information across nations to share optimal techniques for utilizing renewable energy and digitizing agriculture. Despite these common factors, significant disparities exist in the rate and scale of adoption across various areas, particularly between industrialized and developing nations. Economic disparities, financial accessibility, and infrastructural deficiencies are hurdles to broader dissemination in certain places.[24]

In several developing regions, the substantial initial investment costs of AI, IoT, and renewable energy technologies remain prohibitive. Although a significant proportion of the agricultural workforce in sub-Saharan Africa and Southeast Asia consists of smallholder farmers, they typically lack the financial capacity to participate in these advances, despite being the primary beneficiaries. Farmers in industrialized nations possess superior access to loans, subsidies, and governmental assistance, facilitating the seamless adoption of these technology. Furthermore, significant infrastructural issues continue to exist in the majority of emerging areas. The deployment of digital agriculture solutions in rural regions is obstructed by the lack of dependable internet, energy, and transportation infrastructure. IoT systems operate through constant data transfer, whereas AI relies on predictive models, necessitating stable internet access. These are frequently contrasted with developed regions, where extensive infrastructure underpins the provision of AI, IoT, and renewable energy technologies.[25] The disparity in technical literacy and competencies may be an additional problem. In regions with limited educational and training resources, farmers may struggle to comprehend or manage modern digital technologies. A significant disparity exists in underdeveloped nations that provide inadequate formal education in digital agriculture. In contrast, most developed areas often provide extensive training programs, seminars, and technical assistance that enable farmers to adapt to and utilize AI, IoT, and renewable energy systems more efficiently.

CONCLUSION

The amalgamation of renewable energy, Artificial Intelligence (AI), and the Internet of Things (IoT) is revolutionizing agriculture into a more sustainable, resource-efficient, and climate-resilient industry. Artificial intelligence and the Internet of Things facilitate real-time surveillance, predictive analytics, and precision agriculture, whilst renewable energy sources like solar and wind diminish reliance on fossil fuels, cut operating expenses, and lower greenhouse gas emissions. Technologies like smart irrigation systems and bioenergy generation from agricultural waste promote environmental sustainability and economic resilience. Notwithstanding these advantages, adoption is inconsistent among areas owing to financial, infrastructural, and technical limitations, especially in poorer nations. Successful projects in nations like India and Kenya illustrate that cost-effective and scalable solutions may surmount these obstacles. Open-source platforms augment accessibility by lowering expenses and facilitating information exchange among farmers. Future research must concentrate on creating economical AI and IoT solutions for smallholder farmers, assessing the impact of open-source platforms on technology distribution, and enhancing predictive models for renewable energy management in agriculture. Research on life-cycle evaluation, economic viability, legislative measures, and farmer education programs is crucial to expedite adoption and optimize the advantages of intelligent and sustainable agricultural systems.

REFERENCES

[1.] Zhang Chen, Wang Hong, Li Yuchen. Applications of Internet of Things in Agriculture. Agricultural Engineering Research. 2019;25(3):45–52. https://doi.org/10.1016/j.agrengres.2019.04.003

[2.] Jones Michael, Wang Lin, Taylor Susan. AI-driven decision support systems in precision agriculture. Computers and Electronics in Agriculture. 2020;170:105256. https://doi.org/10.1016/j.compag.2020.105256

[3.] Li Min, Wang Yang, Zhao Ling. Blockchain for traceable food supply chains: A review. Future Internet. 2020;12(3):65. https://doi.org/10.3390/fi12030065

[4.] Thomas James, Singh Aarti, Kapoor Rohan. AI models for pest and disease detection in crops. Computers in Biology and Medicine. 2021;134:104453. https://doi.org/10.1016/j.compbiomed.2021.104453

[5.] Oliveira Pedro, Santos Joana, Costa Daniel. Smart farming and IoT: A systematic review. Sensors. 2021;21(8):2891. https://doi.org/10.3390/s21082891

[6.] Mangirdas Morkūnas [1,*], Yufei Wang [2] and Jinzhao Wei [3] Role of AI and IoT in Advancing Renewable Energy Use in Agriculture *Energies*2024, *17*(23), 5984;https://doi.org/10.3390/en17235984

[7.] Riccardo Bertoglio, Chiara Corbo, Filippo M. Renga, Matteo Matteucci The Digital Agricultural Revolution: a Bibliometric Analysis Literature Review Related DOI:-

https://doi.org/10.1109/ACCESS.2021.3115258 arXiv:2103.12488 [cs.DL] - (or arXiv:2103.12488v2 [cs.DL] for this version) Journal reference:-IEEE Access 9 (2021) 134762-134782

[8.] Hongyun Zheng, Wanglin Ma & Quan He Climate-smart agricultural practices for enhanced farm productivity, income, resilience, and greenhouse gas mitigation: a comprehensive review Original article Open access Published: 21 March 2024 Volume 29, article number 28 (2024)

[9.] Dalhatu Muhammed a,,Ehsan Ahvar b,Shohreh Ahvar b,Maria Trocan a,Marie-José Montpetit c, Reza Ehsani Artificial Intelligence of Things (AIoT) for smart agriculture: A review of architectures, technologies and solutions June 2024 Journal of Network and Computer Applications 228(7):103905 DOI:10.1016/j.jnca.2024.103905

[10.] Hammad Shahab [a], Muhammad Iqbal [a], Ahmed Sohaib [a], Farid Ullah Khan [b], Mohsin Waqas IoT-based agriculture management techniques for sustainable farming: A comprehensive review Computers and Electronics in Agriculture Date: May 2024 Article: 108851 Volume: Volume 220

[11.] Ajit Singh Rathor [1], Sushabhan Choudhury [1], Abhinav Sharma [1], Pankaj Nautiyal [2], Gautam Shah [1] Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review Heliyon 2024 Jul 23;10(15):e34998. doi: 10.1016/j.heliyon.2024.e34998. eCollection 2024 Aug 15.

[12.] Ahmed Faisal, Mohammed Salim, Zhang Wei. Enhancing farm productivity with remote sensing and machine learning. Remote Sensing. 2020;12(5):825. https://doi.org/10.3390/rs12050825

[13.] Lin Xiang, Zhang Rui, Chen Fang. Real-time soil health assessment using AI algorithms. Computers and Geosciences. 2021;152:104743. https://doi.org/10.1016/j.cageo.2021.104743

[14.] Taylor Benjamin, Huang Mei, Kumar Sunil. Ethical issues in AI adoption in agriculture. AI & Society. 2022;37(1):191–203. https://doi.org/10.1007/s00146-021-01196-4

[15.] Dube Monique, Shrestha Saroj, Narayan Vivek. Water use efficiency through precision irrigation systems. Water Resources Management. 2020;34(10):3053–66. https://doi.org/10.1007/s11269-020-02584-1

[16.] Zhao Xinyi, Wang Jiajun, Liu Yuan. Federated learning and edge computing in agri-tech. Journal of Systems Architecture. 2022;122:102333. https://doi.org/10.1016/j.sysarc.2021.102333

[17.] Enemosah A, Chukwunweike J. Next-Generation SCADA Architectures for Enhanced Field Automation and Real-Time Remote Control in Oil and Gas Fields. Int J Comput Appl Technol Res. 2022;11(12):514–29. doi:10.7753/IJCATR1112.1018

[18.] Ndungu Charles, Otieno Grace, Mwangi Philip. AI-enhanced drought prediction for African agriculture. Climate Services. 2021;23:100251. https://doi.org/10.1016/j.cliser.2021.100251

[19.] Becker Lisa, Johnson Michael, Teixeira Adriano. Use of LIDAR in mapping agricultural land cover. International Journal of Applied Earth Observation and Geoinformation. 2020;90:102112. https://doi.org/10.1016/j.jag.2020.102112

[20.] Singh Aman, Mehta Preeti, Gupta Ishaan. Risk scoring for green agricultural finance. Sustainable Finance. 2021;3(2):88–98. https://doi.org/10.1016/j.susfin.2021.06.002

[21.] Adekoya YF, Oladimeji JA. The impact of capital structure on the profitability of financial institutions listed on the Nigerian Exchange Group. World J Adv Res Rev. 2023;20(3):2248–65. DOI: https://doi.org/10.30574/wjarr.2023.20.3.2520.

[22.] Alabi Tunde, Bello Sodiq, Musa Halima. Digital identity in agriculture subsidy delivery. Technology in Society. 2022;68:101870. https://doi.org/10.1016/j.techsoc.2021.101870

[23.] López Jorge, Hernández Alicia, Moreno Carlos. Autonomous drones for pesticide application. Precision Agriculture. 2021;22(4):908–923. https://doi.org/10.1007/s11119-020-09734-5

[24.] Adeniyi A, Adekoya Y, Namboozo S. Bridging the infrastructure gap: assessing the impact of critical infrastructure investments on economic growth in the United States and emerging markets. Int J Fundam Multidiscip Res. 2024 Sep–Oct;6(5). DOI: https://doi.org/10.36948/ijfmr.2024.v06i05.28772.

[25.] Mwenda Alex, Wambugu Ruth, Kilonzo Patrick. Blockchain for land tenure in sub-Saharan Africa. Land Use Policy. 2020;99:105086. https://doi.org/10.1016/j.landusepol.2020.105086