University of Birjand

Water Harvesting Research Vol. 7, No. 1, Spring & Summer 2024, p. 106-124

doi 10.22077/JWHR.2024.7921.1145

REVIEW ARTICLE

Advancing Sustainable Agriculture: Renewable Energy Integration and Policy Implications for Irrigation in Nigeria – A Systematic Review

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Received: 18 July 2024/ **Revised**: 11 August 2024/ **Accepted**: 15 August 2024

Abstract

This research review explores the application of renewable energy sources, such as solar, wind, and biomass, in irrigation practices throughout Nigeria. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Standard, we identified 295 articles published between 2010 and 2023, with 65 articles reviewed specifically for insights into energy transitions in Nigerian irrigation, the impact of sensor design and technology on irrigation automation, and the influence of government policy on renewable energy adoption in irrigation. Synthesizing findings from diverse studies, we discuss the benefits, limitations, and performance assessments of these renewable energy systems. While recognizing their potential to reduce environmental impact and operational costs while promoting sustainability, the review highlights discrepancies in study outcomes, particularly concerning the effectiveness and scalability of automated irrigation systems. Additionally, we examine the pivotal role of government policies in shaping the development and uptake of renewable energy technologies in agriculture. The review underscores the necessity of standardized evaluations and supportive policies to facilitate the widespread adoption of renewable energy for irrigation in Nigeria.

Keywords: Government policy, Irrigation, Nigeria, Renewable energy, Sustainable agriculture.

1. Introduction

Irrigation plays a crucial role in global agriculture. This is even more important considering that the world population is expected to continue to grow to 14.4 billion by the year 2050 (Cohen, 2001). Irrigation plays an important role in increasing food production, adapting to population and economic growth, improving efficiency, contributing to sustainability and food security, and adapting to various environmental and socioeconomic conditions (Sauer et al., 2010). The importance of improving irrigation performance through improved water management practices to conserve water resources, thereby emphasizing the need for policy and institutional support has also been widely documented (Dhehibi et al., 2016). Though not on the African continent, but a typical contribution of the roles of irrigation was demonstrated by Zhu et al. (2013), who provide insights into how the most populous county in the world, China's reliance on irrigation to achieve food self-sufficiency and highlight its role in increasing crop yields, reducing rural poverty, and stabilizing production. More so, the contribution of irrigation was also highlighted in the context of the reduction of drought risks and significant increase in yields of irrigated crops (Wamalwa et al., 2023). Overall, these results highlight the critical role of irrigation in ensuring global food security, increasing agricultural productivity and mitigating environmental risks.

However, the success of irrigation practices depends on the resources available for use in irrigation (fuel/energy, funds, technology, and government policies). Until recently, given the current decline in global fossil fuel prices (Kreps, 2020; Shafiee and Topal, 2010) and the health and environmental concerns arising from the use of fossil fuels in irrigation practices (Maciejczyk et al., 2021; Wuebbles and Jain, 2001; Yi et al., 2023), research into suitability of renewable energy sources was ongoing, yet, the sustainability of the use of renewable energy in the field of irrigation did not attract outstanding attention.

Several studies on energy use in agriculture have been researched with documented findings in Nigeria. Despite numerous studies in recent decades, there are still some unanswered questions. With this in mind, the study was planned and conducted with the intention of answering the following research questions (RQs).

1. What are the economic and environmental implications of transitioning from conventional fossil fuel-powered irrigation systems to renewable energy sources in Nigeria?
2. What are the technological innovations and advancements as well as the socio-economic implications of adopting automated irrigation systems powered renewable energies in Nigeria?
3. How do government policies and regulations influence the adoption and implementation of renewable energy solutions for irrigation in Nigeria?

2. Materials and Methods

2.1.Search strategy

For this systematic review, we developed a search strategy to identify relevant literature. This strategy was tailored to two databases: Google Scholar. The following search terms were used: Renewable Energy AND Nigeria AND Irrigation/"Irrigation System" spanned between 2010 and 2023.

2.2. Selection Criteria

The selection criteria were based on the documented PRISMA guidelines (Moher et al., 2009). The search span was from 2010-2023. All articles published before 2010 and after 2023 were excluded. The selection process is shown in.

2.3. Data Extraction

In the data extraction phase, 65 articles relevant to answering the Research Questions (RQs) were selected from a total of 295 records identified and the characteristics extracted were:

1. Article must be an original paper. Review papers, reports, and case studies; while textbooks were excluded.
2. The article must be must be complete paper published in English language.
3. The extracted articles were published between 1992 to 2023

3. Implication of the transmission from fossil fuel to renewable energy in irrigation in Nigeria

3.1.Conventional/fossil fuel application in irrigation in Nigeria

Globally, demand for electricity has seen a steady increase, with nations striving to meet the demand. However, Nigeria is abysmally struggling to meet the increasing demand with the meagre per capita electricity consumption of 151 kWh (Owebor et al., 2021), which is lower than the average of per capita electricity in Africa. Presently, the grid-tied electricity installed capacity in Nigeria, estimated at 13,435 MW is primarily generated by fossil and hydro-power plants at approximate distribution of 82.3% and 17.7%, respectively. Over 80% of the current Nigerian primary energy consumption is met by petroleum (Akorede et al., 2016). This overdependence on fossil fuels derived from petroleum for local consumption requirements should be a serious source of concern for the country in two ways-depletion of the resources and negative impact on the environment.

Nigeria is the most populous country and the largest economy in the African continent; but its power sector is currently underdeveloped. Remarkably, its economic and energy security depend on dwindling fossil fuel reserves. Yet, the Nigerian landscape experiences an average daily solar intensity of 20.1 $MJ/m^2/day$; and the wind speed across the states ranges from 1.5 to 4.1 msâˆ'1; with potential for harnessing energy from biomass, geothermal and water. With a projected population of 300 million by 2050, the current 7566.2 MW electricity generation capacity would continue to impede socio-economic development of the nation (Ogbonnaya et al., 2019). Their study recommended that the RETs, particularly distributed hybrid/integrated power systems, should be promoted in Nigeria based on the availability of diverse renewable sources.

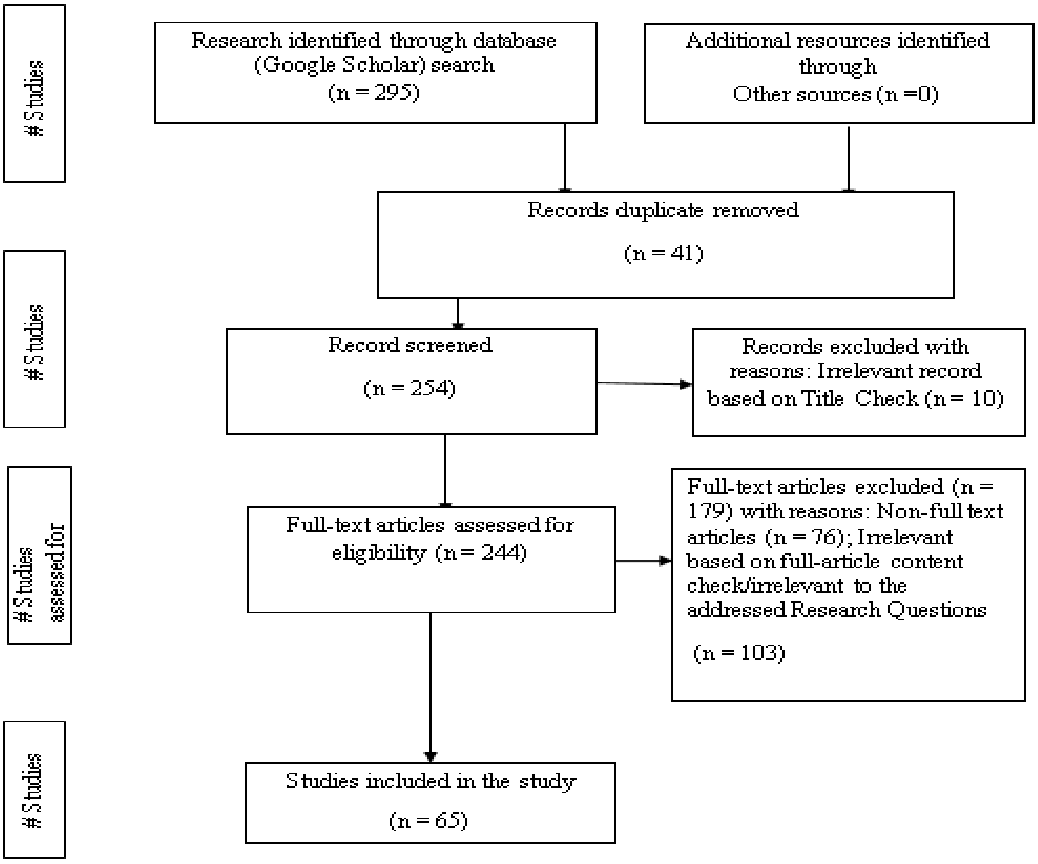

Fig. 1. PRISMA Flowchart for article selection process

Mahmud et al. (2022) investigated the current state of grid electricity supply in Nigeria. Results showed that 75% of the respondents who are connected to the grid do not have electricity supply beyond 12 h. The implication of this is that many of these respondents resort to fossil fuel power supply while seeing solar PV as expensive. The current condition of electrical power supply in Nigeria poses serious risks to the wellbeing of its citizenry, economic progress and overall growth of the nation (Esan et al., 2019). The findings by Esan et al. (2019) revealed - hydro, wind, biomass and solar as the most significant renewable energy sources and that all of those have high potential for power generation in Nigeria.

The application of conventional fossil fuels, such as petrol and diesel, in water pumping for irrigation in Nigeria has been a longstanding practice due to various factors, including accessibility, affordability, and reliability (Aliyu et al., 2018; Cloutier and Rowley, 2011; Ghavidel et al., 2016; Lorenzo et al., 2018). Several studies have highlighted both the benefits and challenges associated with this traditional approach. One of the primary advantages of using petrol and diesel-powered pumps for irrigation is their widespread availability and ease of use, especially in remote rural areas where grid electricity may not be accessible (Aliyu et al., 2018; SABO et al., 2023). These pumps provide farmers with a reliable source of power to extract water from wells, rivers, or boreholes, enabling them to irrigate their fields and sustain agricultural production throughout the year, even during periods of drought (Cloutier and Rowley, 2011). Moreover, petrol and diesel-powered pumps offer flexibility in terms of operation and mobility, allowing farmers to move them easily between different irrigation sites or fields as needed (Aliyu et al., 2018). This flexibility is particularly advantageous for smallholder farmers or those practicing rain-fed agriculture, as it enables them to adapt to changing weather conditions and water availability. A review of the usage of fossil fuel in water pumping for irrigation in Nigeria reveals its longstanding role in supporting agricultural activities, particularly in regions with limited access to reliable electricity grids. Fossil fuel-powered pumps have traditionally served as a dependable source of energy for water extraction, ensuring consistent irrigation water supply vital for crop growth and productivity (Mohammed et al., 2022). This reliability stems from the accessibility of fossil fuels such as diesel and petrol, which are readily available across Nigeria, even in remote rural areas (Salihu et al., 2020).

Onwuegbengbe et al. (2020) examines the fuel consumption rates of a centrifugal water pump in a pressurized drip irrigation system (PDIS), focusing on varied system operating pressures and lateral lengths. Results indicate varying fuel consumption rates across different operating pressures, with the highest rate at 206.84 KPa (1.04 l/hr) and the lowest at 103.42 KPa (0.43 l/hr). Statistical analysis reveals significant differences in fuel consumption based on operating pressures but not lateral length. The study suggests that PDIS with pressure compensating emitters ensures uniform water application, particularly in undulating terrains where gravitational effects may compromise application uniformity. However, limitations may arise concerning the generalizability of findings beyond the specific context of the study site and the need for further research to explore additional factors influencing fuel consumption in PDIS.

While the usage of fossil fuel-powered pumps offers certain advantages, including reliability, accessibility, and flexibility in operation, there are notable concerns and controversies surrounding their continued reliance in the agricultural sector. One of the most significant drawbacks is their high operational costs, including fuel expenses and maintenance requirements (Aliyu et al., 2018; Cloutier and Rowley, 2011). The fluctuating prices of petrol and diesel can significantly impact farmers' operating expenses and profitability, especially in regions with limited financial resources (Cloutier and Rowley, 2011). Furthermore, the reliance on fossil fuels for water pumping contributes to environmental degradation and air pollution, as these pumps emit greenhouse gases and other harmful pollutants during combustion (Aliyu et al., 2018; Ghavidel et al., 2016; Lorenzo et al., 2018). The cumulative impact of these emissions on local air quality, public health, and climate change underscores the urgent need for more sustainable alternatives in agricultural water management. Nigeria, despite being a major exporter of fossil fuels, faces significant energy challenges, including power shortages, unreliable electricity supply, and high dependence on imported fuels (Adewuyi, 2020). This dependency on fossil fuels hampers the country's efforts to achieve energy security, reduce carbon emissions, and promote sustainable development. Another issue revolves around the environmental impact of fossil fuel combustion, contributing to air pollution and greenhouse gas emissions (Hamidinasab et al., 2023). The combustion of fossil fuels releases pollutants such as carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter, exacerbating climate change and posing health risks to both humans and ecosystems (Falchetta et al., 2023).

Moreover, the cost-effectiveness of fossil fuel-powered pumps compared to renewable energy alternatives remains a subject of debate. While fossil fuels may offer lower upfront investment costs, the ongoing expenses associated with purchasing fuel can accumulate over time, potentially outweighing the initial savings (Esanet al., 2019). Additionally, the volatility of fuel prices and dependency on external fuel sources present economic risks and uncertainties for farmers relying on fossil fuel-powered irrigation systems (Ahmed et al., 2023).

Oladipo (2010) discusses the urgent need to boost Nigeria's agriculture sector amidst challenges like increasing population, volatile crude oil prices, dwindling oil revenue, and environmental factors leading to decreasing land resources. While Nigeria has vast cultivable land, only a fraction is currently under cultivation, with most of it in the arid Northern region. Drawing lessons from the American experience, the paper emphasizes the importance of innovative irrigation technology and practices in increasing food production, particularly in dry areas. It highlights the lack of a coordinated national policy and ineffective institutional framework for irrigation development in Nigeria and calls for concerted efforts from the government and private sector to achieve food security.

3.2. Renewable energy application in irrigation in Nigeria

Effort towards the development of renewable energy in Nigeria can be observed in research and development processes of various academic and research institutions. For example the National Centre for Energy Research and Development, University of Nigeria, Nsukka, has developed viable renewable energy technology devices which include solar powered dryers, solar chicken brooders, solar incubators and solar PV system and biogas production system. And has analyzed the applications of these renewable energy devices and challenges to their deployment for sustainable rural agricultural development (Onah et al., 2021). Although these devices are not irrigation-related, but their findings highlighted the lack of knowledge of modern technologies that could lead to boosting rural agriculture as the major hitch to the widespread adoption of the solar-powered equipment. A study by Nwulu and Agboola (2011) investigated the use of renewable energy sources to address electricity generation issues in Nigeria. The study found that Nigeria is rich in renewable energy resources, including over 10,734 MW of hydropower potential. Additionally, the country has millions of hectares of firewood and produces over 60 million tons of biomass annually (Table, 1).

Table 1. Renewable Energy sources in Nigeria

S/No.	Energy Source	Capacity
1	Hydropower (large scale)	10,000 MW
2	Hydropower (small scale)	734 MW
3	Firewood	13,071,464 ha
4	Animal waste	61 million tons /year
5	Solar radiation	3.5- 7.0 kWh/m^2/day
6	Wind energy	2-4 m/s (annual average)

(Source: Nwulu and Agboola, 2011)

Table 2 presents the various energy sources that have been adopted in the field of irrigation in Nigeria. It showed the application of solar energy (Obasanya et al., 2022; Suleiman and Ojomoh, 2023); wind energy (Lorenzo et al., 2018) and biomass energy (SABO et al., 2023). Solar energy has emerged as a promising solution for irrigation in Nigeria, showing considerable success in various studies (Bhandari et al., 2021; Chinonyelum et al., 2023; El Mezouari et al., 2022; Elkadeem et al., 2019; Ghavidel et al., 2016; Habib et al., 2023; Lorenzo et al., 2018; Nwazor et al., 2019; Obasanya et al., 2022; Umar et al., 2021). Some of the documented benefits associated with the application of renewable energy, specifically the solar energy is the water savings. Habib et al. (2023) reported a performance ratio of 74.62% for a solar photovoltaic water pumping system (SPVWPS), which supplied 92.93% of irrigation demand with a significantly lower unit cost of 0.17 €/kWh compared to diesel and grid electricity. Obasanya et al. (2022) demonstrated approximately 49% water savings compared to traditional methods, showcasing the potential for significant resource conservation.

Akorede et al. (2016) presents a critical review of the available renewable energy resources in Nigeria, namely; biomass, hydropower, solar and wind energy. It examines the current energy situation in the country and equally discusses the various energy policy documents developed by the government. Using the scenario-based International Atomic Energy Agency models, the projected energy demand and supply structure of the country through 2030 are presented and analyzed. Overall, this study shows that Nigeria will overcome her present energy crisis if she explores the abundant renewable energy resources in the country.

Billy-konha (2022) highlights the potential of renewable energy, particularly micro grids, to enhance energy reliability and resilience in Nigeria, addressing longstanding issues of power failure. It proposes the implementation of low-cost, low-technology windmills for irrigation at a small scale, which can be scaled up to contribute to the national grid, thus upgrading food production and industrial energy provision. The government's renewable energy programs are identified as pivotal in leveraging these benefits and advancing Nigeria's energy sector. Gbadamosi and Nwulu (2020) explores the optimal power dispatch for a hybrid combined heat and power (CHP), wind, PV, and battery system, aiming to enhance energy provision for farming applications in rural communities. Utilizing probability concepts and a mathematical model to minimize system operation costs, the study validates its approach through five case studies with consistent parameters. Results demonstrate that the hybrid system achieves higher reliability and offers.

Table 2. Benefits and limitation of the various energy sources used in irrigation system in Nigeria

Fuel/Energy Source	Benefits	Limitations	Reference
Solar Energy	Clean and renewable source, reduces carbon emissions, abundant solar resource in Nigeria, low operational and maintenance cost, potential for decentralized energy production, long-term cost savings due to free fuel source	High initial investment cost, dependence on weather conditions (e.g., sunlight availability), intermittency in energy generation (nighttime or cloudy days), land use requirements for solar panel installation, limited energy storage capacity	(Elkadeem et al., 2019; Ghavidel et al., 2016; Habib et al., 2023; Obasanya et al., 2022; Okomba et al., 2023)
Wind Energy	Renewable and abundant energy resource, reduces carbon emissions, potential for decentralized energy production, relatively low operational and maintenance cost, scalable technology, potential for hybrid systems with other renewables	Variability in wind speed and direction, intermittency in energy generation, visual and noise impact (potential opposition from communities), high initial investment cost for installation and grid connection, land use conflicts with other activities	(Lorenzo et al., 2018; Ndunagu et al., 2022; Okine et al., 2020; Suleiman and Ojomoh, 2023)
Biomass Energy	Renewable energy source utilizing locally available feed-stocks, potential for waste utilization and economic development in rural areas, reliable baseload power generation, reduced dependency on fossil fuels, potential for carbon neutrality if managed sustainably	Pollution from burning biomass (e.g., emissions of particulate matter, volatile organic compounds), competition with food production and land use for cultivation, land use conflicts with biodiversity conservation, resource availability and supply chain challenges, potential for deforestation and ecosystem degradation	(Abdelkerim et al., 2013; SABO et al., 2023; Nwazor et al., 2019)
Fossil Fuel	Readily available and established energy source, reliable power generation, high energy density, existing infrastructure and supply chains, flexible and dispatchable power output, potentially lower upfront investment costs	Non-renewable and finite resource, pollution and environmental degradation (e.g., greenhouse gas emissions, air and water pollution), contribution to climate change, geopolitical risks and energy security concerns, fluctuating fuel prices, dependency on imports for some fossil fuels	(Al-Waeli et al., 2017; Aliyu et al., 2018; Chinonyelum et al., 2023; Cloutier and Rowley, 2011; Umar et al., 2021)

Cloutier and Rowey (2011) focused on a techno-economic analysis in order to assess the feasibility of renewable energy sources and technologies to substitute for fossil-fuel powered pumping platforms. Their results indicate that there is sufficient solar resource throughout these regions to facilitate relatively cost effective water pumping solutions, as well as a potentially effective wind resource depending on the exact location of the pumping station. Although systems based on these resources have high capital costs compared to petrol or diesel-based platforms, over a 20-year project life, the analysis indicates that ongoing fuel costs for a fossil-fuel-based system greatly outweigh the increased up-front costs of renewable alternatives. Ishyaka et al. (2023) highlights the importance of alternative energy sources for powering water pumps in irrigation systems, particularly in rural areas lacking grid connectivity. Solar energy emerges as a viable solution due to its accessibility, environmental friendliness, and abundance. However, the high cost of batteries for storing solar energy presents a significant challenge. The study proposes the use of recycled laptop batteries as a cost-effective alternative to deep-cycle batteries, potentially reducing costs by over 60%. Experimental results demonstrate that recycled lithium-ion batteries can effectively power irrigation pumps, offering a satisfactory solution for the irrigation process. This approach not only addresses the energy needs of irrigation systems but also promotes sustainability through the reuse of materials.

Ohunakin (2010) examined the current and future perspectives of energy utilization and renewable energy options in Nigeria are examined and discussed from the standpoint of sustainable development. Their study revealed that the over dependence on oil as a major source of energy has put the country at a risk in view of the fast diminishing oil reserves, inadequate refining capacity to meet domestic consumption and serious cases of energy insecurity such as that of the Niger Delta. The electricity production capacity based largely on fossil fuel sources is at present below 3149 MW in a country with an approximate population of 150 million people. And yet her vast renewable energy resources comprising mainly hydro, solar, biomass and wind is very enormous and remain largely untapped. Projection based on four different growth scenarios shows a geometric increase in total energy demand by the year 2030. Elum and Momodu (2017) examine the utilization of renewable energy sources in Nigeria and the factors prevailing against their development. Their findings identified social and political obstacles as most significant roadblocks towards rapid implementation of a green economy through the deployment of renewable energy for sustainable development. The transformation of agricultural practices to a level that well-articulated programs, mechanized equipment and clean energy input can ensure its sustainability (Chilakpu et al., 2018). The research by Chilakpu et al. (2018) has highlighted the potentials of clean, renewable and environmentally friendly sources of energy in the sustainability of agriculture and food production in Nigeria. Their findings revealed that, Nigeria being one of the growing economies in the world, must embrace clean and sustainable sources of energy in the agricultural sector to pull herself out of impending economic crises that may result from the possible collapse of the non-renewable energy sources as being predicted by research findings conducted in major oil producing nations.

3.3. Solar energy application in irrigation in Nigeria

Numerous studies elucidate the design intricacies and practical implementation of solar-powered irrigation systems, emphasizing their potential to provide a sustainable and eco-friendly alternative to conventional fossil fuel-dependent pumps. Idris et al. (2024) analyzed the solar potential in Nigeria using 21 years of data (2002–2021) from Era5-Land. Their study found that the highest recorded solar radiance was 34,914.732 kWh/m² in 2002 and 2003, while the lowest was 26,967.168 kWh/m² in 2008. Additionally, their findings indicated that the Northern states have higher solar energy potential compared to the Southern states. Although previous research has explored solar energy potentials, data on the utilization of solar energy for irrigation purposes is still lacking. Nonetheless, previous studies (Oyedokun et al., 2017; Samaila et al., 2016) have meticulously evaluated the irrigation application efficiency of the Chanchaga irrigation scheme in Niger state, Nigeria, revealing the feasibility of utilizing solar energy to power irrigation systems. Ozoma et al. (2011) focuses on renewable energy penetration in Nigeria with emphasis on the Southeast zone of the country based on a survey data obtained from the region. It was concluded that renewable energy technologies have not significantly penetrated the energy scene of Nigeria's Southeast zone. Regardless, solar photovoltaic is the only renewable energy application in use scoring a few points in some areas in the region. A policy drive is therefore needed to create the enabling environment for Renewable Energy Technologies to thrive in the region. Oyedokun et al. (2017) precisely constructed and simulated a solar-powered water pumping system for irrigation in Kaduna, Nigeria, forecasting a notable pumping efficiency of 65.8% and affirming the viability of solar-powered irrigation in the locale.

Fdelis et al. (2020) focuses on the design and implementation of a "Solar Powered Automatic Sprinkler Irrigation System" utilizing an AT89C51 microcontroller to automate irrigation processes based on set-time intervals. It aims to enhance water management in irrigation while reducing manual intervention. The system, triggered by the microcontroller, operates a 12v relay to activate a DC water pump for 3 minutes at set times of 7am and 7pm daily. Input is facilitated through a keypad, with an LCD displaying system status. Powered by a 12v, 130watts Monocrystalline solar panel and a 60AH deep cycle solar battery, the system eliminates the need for grid electricity. While demonstrating advancements in irrigation automation and energy conservation, limitations such as scalability and cost-effectiveness in widespread adoption may arise, particularly in regions with inconsistent sunlight or high initial setup costs. Furthermore, investigations by (Adeyanju, 2022; George et al., 2021) delve into the development and execution of solar-powered automated sprinkler systems, integrating IoT technology and Arduino programming for efficient irrigation management. These sophisticated systems leverage solar energy to energize pumps and regulate irrigation processes, offering advantages such as diminished manual intervention, cost-efficiency, and refined water resource management. Yusuf et al. (2022) embarked on simulation studies and experimental designs to scrutinize a solar-powered smart irrigation system, showcasing heightened irrigation efficiency and diminished water and electricity consumption. In parallel, Wudil et al. (2023) scrutinized the efficacy of solar-powered irrigation for rice fields in Nigeria, disclosing average yields and net farm incomes commensurate with traditional irrigation methodologies.

However, amid these accomplishments, challenges and limitations persist. Studies such as those by Bashir and Kyung-Sook (2018) and Fletcher and Lafia (2022) accentuate issues such as scalability, economic viability, and environmental repercussions that necessitate resolution for broader adoption of solar energy in irrigation. Additionally, the intermittent nature of solar energy supply and climatic vagaries pose challenges to reliable operation, demanding effective system design and management strategies (Emmanuel et al., 2020). More so, such challenges persist, as noted by Ogidan et al. (2021), who identified high upfront capital costs as a barrier to adoption, with maximum power thresholds ranging from 31.55 W to 72.68 W for solar PV systems. More so, intermittent solar irradiance poses a limitation, as highlighted by Okine et al. (2020), necessitating efficient energy storage solutions or hybrid systems to ensure continuous operation during periods of low sunlight. Despite these challenges, the comparative success of solar energy in providing cost-effective and sustainable irrigation solutions underscores its potential to address water scarcity and enhance agricultural productivity in Nigeria.

Okakwu et al. (2022) presents the effects of total system head and solar radiation on the techno-economic design of PV-pumping system for groundwater irrigation of crop production in Nigeria. It also calculates the quantity of emissions avoided by the PV. The technical design is based on standard methodology to determine the PV capacity that can operate the pump to satisfy the daily water requirements for the crops, while the economic aspect involves the assessment of the life cycle cost and the cost of water per m^3. The result reveals that the pump power ranges from 0.158 kW to 0.293 kW and the PV power ranges from 1.90 kW to 3.52 kW for a system head of 10 m and solar irradiation of 5.25 $kWh/m^2/day$, respectively, while the unit cost of water ranges from \$ 0.05/m^3 to \$ 0.054/m^3, and the life cycle cost ranges from \$ 7004 to \$ 12331. This provides insights into the effects of varying the system head and the solar radiation, demonstrating that the PV-pumping system underperforms at higher system heads, but performs effectively at higher solar radiation. This is due to the decrease in the discharge rate and an increase in power output, respectively. The study will be useful for planning PV-based water pumping system for agricultural purposes.

3.4. Wind energy application in irrigation in Nigeria

Wind energy is another renewable energy source that has been adopted for irrigation purposes in Nigeria (Al-Waeli et al., 2017; Ndunagu et al., 2022; Okine et al., 2020; Okomba et al., 2023). Nigeria has significant wind energy potential. A typical assessment of wind energy across various Nigerian states is provided by Ojosu and Salawu (1990; as cited in Baba and Garba, 2014), and illustrated in Figure 2. The study indicates that Nigeria's total annual wind power potential is 714.07 MW/year. Of this, approximately 38.77% (276.88 MW/year) is concentrated in three states: Yobe (85.29 MW/year), Plateau (94.55 MW/year), and Sokoto (97.04 MW/year). The remaining 61.23% of the annual wind power potential is distributed across the other states in the country.

While previous studies have demonstrated the wind energy potential of the various parts of the country, the extent of the wind power utilization by state is not readily available. However, previous studies, such as those by

Falchetta et al. (2023) underscore the significance of standalone wind energy systems, particularly in addressing the challenges of inadequate rural electricity supply for irrigation in sub-Saharan Africa.

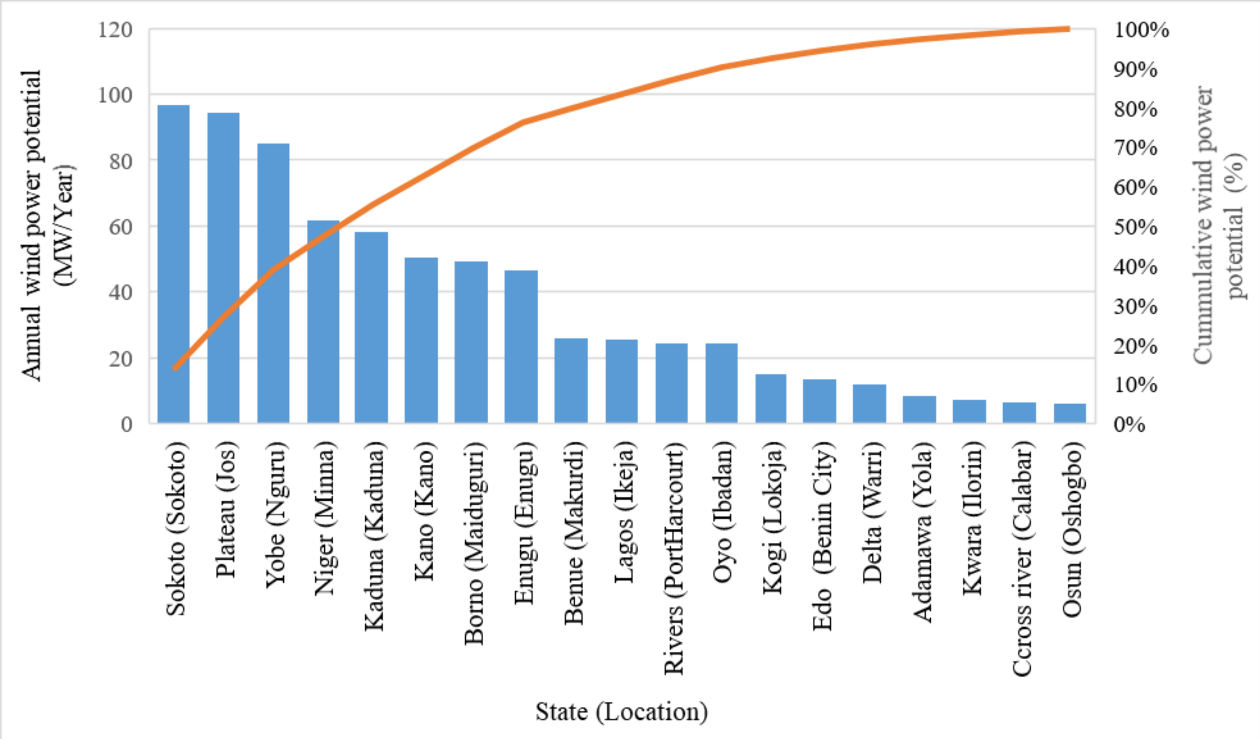

Fig. 2. Pareto plot for the distribution of Wind power potential in Nigeria

Through spatially explicit integrated modeling, their research estimates the potential coverage of unmet crop water requirements by wind-powered irrigation systems, emphasizing the substantial profit potential and increased food security facilitated by such initiatives. However, the study also highlights the importance of sustainable land and water resource management to mitigate potential environmental degradation.

Adetunla et al. (2022) focuses on addressing the energy needs of developing nations through the utilization of renewable energy systems, specifically by designing and fabricating a small-scale horizontal axis wind turbine (HAWT) using locally sourced materials for irrigation purposes. The study utilizes wind data from a weather station and evaluates the turbine's performance by measuring power capacity at different wind speeds. The turbine's power capacity was found to be 40 W, 41 W, and 43 W at wind speeds of 5 m/s, 10 m/s, and 15 m/s, respectively. Regression analysis indicates that the turbine operates optimally at a low speed of 5 m/s with an R^2 value of 0.96. Additionally, the turbine is integrated into a hybrid power system with a 40 W solar tracking system to enhance stability, providing a sustainable energy source for smart irrigation systems. The use of locally sourced materials underscores the cost-effectiveness and accessibility of this renewable energy solution for irrigation in developing regions like Nigeria. However, the study's limitations may include the scalability and long-term durability of the fabricated turbine, as well as the generalizability of the findings beyond the specific experimental conditions.

The literature also delineates the technical aspects and performance evaluations of wind-powered irrigation systems. While empirical studies specifically focusing on wind energy for irrigation in Nigeria are limited, insights can be drawn from broader discussions on renewable energy applications in agriculture. For instance, studies like (Babatunde et al., 2019; Darko et al., 2016) discuss the integration of wind energy technologies into the agricultural sector, emphasizing its potential to electrify regions disconnected from power grids and enhance productivity sustainably. However, these discussions often encompass a wide array of renewable energy sources, including solar and biomass, reflecting the holistic approach to addressing energy needs in agriculture.

Challenges inherent in wind energy utilization for irrigation include variability in wind patterns, intermittency of energy generation, and infrastructural requirements for wind turbine installation and maintenance. Additionally, the upfront capital investment for wind energy systems may pose financial barriers to adoption, particularly for smallholder farmers in rural areas (Mohammed et al., 2022). Studies such as (Ghavidel et al., 2016; Lorenzo et al., 2018) have explored the feasibility of large-scale wind-powered irrigation systems in the ECOWAS region, including Nigeria, showing promising results. Ghavidel et al. (2016) proposed a hybrid system incorporating a Pump as Turbine (PAT), photovoltaic plant (PV), batteries (BAT), and a diesel internal combustion engine (ICE), which demonstrated the potential for maximizing economical operation while reducing diesel consumption. Similarly, Al-Waeli et al. (2017) investigated standalone photovoltaic arrays for water pumping systems in rural and desert areas, emphasizing the cost-effective energy production and lower environmental impact compared to diesel generators.

However, the spread and application of wind energy for irrigation in Nigeria face several limitations and controversies. While wind energy holds promise, its feasibility is highly dependent on local wind resources and geographical factors. Okomba et al. (2023) pointed out that wind resources may not be uniformly distributed across Nigeria, which could limit the widespread adoption of wind-powered irrigation systems. Additionally, the initial investment costs for wind turbines and infrastructure can be significant, potentially hindering widespread deployment, as noted by Ndunagu et al. (2022). Moreover, the intermittent nature of wind energy poses challenges for consistent water pumping, especially during periods of low wind speeds, which may require backup systems or energy storage solutions to ensure reliable irrigation.

3.5. Biomass energy application in irrigation in Nigeria

The third category of the renewable energy that is used for irrigation purpose in Nigeria is the biomass energy. The application of biomass energy in irrigation systems in Nigeria presents both opportunities and challenges. Biomass, derived from organic materials such as agricultural residues, animal waste, and dedicated energy crops, has the potential to provide a sustainable source of energy for irrigation purposes (Nwazor et al., 2019; Umar et al., 2021). Studies such as those by Darko et al. (2015) and Babatunde et al. (2019) underscore the significance of integrating biomass energy technologies into the agricultural sector, highlighting its potential to achieve sustainable development goals. Biomass, derived from organic materials such as crop residues, animal waste, and energy crops, can be converted into various forms of energy, including biogas, biofuels, and bio-char. These energy forms serve as viable options to power irrigation pumps and provide heat for agricultural processes, offering decentralized and renewable energy sources for rural areas.

Technical evaluations and performance assessments of biomass energy in irrigation systems vary, contingent upon factors such as feedstock type, conversion technology, and system design. Jibril et al. (2021) present a case study focusing on the design of a solar-powered intelligent drip irrigation system for a small garden egg research plot. While solar energy predominantly powers this system, there's potential for biomass integration, particularly through biogas generation from agricultural waste, which could enhance system reliability and energy resilience. Despite these challenges, there are areas of agreement among various studies regarding the potential benefits of biomass energy for irrigation in Nigeria. Research by Ghavidel et al. (2016) and Al-Waeli et al. (2017) underscores the economic and environmental advantages of biomass-based systems, including lower operational costs and reduced carbon emissions compared to conventional fossil fuel-powered alternatives. Nevertheless, controversies arise regarding the scalability and sustainability of biomass energy production, particularly in the context of competing demands for land and resources in Nigeria's agricultural sector. Further research and investment are needed to address these challenges and realize the full potential of biomass energy for irrigation in Nigeria.

However, leveraging biomass energy for irrigation also presents challenges. These encompass the availability and sustainability of biomass feed-stocks, the efficiency of conversion technologies, and environmental considerations such as greenhouse gas emissions and land use impacts (Mohammed et al., 2022). Moreover, the decentralized nature of biomass energy production may necessitate community-level infrastructure and capacity building to ensure effective implementation.

3.6. Socio-economic implications of adopting automated irrigation systems in Nigeria

The design and development of sensors, devices, and technologies play a pivotal role in automating the irrigation process in Nigeria, contributing to improved water management, resource efficiency, and agricultural productivity. Table 3 presents the some of the various innovations and technologies that have been deployed into the process of irrigation in Nigeria. Several of the reviewed studies highlight the significance of these innovations in transforming traditional irrigation practices and addressing the challenges faced by farmers (Chinonyelum et al., 2023; El Mezouari et al., 2022; Obasanya et al., 2022).

Advancements in sensor technology have enabled precise monitoring of soil moisture, humidity, temperature, and other relevant parameters, allowing for real-time data collection and analysis. For instance, Chinonyelum et al. (2023) emphasize the importance of integrating weather parameters like humidity, temperature, and moisture sensors into automated sprinkler systems, enabling efficient irrigation based on preset design parameters. Winston et al. (2022) presents an improved automatic irrigation system for arid regions, utilizing wireless technology for communication between a field-soil-moisture monitoring device (transmitter) and receiver modules. The system includes a soil moisture level detector device placed within the field, communicating wirelessly with the receiver device consisting of a microcontroller, LCD screen, RF receiver module, mechanical switching device, monitoring buzzer, and associated circuitry. The experiment conducted using three soil samples (top soil, loamy soil, and sandy soil) shows that as soil water increases, resistance decreases until saturation is reached, indicating optimal moisture level. Sandy soil exhibits the highest conductivity, followed by loamy soil and top soil, indicating varying levels of moisture retention. This innovative system demonstrates potential for efficient irrigation management in arid regions.

Bolu et al. (2019) developed a prototype to increase crop yield while considering adequate agricultural water management and labour reduction, by adequate control measures in the irrigation process. by designing and developing an automatic irrigation system based on the integration of several hardware and software features. The system was designed to determine when exactly the soil of crops need water and deliver a controlled amount of water to the root zone of the crops based on the soil moisture state. With the microcontroller, the data obtained from the soil at the roots of the crops will determined how much water for irrigation is needed at a point in time, and supplies it, thereby incorporating good water management practice. the system was designed to run on renewable solar energy.

Correspondingly, Obasanya et al., (2022) highlight the role of soil moisture sensors in IoT-based irrigation systems, which enable remote monitoring and control of water levels, thereby reducing water wastage and optimizing irrigation practices. Likewise, the development of IoT devices and wireless communication technologies has facilitated connectivity and data exchange among various components of automated irrigation systems. (Umar et al., 2021) discuss the implementation of Arduino-based smart irrigation systems using a wireless sensor network, which enables remote control via the internet and ensures timely operation based on soil moisture levels. Likewise, (Suleiman and Ojomoh, 2023) focus on the design and construction of a solar-powered irrigation system using ZigBee wireless communication technology, enabling real-time data collection and monitoring of soil moisture, humidity, and temperature.

Moreover, the integration of automation technologies, such as microcontrollers and programmable logic controllers (PLCs), has enabled the development of smart irrigation systems capable of autonomous operation and decision-making. El-Mezouari et al. (2022) present an automatic irrigation system utilizing smart sensors and Arduino microcontrollers, which automatically control the pumping motor based on soil moisture levels, thereby optimizing resource usage and reducing manual intervention.

Table 3. Deployed innovations and technology for irrigation in Nigeria

Innovation/Technology	Benefits	Implications and Limitations	References
Arduino-Based Smart Irrigation System	Optimizes water utilization, reduces manual labor, enhances time efficiency in farming, promotes healthy plant growth, facilitates year-round crop cultivation	Potential scalability, reliability, and cost-effectiveness issues under varying environmental conditions and agricultural contexts	(Obasanya et al., 2022; Umar et al., 2021)
Solar-Powered Automated Sprinkler System	Reduces human effort, saves costs, ensures timely irrigation, applicable in remote areas and oil fields	Reliability of IoT technology and sensors, scalability for large-scale implementation, potential for technological failures	(Chinonyelum et al., 2023; Yusuf et al., 2022)
IoT-Enabled Soil Monitoring System	Enables precise irrigation control, optimizes crop yield, conserves water resources, reduces water and electricity consumption	Reliability of IoT connectivity, scalability for large-scale deployment, initial investment cost, data privacy and security concerns	(El Mezouari et al., 2022; Okomba et al., 2023)
SCADA-Based Solar-Powered Irrigation System	Reduces energy costs and pollution, improves monitoring and control, suitable for areas with abundant sunlight	Initial investment cost, technical expertise required for setup and maintenance, potential for equipment malfunctions	(Abdelkerim et al., 2013)
Wireless Sensor Network for Soil Moisture Monitoring	Enhances irrigation efficiency, reduces water wastage, improves crop yield and resource management	Reliability of sensor network, scalability for large agricultural areas, vulnerability to environmental conditions and interference	(Okine et al., 2020; Suleiman and Ojomoh, 2023)
Mobile App-Controlled Irrigation Systems	Allows remote monitoring and control, facilitates real-time adjustments, improves water management and labor efficiency	Dependence on stable mobile network connectivity, potential for app malfunction or cyber threats, user training and adaptation	(Ndunagu et al., 2022; Ogidan et al., 2021)
Low-Cost Automated Irrigation System	Reduces upfront investment, increases access to irrigation technology for small-scale farmers, improves crop productivity	Quality and durability of low-cost components, maintenance requirements, compatibility with varying soil and climate conditions	(Nwazor et al., 2019; Uzoma et al., 2011)
Solar-Powered IoT Water Pumping System	Provides sustainable energy source, reduces carbon footprint, offers remote monitoring and control capabilities	Reliability of solar power generation, scalability for large-scale irrigation needs, technical expertise for installation and maintenance	Salman et al. (2023), Olubosade et al. (2023)
Hybrid Renewable Energy Systems	Combines multiple renewable energy sources for continuous power supply, reduces dependence on fossil fuels, lowers operational costs	Complexity of system integration, initial investment cost, variability in renewable resource availability and efficiency	(Elkadeem et al., 2019; Lorenzo et al., 2018)
Smart Sensors and IoT for Precision Irrigation	Enables real-time monitoring of soil conditions, optimizes water usage, improves crop yield and resource efficiency	Reliability and accuracy of sensor data, scalability for different crop types and farm sizes, compatibility with existing irrigation infrastructure	(Al-Waeli et al., 2017; Bhandari et al., 2021)

Similarly, Yusuf et al. (2022) simulate and construct a solar-powered smart irrigation system using the Blynk Mobile App and IoT, which enables real-time monitoring and control of irrigation parameters, enhancing efficiency and reducing water and electricity consumption.

Variations in findings among studies regarding the performance evaluation of automated irrigation systems exist, showcasing both promising results and limitations. For example, Obasanya et al. (2022) demonstrated approximately 49% water savings compared to traditional methods, indicating the potential for significant improvements in water conservation. Additionally, Okomba et al. (2023) highlighted the successful implementation of a solar-powered pump system integrated with IoT technology for agricultural irrigation control, resulting in decreased temperature and balanced soil moisture levels.

However, the widespread application of biomass energy for irrigation in Nigeria faces several limitations. One key challenge is the availability and accessibility of biomass feed-stocks. While Nigeria has significant agricultural residues and waste materials that could be utilized for biomass energy production, logistical constraints and competing uses for these resources may limit their availability for irrigation purposes. Additionally, the efficiency and reliability of biomass energy systems can vary depending on factors such as feedstock quality, technology used, and maintenance practices, as noted by Habib et al. (2023). Chinonyelum et al. (2023) pointed out challenges related to scalability and reliability in remote areas and oil fields, where human intervention is limited. Additionally, Ogidan et al. (2021) discussed the need for further assessment of economic feasibility and scalability for solar-powered smart irrigation systems, emphasizing the importance of addressing these limitations for practical implementation in rural areas without grid power access.

These inconsistencies highlight the necessity for more comprehensive and standardized assessments to evaluate the effectiveness and suitability of automated irrigation technologies across diverse agricultural contexts in Nigeria. By conducting rigorous evaluations that consider factors such as system scalability, reliability under varying environmental conditions, and long-term cost-effectiveness, researchers can provide valuable insights into the practical implications and potential challenges associated with the adoption of automated irrigation systems in Nigeria. This approach will facilitate informed decision-making and the development of tailored solutions that address the specific needs and constraints of different agricultural settings, ultimately enhancing the sustainability and resilience of irrigation practices in Nigeria.

3.7. Government policy implication on the development and adoption of renewable energy in irrigation in Nigeria

Government policy plays a crucial role in shaping the development, growth, and adoption of renewable energy for irrigation in Nigeria. Table 4 presents the implication of government policies on the development and adoption of the renewable energy sources in the field of irrigation in Nigeria. Various studies highlight the importance of supportive policies in driving the transition towards sustainable energy solutions (Al-Waeli et al., 2017; Edodi et al., 2022; Nwazor et al., 2019; Umar et al., 2021). Studies such as those by Bashir and Kyung-Sook (2018) and Falchetta et al. (2023) highlight the importance of a supportive policy framework in promoting renewable energy adoption for irrigation. Adequate policies can provide incentives, subsidies, and regulatory frameworks that encourage investment in renewable energy technologies, thereby driving innovation and market growth. Bashir and Kyung-Sook (2018) emphasize the need for proper policy frameworks to address challenges such as inconsistent government policies and low awareness among farmers, which hinder the effective utilization of irrigation systems. Okwanya et al. (2020) examined the effects of policy incentives and cost on the choice and use of renewable energy in North-Central Nigeria using sample of 290 respondents drawn from across 6 states in North-Central Nigeria, including the Federal Capital Territory. Their findings reveal that there is a huge potential demand for renewable energy sources (particularly solar photovoltaic) in the rural communities in Nigeria. It also indicates a positive and highly significant relationship between the level of awareness, availability and income and the use (consumption) of renewable energy sources among the rural communities. Furthermore, the cost of installation and maintenance of renewable energy, its reliability and availability are significant determinants of renewable energy choices among rural inhabitants in Nigeria.

Similarly, studies such as those by Bashir and Kyung-Sook (2018) and Falchetta et al. (2023) highlight the importance of a supportive policy framework in promoting renewable energy adoption for irrigation. Adequate policies can provide incentives, subsidies, and regulatory frameworks that encourage investment in renewable energy technologies, thereby driving innovation and market growth. Bashir and Kyung-Sook (2018) emphasize the need for proper policy frameworks to address challenges such as inconsistent government policies and low awareness among farmers, which hinder the effective utilization of irrigation systems.

Lorenzo et al. (2018) emphasize the significance of policy frameworks that incentivize the adoption of renewable energy systems, such as solar and wind, for irrigation purposes. Okine et al. (2020) advocate for green technology policies that promote the utilization of solar energy in irrigation, emphasizing the need for government support to encourage investment and innovation in this sector.

Table 4. Influence of government policy on the application of renewable energy in irrigation in Nigeria

Existing Government Policy	Benefits of the Policy	Limitations	References
Renewable Energy Incentives and Subsidies	Encourages investment in renewable energy infrastructure, reduces reliance on fossil fuels	Lack of adequate funding or implementation delays, inconsistent policies and regulations	(Adewuyi, 2020; Ghavidel et al., 2016)
Renewable Energy Targets and Mandates	Sets clear goals for renewable energy deployment, drives innovation and market growth	Challenges in enforcement and monitoring, unrealistic or unattainable targets	(SABO et al., 2023; Okomba et al., 2023)
Feed-in Tariffs and Power Purchase Agreements (PPAs)	Provides financial incentives for renewable energy producers, promotes project development	Potential for increased electricity prices for consumers, uncertainty in long-term tariff structures	(Obasanya et al., 2022; Okine et al., 2020)
Renewable Energy Financing Programs and Grants	Facilitates access to capital for renewable energy projects, supports small-scale initiatives	Limited availability or accessibility of funding, bureaucratic hurdles and red tape	(Habib et al., 2023; Ndunagu et al., 2022)
Renewable Energy Research and Development Initiatives	Stimulates innovation and technology advancement, improves efficiency and cost-effectiveness	Insufficient funding or prioritization, lack of collaboration between government and research institutions	(Elmorshedy et al., 2022; Lorenzo et al., 2018)
Net Metering and Energy Storage Incentives	Encourages integration of renewable energy into the grid, promotes self-sufficiency and resilience	Technical challenges in-grid integration, lack of standardized regulations and guidelines	(Abdelkerim et al., 2013; Ogidan et al., 2021)
Environmental Regulations and Emission Standards	Promotes cleaner energy sources and reduces environmental impact, protects public health	Compliance costs for industry players, resistance from fossil fuel lobbyists and interest groups	(Al-Waeli et al., 2017; Bhandari et al., 2021)

Furthermore, government policies can influence the affordability and accessibility of renewable energy technologies for farmers and agricultural communities. Nwazor et al. (2019) discuss the importance of low-cost irrigation systems and suggest that government subsidies or incentives could help make renewable energy solutions more affordable and accessible to peasant farmers in Nigeria. Obasanya et al. (2022) emphasize the role of government in providing financial support or grants to farmers interested in adopting IoT-based irrigation systems powered by renewable energy sources such as solar.

Moreover, regulatory frameworks and standards set by the government can impact the quality and reliability of renewable energy systems deployed for irrigation purposes. Ogidan et al. (2021) stress the need for government regulations to ensure the optimal performance of solar-powered irrigation systems, particularly in terms of system design and maintenance standards. Additionally, government policies related to land use and agricultural practices can influence the deployment of renewable energy technologies in irrigation. For instance, Suleiman and Ojomoh (2023) discuss the implementation of a solar-powered irrigation system using ZigBee technology, highlighting the importance of land tenure policies that support the establishment of solar panels for irrigation purposes.

However, despite the potential benefits of government policy support, there are challenges and limitations in the regulatory landscape that may hinder the widespread adoption of renewable energy in irrigation. Studies such as Oriola (2009) and Mohammed et al. (2022) point out the limitations and inconsistencies in government policies that hamper the widespread adoption of renewable energy in irrigation. Oriola (2009) discusses poor and inadequate services from irrigation agencies and limited access to farm inputs and microcredit for farmers, indicating a lack of effective government support for irrigation projects. Similarly, Mohammed et al. (2022) highlight the challenges posed by rising fossil fuel prices and inadequate electric grids in remote areas, which hinder traditional water pumping methods and necessitate the adoption of renewable energy alternatives. SABO et al. (2023) note that the absence of clear policies and regulations governing the integration of solar-powered irrigation systems into existing agricultural practices could impede their adoption. Additionally, inconsistencies in government incentives or subsidies for renewable energy projects may create uncertainties for investors and developers, as highlighted by Ghavidel et al. (2016).

The variation in the role of government policy underscores the complexity of the regulatory environment and the need for coherent and consistent policy frameworks to support renewable energy adoption in irrigation. While some studies illustrate the positive impact of supportive policies in driving innovation and investment, others emphasize the challenges arising from inadequate or inconsistent government support. Addressing these challenges requires concerted efforts to develop and implement robust policy measures that incentivize renewable energy investment, facilitate technology transfer, and promote sustainable agricultural practices. Therefore, Nigeria can reduce greenhouse gas emissions through political will that ensures that policies that will strictly prohibit gas flaring and encourage the PV industry in the country are enforced in order to make clean energy accessible to all.

4. Conclusion

The review of literature on conventional and renewable energy applications in irrigation in Nigeria underscores the multifaceted challenges and opportunities facing the agricultural sector in transitioning towards sustainable energy solutions. While conventional fossil fuel-powered irrigation systems have long served as a reliable source of energy, their dependence poses environmental, economic, and social risks. In contrast, renewable energy sources, such as solar, wind, and biomass, offer promising alternatives with the potential to enhance water management, increase agricultural productivity, and mitigate climate change impacts. However, the adoption of renewable energy technologies for irrigation is hindered by various challenges, including upfront costs, scalability issues, and inadequate government policies. Addressing these challenges requires comprehensive strategies that promote technological innovation, incentivize investment, and foster supportive regulatory frameworks. By embracing renewable energy solutions and implementing effective policies, Nigeria can achieve sustainable agricultural development, improve energy access, and contribute to global efforts towards a greener future.

Further studies should focus on conducting cost-benefit analyses to assess the economic viability of renewable energy adoption in irrigation, while also examining the socio-economic and environmental implications of such integration. Additionally, research should investigate the effectiveness of policy interventions in promoting renewable energy uptake in Nigeria's agricultural sector.

5. Disclosure Statement

No potential conflict of interest was reported by the authors

6. References

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