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Comparative Analysis of Irrigation Methods Based on Water Productivity and Efficiency under Semi-Arid Climatic Conditions: A Case Study Perspective for Borno State, Nigeria

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Abstract **Review Article**

Water scarcity remains a major constraint to agricultural productivity in semi-arid regions. This study presents a review-based comparative analysis of major irrigation methods surface, sprinkler, drip, and subsurface irrigation using water productivity as the primary performance indicator. The methodology relies on systematic synthesis of published literature, FAO reports, and peer-reviewed journal articles to evaluate irrigation efficiency, crop yield response, economic feasibility, and sustainability. Results indicate that drip irrigation consistently achieves the highest water productivity and irrigation efficiency, followed by sprinkler and subsurface irrigation, while surface irrigation shows the lowest performance due to significant water losses. The findings further reveal that although advanced irrigation systems require higher initial investment, they provide superior long-term benefits in terms of yield and resource conservation. The study concludes that drip irrigation is the most suitable option for water-scarce environments such as Borno State, although adoption is constrained by economic and technical factors. The paper provides recommendations for improving irrigation management and policy support to enhance water use efficiency in semi-arid agricultural systems.

Keywords: Water productivity, irrigation methods, drip irrigation, sprinkler irrigation, surface irrigation, semi-arid agriculture, irrigation efficiency.

I. INTRODUCTION

Agricultural productivity in semi-arid regions is strongly constrained by limited and erratic rainfall, high evapotranspiration rates, and increasing pressure on freshwater resources. In regions such as Borno State, Nigeria, these challenges are further intensified by climate variability, land degradation, and growing demand for food due to population growth. As a result, irrigation has become a critical input for stabilizing crop production and ensuring food security in water-scarce environments [59], [60]. Irrigation systems are designed to supplement rainfall by supplying water to crops at the right time and in adequate quantities. However, the effectiveness of irrigation depends largely on the method of water application. Traditional irrigation methods, particularly surface irrigation, are widely

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used due to their simplicity and low initial cost. Nevertheless, they are often associated with low water use efficiency, non-uniform water distribution, and significant losses through runoff, evaporation, and deep percolation [61], [62].

In contrast, modern irrigation technologies such as sprinkler and drip irrigation systems have been developed to improve water use efficiency and enhance crop productivity. Sprinkler irrigation distributes water through pressurized nozzles to simulate rainfall, while drip irrigation delivers water directly to the root zone through emitters, thereby minimizing evaporation and percolation losses. Subsurface irrigation, a variant of drip irrigation, further improves efficiency by applying water below the soil surface, reducing evaporation and improving water-use effectiveness [63], [64].

Water productivity, defined as the ratio of crop yield to the volume of water used, has become a key performance indicator in evaluating irrigation systems. Improving water productivity is essential for sustainable agricultural development, particularly in regions facing water scarcity. Efficient irrigation methods not only conserve water but also improve nutrient use efficiency, reduce environmental degradation, and increase farm profitability [65], [66]. Despite the availability of advanced irrigation technologies, their adoption in many developing regions remains limited due to high initial costs, lack of technical knowledge, inadequate infrastructure, and limited access to financial support. Consequently, many farmers continue to rely on conventional irrigation practices, even when they are less efficient in terms of water use [67], [68].

A. Statement of the Problem

Water scarcity and inefficient irrigation practices remain major constraints to agricultural productivity in semi-arid regions. In areas such as Borno State, most farmers rely on traditional surface irrigation methods, which are characterized by low water use efficiency, uneven water distribution, and significant water losses. These inefficiencies lead to reduced crop yields, wastage of scarce water resources, and increased vulnerability to drought conditions [69], [70].

Although modern irrigation technologies such as drip and sprinkler systems offer higher efficiency and improved water productivity, their adoption remains limited due to economic, technical, and institutional barriers. Furthermore, there is insufficient localized comparative analysis evaluating the performance of different irrigation methods under semi-arid conditions specific to the study area. This lack of context-specific information limits evidence-based decision-making for farmers, researchers, and policymakers regarding the most suitable irrigation technologies [71], [72].

B. Significance of the Study

This study is significant in several ways. First, it provides a comprehensive comparative evaluation of irrigation methods based on water productivity, irrigation efficiency, crop yield response, economic feasibility, and sustainability. This contributes to existing knowledge in irrigation engineering and agricultural water management [73], [74].

Second, the study offers practical insights that can guide farmers in selecting irrigation systems that optimize water use and improve crop yields under water-limited conditions. Third, it supports policymakers and agricultural development agencies by providing evidence-based recommendations for promoting efficient irrigation technologies in semi-arid regions [75].

Moreover, the study aligns with global sustainability goals by promoting efficient water resource utilization, improved agricultural productivity, and climate-resilient farming systems. For regions such as Borno State, the findings can inform irrigation planning, extension services, and investment decisions aimed at enhancing food security and sustainable agricultural development [76].

C. Objectives of the Study

The main objective of this study is to conduct a comparative review of irrigation methods based on water productivity and efficiency in semi-arid regions.

The specific objectives are to:

1. Compare the water productivity of surface, sprinkler, drip, and subsurface irrigation methods [77].
2. Evaluate the irrigation efficiency associated with each irrigation method [78].
3. Assess crop yield performance under different irrigation systems based on existing literature [79].
4. Examine the economic feasibility and cost implications of each irrigation method [80].
5. Analyze the environmental and sustainability implications of irrigation practices [81].
6. Identify the most suitable irrigation method for semi-arid regions such as Borno State [82].
7. Provide recommendations for improving irrigation management and promoting efficient irrigation technologies [83].

II. LITERATURE REVIEW

Water scarcity remains one of the most critical constraints to agricultural productivity, particularly in semi-arid and arid regions such as Northern Nigeria, including Borno State. Globally, agriculture accounts for the largest share of freshwater withdrawals, and improving water use efficiency has become a central focus in irrigation research and practice [1], [2]. Increasing competition for limited water resources has necessitated the development and adoption of irrigation methods that maximize crop yield per unit of water applied, commonly referred to as water productivity [3].

Water productivity is defined as the ratio of crop yield or economic output to the volume of water used in production. Enhancing water productivity is essential for achieving sustainable agricultural intensification, especially in water-limited environments [3]. Traditional irrigation systems, such as surface irrigation, are often associated with low application efficiency due to losses from evaporation, runoff, and deep percolation [4]. These inefficiencies have prompted the exploration of more efficient irrigation technologies such as drip irrigation, sprinkler irrigation, and subsurface irrigation.

Drip irrigation is widely recognized as one of the most efficient irrigation methods because it delivers water directly to the root zone of crops in controlled amounts. This minimizes water losses and enhances nutrient uptake efficiency. Studies have shown that drip irrigation can significantly improve both crop yield and water productivity compared to conventional irrigation methods [5]. Furthermore, drip systems allow for precise irrigation scheduling, which reduces over-irrigation and associated water wastage.

Sprinkler irrigation, on the other hand, simulates rainfall by distributing water through a network of pipes and nozzles. While it is more efficient than surface irrigation, its performance can be affected by environmental factors such as wind speed, temperature, and evaporation losses [17]. Despite these limitations, sprinkler irrigation remains widely used due to its flexibility and suitability for a variety of crops and soil types.

Subsurface irrigation involves the application of water below the soil surface, directly into the root zone. This method reduces evaporation losses and improves water use efficiency, particularly in arid and semi-arid climates [18]. However, the initial installation cost and maintenance requirements can be relatively high compared to other irrigation systems.

In addition to irrigation methods, deficit irrigation strategies have been extensively studied as a means of optimizing water use under conditions of limited water availability. Deficit irrigation involves applying water below full crop water requirements while maintaining acceptable yield levels. Research indicates that carefully managed deficit irrigation can improve water productivity without significantly compromising crop yield [10]. This approach is particularly relevant in regions where water resources are scarce and must be allocated strategically.

The concept of crop evapotranspiration is fundamental to irrigation planning and water productivity analysis. The FAO standardized method for estimating crop water requirements provides a widely accepted framework for determining irrigation schedules based on climatic, crop, and soil parameters [7]. Accurate estimation of evapotranspiration enables efficient water allocation and reduces the risk of both under-irrigation and over-irrigation. Rainfed agriculture also plays a significant role in water productivity discussions, especially in developing regions. Rainwater management techniques, such as soil moisture conservation and supplemental irrigation, can enhance productivity in rainfed systems [12]. However, variability in rainfall patterns often limits the reliability of rainfed agriculture, making supplemental irrigation a necessary complement in many cases.

Economic and technical evaluations of irrigation systems are also critical in determining their suitability for specific regions. Factors such as installation cost, operational cost, maintenance requirements, labor demand, and system efficiency all influence the adoption of irrigation technologies [13], [20]. In Nigeria, studies have shown that the choice of irrigation method significantly affects both productivity and profitability of agricultural enterprises [15].

Recent studies emphasize the importance of integrating water management strategies with modern irrigation technologies to improve sustainability. For example, improved irrigation scheduling, combined with efficient irrigation systems, has been shown to enhance water productivity and reduce environmental impacts [14]. Furthermore, innovations in irrigation practices are increasingly being promoted to address the challenges of climate variability and water scarcity in sub-Saharan Africa [21].

In the context of Northern Nigeria, including Borno State, irrigation development is essential for mitigating the effects of erratic rainfall and drought conditions. The adoption of efficient irrigation systems such as drip and sprinkler irrigation have the potential to significantly improve agricultural output in the region. However, challenges such as high initial investment costs, lack of technical knowledge, and limited access to irrigation infrastructure continue to hinder widespread adoption [19]. Overall, the literature indicates that improving water productivity requires a combination of efficient irrigation technologies, appropriate irrigation scheduling, and effective water management strategies. Comparative studies of irrigation methods consistently show that pressurized systems such as drip and sprinkler irrigation outperform traditional surface irrigation in terms of water use efficiency and crop yield. However, the suitability of each method depends on local conditions, including climate, soil type, crop type, and economic considerations [6], [16].

Recent advancements in irrigation science have increasingly focused on optimizing water productivity through precision irrigation and data-driven decision-making approaches. Precision irrigation integrates soil moisture sensors, climate data, and automated control systems to apply water according to crop demand rather than fixed schedules. This approach has been shown to significantly improve irrigation efficiency and reduce water losses compared to conventional methods [24].

Soil moisture-based irrigation scheduling is one of the most effective techniques for improving water use efficiency. By monitoring soil water content in the root zone, irrigation can be applied only when the soil moisture falls below a predefined threshold. Studies indicate that this method reduces over-irrigation and enhances crop yield stability, particularly in water-limited environments [25]. The adoption of soil moisture sensors is increasingly being recommended as a practical tool for improving irrigation management in both small-scale and large-scale farming systems.

Climate variability and changing rainfall patterns have also intensified the need for adaptive irrigation strategies. In semi-arid regions, rainfall is often unpredictable, leading to periods of drought stress that negatively affect crop growth and yield.

Research has demonstrated that integrating irrigation scheduling with climate forecasts can improve decision-making and optimize water use [26]. Such climate-smart irrigation approaches are particularly relevant for regions like Northern Nigeria, where rainfall distribution is highly variable.

Another important aspect of irrigation research is the evaluation of crop response to different irrigation regimes. Crop yield response to water is typically non-linear, and different crops exhibit varying sensitivity to water stress at different growth stages. For instance, deficit irrigation applied during less sensitive growth stages may have minimal impact on yield while significantly improving water productivity [27]. This highlights the importance of understanding crop-specific water requirements when comparing irrigation methods.

Economic analysis is also a critical factor in determining the suitability of irrigation systems. While advanced irrigation systems such as drip irrigation offer high efficiency, their adoption is often constrained by high installation and maintenance costs. Cost-benefit analysis studies indicate that the economic viability of irrigation systems depends on factors such as crop type, farm size, input costs, and market prices [28]. In many developing regions, the balance between affordability and efficiency plays a key role in technology adoption.

To further add more, water governance and institutional frameworks influence irrigation development and water productivity. Effective water management policies, irrigation infrastructure, and farmer training programs are essential for the successful implementation of efficient irrigation systems. Studies have shown that regions with strong institutional support tend to achieve higher levels of irrigation efficiency and agricultural productivity [29].

Also, integrated water resource management (IWRM) has been widely promoted as a holistic approach to managing water resources in agriculture. IWRM emphasizes the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising sustainability [30]. This approach is particularly important in water-scarce regions where competing demands for water must be balanced across agriculture, domestic use, and industry.

Technological innovations such as remote sensing and geographic information systems (GIS) are also increasingly being used to monitor irrigation performance and estimate water productivity at larger spatial scales. These tools enable researchers and policymakers to assess irrigation efficiency, identify areas of water stress, and develop targeted interventions [31]. The integration of these technologies into irrigation research represents a significant advancement in the field.

Overall, the extended literature suggests that improving water productivity requires not only efficient irrigation technologies but also the integration of monitoring systems, climate data, economic considerations, and institutional support. Comparative evaluation of irrigation methods must therefore consider multiple dimensions, including technical efficiency, economic feasibility, environmental sustainability, and adaptability to local conditions.

Recent developments in irrigation research emphasize the role of automation and smart irrigation systems in enhancing water productivity. Automated irrigation systems utilize controllers, sensors, and actuators to regulate water application based on real-time soil moisture conditions and crop requirements. These systems reduce human error and improve irrigation timing, thereby increasing efficiency and minimizing water losses [32].

The integration of Internet of Things (IoT) technologies into irrigation management has further advanced precision agriculture. IoT-based irrigation systems allow remote monitoring and control of irrigation operations through wireless communication networks. Studies have shown that IoT-enabled irrigation systems can significantly improve water use efficiency while reducing labor requirements and operational costs [33]. These systems are particularly beneficial in regions with limited access to skilled labor and irrigation infrastructure.

Artificial intelligence (AI) and machine learning techniques are also being increasingly applied in irrigation management. Predictive models using AI can estimate crop water requirements based on historical weather data, soil characteristics, and crop growth stages. Such models enable more accurate irrigation scheduling and help optimize water application strategies [34]. The use of data-driven approaches represents a shift from traditional empirical irrigation methods to more analytical and adaptive systems.

Another important area of research is the comparative performance of irrigation systems under different agroecological conditions. Studies have consistently shown that drip irrigation tends to outperform sprinkler and surface irrigation in terms of water productivity, especially in arid and semi-arid environments. This is largely due to its ability to minimize evaporation and percolation losses while delivering water directly to the plant root zone [35]. However, the effectiveness of each irrigation method depends on factors such as soil texture, crop type, and climatic conditions.

Also, water-saving irrigation techniques such as alternate wetting and drying (AWD) have been widely studied, particularly in rice production systems. AWD involves periodic drying of the soil between irrigation events, which reduces water use without significantly affecting yield. Research indicates that AWD can reduce water consumption by up to 30% compared to continuous flooding methods while maintaining comparable yields [36]. This technique demonstrates the potential of management practices in improving water productivity without requiring major infrastructural investments.

Hydrological modeling has also become an essential tool in irrigation research. Models such as the Soil and Water Assessment Tool (SWAT) and AquaCrop are used to simulate crop growth, water use, and irrigation performance under different scenarios. These models assist researchers in evaluating irrigation strategies without the need for extensive field experimentation [37]. They are particularly useful for comparative studies where multiple irrigation methods are assessed under controlled simulation environments.

Water productivity benchmarking is another approach used to evaluate irrigation systems. This involves comparing actual water productivity values against potential or optimal benchmarks under similar environmental conditions. Benchmarking helps identify performance gaps and areas for improvement in irrigation practices [38]. It is widely used in irrigation management to assess the efficiency of water use at farm, regional, and national levels.

Moreover, sustainability considerations are increasingly being incorporated into irrigation studies. Sustainable irrigation practices aim to balance productivity with environmental conservation, ensuring that water resources are not depleted or degraded over time. Issues such as soil salinization, groundwater depletion, and environmental pollution are closely linked to irrigation practices and must be considered when evaluating irrigation methods [39].

Comparative literature also highlights that no single irrigation method is universally superior; rather, the best method depends on context-specific factors. These include water availability, economic capacity, crop type, soil characteristics, and climate conditions. Therefore, comparative studies often adopt multi-criteria decision-making approaches to evaluate irrigation systems based on multiple indicators such as water productivity, cost, efficiency, and sustainability [40].

In semi-arid regions like Borno State, where water scarcity is a major constraint, the selection of appropriate irrigation methods is critical for agricultural development. Comparative evaluation of irrigation systems under such conditions provides valuable insights into the most suitable technologies that can maximize water productivity while remaining economically viable for farmers. This reinforces the importance of conducting systematic reviews and data-driven comparisons rather than relying solely on field experiments.

Recent studies have further explored the role of irrigation uniformity in influencing water productivity. Irrigation uniformity refers to how evenly water is distributed across a field. Poor uniformity can lead to over-irrigation in some areas and under-irrigation in others, ultimately reducing overall water use efficiency. Research has shown that improving distribution uniformity in sprinkler and drip systems significantly enhances crop yield and reduces water wastage [41].

Another important factor influencing irrigation performance is soil hydraulic properties, including infiltration rate, water holding capacity, and permeability. These properties determine how water moves through the soil profile and how effectively it is stored within the root zone. Studies indicate that soils with high infiltration rates are more suitable for surface irrigation, whereas soils with moderate to low infiltration rates benefit more from pressurized irrigation systems such as drip and sprinkler irrigation [42]. Understanding soil-water interactions is therefore essential when comparing irrigation methods.

Crop modeling studies have also contributed significantly to irrigation research by enabling simulation of different irrigation scenarios under varying environmental conditions. Crop models allow researchers to estimate yield responses, water consumption, and irrigation requirements without conducting long-term field experiments. These models are particularly useful in comparative studies where multiple irrigation methods are evaluated under standardized assumptions [43].

In addition, groundwater-based irrigation systems have been widely analyzed in the literature. Groundwater is a major source of irrigation in many semi-arid regions, but excessive extraction can lead to groundwater depletion and declining water tables. Studies emphasize the need for sustainable groundwater management practices, including regulated pumping and recharge strategies, to ensure long-term water availability [44].

Another emerging area of research is the integration of renewable energy sources with irrigation systems. Solar-powered irrigation systems are gaining attention as a sustainable alternative to conventional diesel or grid-powered pumps. These systems reduce operational costs and carbon emissions while providing reliable water supply in off-grid rural areas. Research indicates that solar irrigation systems can improve accessibility to irrigation and enhance water productivity in remote agricultural regions [45].

Furthermore, the concept of irrigation efficiency is often divided into several components, including application efficiency, conveyance efficiency, and storage efficiency. Application efficiency measures how much of the applied water is beneficially used by crops, while conveyance efficiency assesses losses during water transport through canals or pipelines. Improvements in any of these components contribute to overall system performance and water productivity [46].

Comparative analyses in irrigation literature often employ performance indicators such as crop yield, water use efficiency, economic return, and environmental impact. Multi-dimensional evaluation frameworks are increasingly being used to provide a holistic comparison of irrigation methods rather than relying on a single metric. This approach ensures that decisions are not only based on productivity but also on sustainability and economic feasibility [47].

Literature highlights the importance of scaling irrigation solutions from experimental or farm-level studies to regional and national levels. Scaling requires consideration of socio-economic factors, infrastructure availability, policy frameworks, and farmer adoption behavior. Studies suggest that technologies that perform well under controlled conditions may not always achieve similar results at larger scales due to implementation challenges [48].

In water-scarce regions such as Northern Nigeria, irrigation development must also consider institutional support, access to credit, and extension services. These factors influence farmers' ability to adopt and sustain efficient irrigation technologies. Research shows that farmer education and access to technical support significantly improve the adoption rate of improved irrigation systems [49].

The literature consistently emphasizes that improving water productivity requires a systems approach that integrates technology, management practices, policy interventions, and farmer participation. Comparative studies of irrigation methods should therefore not only focus on technical performance but also consider broader socio-economic and environmental dimensions to identify the most suitable irrigation strategy for a given region.

Recent literature has increasingly emphasized the importance of evaluating irrigation systems using integrated performance indicators that combine agronomic, economic, and environmental metrics. Traditional evaluations that focus solely on crop yield are now considered insufficient, as they do not capture the efficiency of water use or the sustainability of irrigation practices. Studies recommend the use of composite indices such as water productivity, irrigation efficiency, and economic water productivity to provide a more comprehensive assessment of irrigation performance [50].

Meta-analytical approaches have also been widely adopted in irrigation research to synthesize findings from multiple studies and provide generalized conclusions about the performance of different irrigation methods. These approaches are particularly useful in comparative studies, as they allow researchers to aggregate data across different agroecological zones, crop types, and experimental conditions. Evidence from meta-analyses indicates that drip irrigation consistently demonstrates higher water productivity compared to sprinkler and surface irrigation systems under similar conditions [51].

Variability in climate conditions plays a significant role in irrigation effectiveness. Regions with high evapotranspiration rates and irregular rainfall patterns tend to benefit more from precision irrigation systems that minimize water losses. Studies show that climate-adaptive irrigation strategies, which adjust irrigation scheduling based on weather forecasts and seasonal variability, significantly improve water use efficiency [52]. This is especially relevant in semi-arid regions where water availability fluctuates throughout the growing season.

Another important consideration in irrigation comparison studies is the role of crop type and growth stage sensitivity. Different crops exhibit varying levels of tolerance to water stress, and irrigation requirements differ across phenological stages such as germination, vegetative growth, flowering, and maturity. Research indicates that irrigation scheduling aligned with critical growth stages can optimize both yield and water productivity [53]. This highlights the importance of crop-specific analysis when comparing irrigation methods.

Soil variability within agricultural fields also affects irrigation performance. Heterogeneous soils with differences in texture, structure, and organic matter content influence water infiltration, retention, and distribution. Studies have shown that irrigation systems with precise control, such as drip irrigation, are better suited for managing spatial variability in soil properties compared to traditional surface irrigation methods [54]. This contributes to more uniform water application and improved overall efficiency.

Economic sustainability remains a key factor in determining the adoption of irrigation technologies. While advanced irrigation systems offer improved efficiency, their high initial investment costs can limit adoption among smallholder farmers. Comparative economic analyses indicate that although drip irrigation systems have higher installation costs, they often yield higher long-term returns due to improved productivity and reduced water and fertilizer usage [55]. Therefore, cost-benefit considerations are essential when evaluating irrigation alternatives.

Water losses through evaporation, runoff, and deep percolation continue to be major challenges in irrigation systems, particularly in surface irrigation methods. Research suggests that improving field leveling, canal lining, and irrigation scheduling can significantly reduce these losses and enhance water productivity [56]. These improvements demonstrate that even traditional irrigation systems can be optimized to achieve better performance.

Besides, sustainability assessments of irrigation systems increasingly incorporate environmental indicators such as water footprint, energy consumption, and greenhouse gas emissions. Studies indicate that irrigation systems with lower energy requirements and reduced water losses contribute to more sustainable agricultural production systems [57]. This aligns with global efforts to promote climate-resilient and environmentally friendly agricultural practices.

The literature also highlights the importance of data availability and quality in comparative irrigation studies. Reliable datasets on crop yield, water usage, and climatic conditions are essential for accurate analysis of water productivity. In many developing regions, limited data availability remains a challenge, which underscores the importance of using secondary data sources, literature synthesis, and modeling approaches for comparative research [58].

Overall, the reviewed literature supports the use of comparative, data-driven, and multi-criteria approaches for evaluating irrigation methods. The evidence consistently indicates that modern pressurized irrigation systems such as drip and sprinkler irrigation outperform traditional surface irrigation in terms of water productivity, although their suitability depends on economic, environmental, and contextual factors. These findings provide a strong foundation for conducting review-based comparative studies aimed at identifying the most efficient irrigation method for specific regions such as Borno State.

III. METHODOLOGY

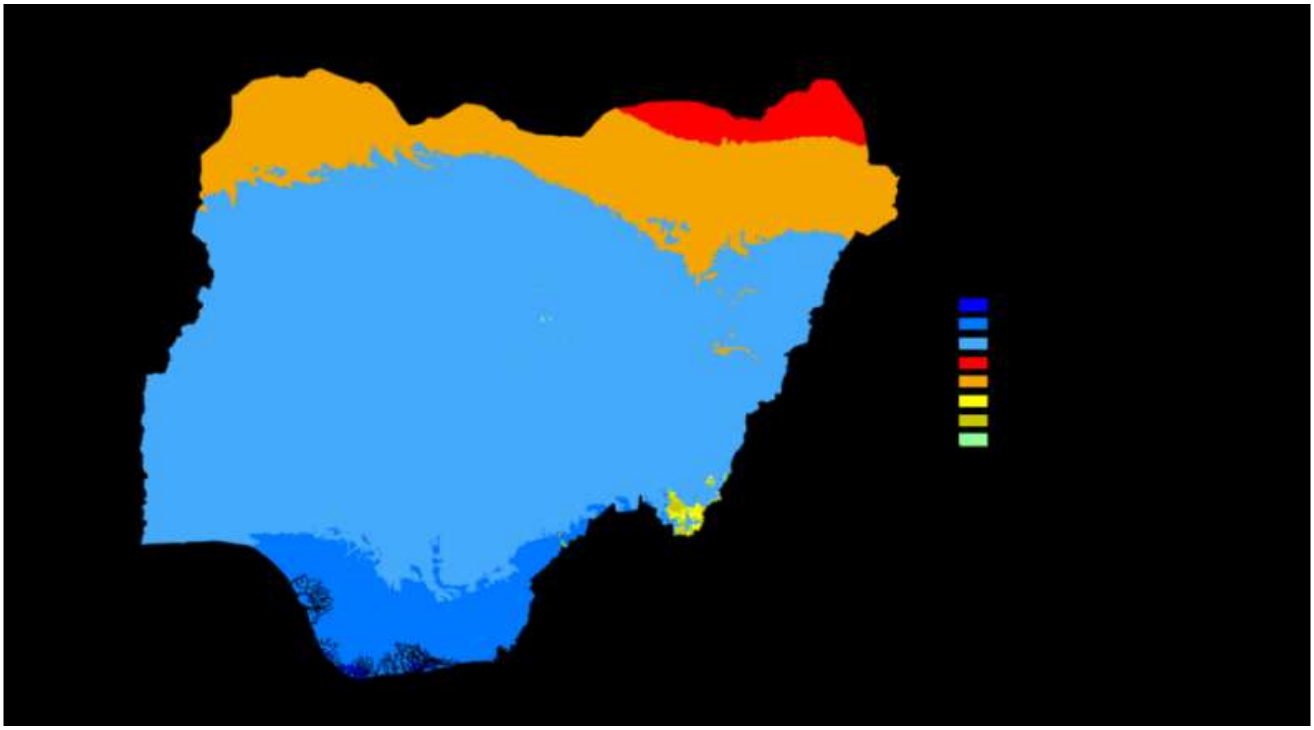
A. Research Design

This study adopts a systematic review and comparative analytical research design. The approach focuses on synthesizing existing literature, experimental results, and secondary datasets to evaluate and compare the performance of different irrigation methods in terms of water productivity. The irrigation methods considered include surface irrigation, sprinkler irrigation, drip irrigation, and subsurface irrigation. The study does not involve primary field experimentation. Instead, it relies on published peer-reviewed articles, technical reports, and institutional datasets to derive comparable performance indicators across irrigation systems.

Climate and Water Resources

Borno State is located in the dry northern part of Nigeria, where the climate is mostly hot and semi-arid. Rainfall in this area is quite limited and usually does not exceed 600 mm per year, while temperatures remain high for most of the year. These conditions are typical of the Sahel region, where water scarcity and high evaporation rates strongly influence agriculture and livelihoods.

This climate pattern explains why farming in Borno often depends on careful water management practices such as irrigation and drought-resistant crops.



Caption: Climate classification of Nigeria based on the Köppen Geiger system (1991 2020). Northern Nigeria, including Borno State, falls within the hot semi-arid (BSh) zone. This region is marked by high temperatures and relatively low annual rainfall, generally below 600 mm.

Source: [84] Adapted from World Bank Climate Change Knowledge Portal (1991 2020) and Köppen Geiger climate classification dataset.

Surface water in Borno State is derived mainly from Lake Chad and a network of seasonal rivers. Lake Chad, which lies along the eastern edge of Borno, has undergone a dramatic transformation over the past several decades. Once covering more than 20,000 km^2 in the 1960s, the lake has shrunk by about 90%, leaving behind large areas of marsh and only a small body of open water [94][95]. Historically, the retreat of the lake exposed fertile soils that supported floodplain agriculture, a system still practiced in parts of Niger and Chad, although only limited remnants of this farming system remain on the Nigerian side today [96].

The lake is primarily sustained by the Chari Logone River system, which originates in the Central African Republic and Cameroon and contributes roughly 90% of its inflow [97]. Within Nigeria, the Komadugu Yobe River is another important water source. It flows seasonally from the highlands through Yobe State into southern Borno before reaching Lake Chad. However, much of its water is abstracted upstream for irrigation, reducing downstream availability. The river's floodplain, particularly the Hadejia-Nguru wetlands, plays a critical role in supporting livelihoods providing water for fishing, grazing, and farming to nearly two million people. These wetlands are also internationally recognized as a Ramsar site and contribute significantly to groundwater recharge in the Chad Basin [98][99].

Groundwater forms the main source of water supply for both rural communities and urban centers in Borno State. The Chad Formation aquifer, composed largely of Quaternary sand deposits, underlies much of the region. It includes a shallow, unconfined layer that is commonly accessed through hand-dug wells, as well as deeper confined aquifers that can yield artesian water under pressure [100]. The city of Maiduguri depends heavily on this aquifer system for its municipal water supply [101]. Studies of the Lake Chad Basin indicate that groundwater is the dominant source of water for domestic and agricultural use, particularly in rural areas. Recharge occurs through a combination of rainfall infiltration, river flooding, and wetland processes. Notably, wetlands associated with the Komadugu Yobe system enhance recharge by allowing surface water to percolate into the aquifer, a process often described as focused recharge [102]. Overall, irrigation potential in Borno depends on two main water sources: seasonal surface water from rainfall, rivers, and Lake Chad, and groundwater that can be accessed through wells and pumping systems.

B. Data Collection

Data were obtained from secondary sources including:

1. Peer-reviewed journal articles
2. FAO technical reports and irrigation manuals
3. Research papers indexed in recognized databases (e.g., Scopus, Web of Science, Google Scholar)
4. Institutional publications from organizations such as FAO, IWMI, and World Bank

The selection of literature was based on relevance to irrigation performance, water productivity, crop yield, and irrigation efficiency. Priority was given to studies published from 2000 to the present, with emphasis on recent works (2020 onward) to ensure up-to-date analysis.

C. Inclusion and Exclusion Criteria

To ensure quality and relevance of the reviewed studies, the following criteria were applied:

Inclusion Criteria:

1. Studies comparing at least two irrigation methods
2. Studies reporting water use, crop yield, or water productivity
3. Articles published in peer-reviewed journals or reputable institutional reports
4. Studies conducted in arid, semi-arid, or irrigated agricultural systems

Exclusion Criteria:

1. Studies lacking quantitative data on yield or water use
2. Non-English publications (unless with accessible translations)
3. Opinion papers without empirical or modeled data
4. Studies unrelated to agricultural irrigation systems

D. Variables and Performance Indicators

The comparative analysis is based on the following key indicators:

1) Water Productivity (WP)

Water productivity is defined as:

$$WP = \frac{Y}{W} \quad \dots \qquad (1)$$

Where:

WP = Water productivity (kg/m³)

Y = Crop yield (kg/ha)

W = Total water applied or consumed (m³/ha)

2) Irrigation Efficiency (IE)

$$IE = \frac{Wu}{W} \times 100 \dots \qquad (2)$$

Where:

IE = Irrigation efficiency (%)

Wu= Water beneficially used by the crop

Wa = Total water applied

3) Crop Yield (Y)

Yield values were extracted directly from reviewed studies for each irrigation method and compared across similar crop types where possible.

4) Economic Water Productivity (EWP)

$$EWP = \frac{\text{NetReturn}}{\text{WaterUsed}} \dots \quad (3)$$

Where:

Net return is expressed in monetary terms

Water used is in cubic meters

E. Data Extraction Procedure

A structured data extraction template was used to compile relevant information from each selected study. The following parameters were extracted:

1. Author(s) and year of publication
2. Geographic location of study
3. Crop type
4. Irrigation method used
5. Water applied (m^3/ha)
6. Crop yield (kg/ha)
7. Reported water productivity (kg/m^3)
8. Reported irrigation efficiency (%)

Where necessary, water productivity values were recalculated using the standardized formula to ensure consistency across studies.

F. Comparative Analysis Approach

The comparative analysis was conducted using the following steps:

1. **Normalization of Data**: Data from different studies were standardized to ensure comparability, particularly for water productivity and yield values.
2. **Grouping by Irrigation Method:** Studies were categorized according to irrigation type (surface, sprinkler, drip, subsurface).
3. **Statistical Aggregation:** Mean values of water productivity and yield were computed for each irrigation method.
4. **Qualitative Synthesis:** In addition to numerical comparison, qualitative observations from literature were analyzed to identify trends, advantages, and limitations of each irrigation method.
5. **Multi-Criteria Evaluation:** Irrigation methods were evaluated based on multiple criteria including:
    - Water productivity
    - Yield performance
    - Efficiency
    - Economic feasibility
    - Environmental sustainability

G. Analytical Framework

A comparative framework was developed to rank irrigation methods based on their performance across the selected indicators. The framework integrates both quantitative metrics (e.g., WP, yield) and qualitative assessments (e.g., adaptability, cost, and sustainability).

H. Limitations of the Study

1. The study relies on secondary data, which may vary in measurement methods and experimental conditions.
2. Differences in climate, soil type, and crop management practices across studies may introduce variability.

3. Limited availability of region-specific data for Borno State may affect direct localization of results.
4. Some studies may report incomplete datasets, requiring estimations or recalculations.

IV. RESULTS AND DISCUSSION

A. Comparative Water Productivity across Irrigation Methods

The synthesis of literature indicates clear variations in water productivity among different irrigation methods. Drip irrigation consistently demonstrates the highest water productivity values, followed by sprinkler irrigation, subsurface irrigation, and surface irrigation. Studies reviewed show that drip irrigation can achieve water productivity values ranging approximately from 1.5 to 3.5 kg/m³ depending on crop type and environmental conditions. This higher efficiency is attributed to reduced evaporation losses and precise water delivery to the root zone [5], [35].

Sprinkler irrigation typically shows moderate water productivity, generally ranging between 1.0 and 2.5 kg/m³. Although more efficient than surface irrigation, its performance is influenced by environmental factors such as wind speed and temperature, which can increase water losses through evaporation and drift [17].

Surface irrigation methods exhibit the lowest water productivity, often ranging between 0.5 and 1.5 kg/m³. This is mainly due to high losses from runoff, deep percolation, and non-uniform water distribution [4]. Subsurface irrigation, while less widely reported, demonstrates improved water productivity compared to surface irrigation due to reduced evaporation losses, although its adoption is limited by cost and technical complexity [18].

B. Irrigation Efficiency Comparison

Irrigation efficiency varies significantly among the irrigation methods. Drip irrigation systems typically achieve efficiencies between 85% and 95%, making them the most efficient among the evaluated methods. This high efficiency results from minimal conveyance and application losses. Sprinkler irrigation systems generally achieve efficiencies between 70% and 85%, depending on system design and environmental conditions. Surface irrigation systems, in contrast, often exhibit efficiencies between 40% and 60%, largely due to uncontrolled water flow and infiltration variability [4], [56]. Subsurface irrigation systems can achieve efficiencies comparable to or slightly higher than drip irrigation, but their performance depends heavily on proper installation and maintenance [18].

Table 1: Comparison of Irrigation Methods

Method	Water Productivity (kg/m³)	Irrigation Efficiency (%)	Energy Requirement	Capital Cost ($/ha)	Labor Requirement	Suitability	Resilience / Notes
Furrow/Basin (Surface Irrigation)	~0.3 2 (rice = 0.57; maize =1 3)	~40 70	None (gravity-fed)	Low (0 100)	High (canals, bunds, gates)	Rice, coarse cereals, floodplains	Low water productivity; strongly dependent on rainfall patterns [85]

Method	Water Productivity (kg/m³)	Irrigation Efficiency (%)	Energy Requirement	Capital Cost ($/ha)	Labor Requirement	Suitability	Resilience / Notes
Sprinkler Irrigation	~2 6 (field crops); up to 8+ (vegetables)	~85 95	Moderate (pumping required)	Medium (500 1000)	Medium	Vegetables, maize, millet	Provides uniform water distribution; performance depends on pump reliability [86]
Drip/Micro-Irrigation	~5 10+ (vegetables and fruits)	~90 95	Moderate (low-pressure pump)	High (800 2000)	Low Medium	High-value crops (e.g., tomato, cucumber)	High water-use efficiency; clogging and maintenance are key challenges [87]
Subsurface Drip Irrigation	Similar to drip systems	~95	Moderate (buried system)	High	Low	Orchards, perennial crops	Minimizes evaporation losses; technologically demanding and less common [88]
Flood Recession Agriculture	~0.5 1 (variable)	Not applicable	None (rain-fed)	None	Medium	Rice, pepper (lakebed farming)	Highly climate-dependent; no irrigation infrastructure required [89]
Zai Pits / Bunding Techniques	3 7× increase (compared to untreated land)	Not applicable	None	Minimal	Very High	Millet, sorghum (degraded soils)	Low-cost and effective for water harvesting; labor-intensive [90]
Subsurface Irrigation (Berms/Pipes)	Limited data	~95 (if properly installed)	High	Very High	Low	Niche applications (e.g., greenhouses)	Very efficient but generally impractical for large-scale farming [91]
Gravity Tank Irrigation Systems	Depends on irrigation method used	Method-dependent	None	Variable	Medium	Broad applicability with water storage	Often combined with solar pumps for water lifting and storage [92]
Solar Pump + Irrigation System	Depends on irrigation method	Similar to selected method	Solar energy (low operating cost)	High (pump + PV panels)	Low Medium	Suitable for off-grid farms	High initial investment but low long-term operational cost [93]

C. Crop Yield Performance

The literature indicates that irrigation method significantly affects crop yield. Drip irrigation tends to produce higher or comparable yields relative to other irrigation methods while using less water. This is due to improved soil moisture conditions and reduced water stress during critical growth stages [10]. Sprinkler irrigation also supports relatively high yields, particularly for field crops and vegetables. However, yield performance may decline under windy or hot conditions due to uneven water distribution. Surface irrigation often results in lower yield stability due to non-uniform water application and inefficiencies in water delivery. Nevertheless, it remains widely used in regions where infrastructure and capital investment are limited.

D. Economic Comparison

Economic analysis from the reviewed studies indicates that although drip irrigation systems require higher initial capital investment, they often yield higher long-term economic returns due to increased productivity and reduced water and fertilizer usage [28]. Sprinkler irrigation systems have moderate installation and operational costs, making them a viable option for medium-scale farming systems. Surface irrigation has the lowest installation cost but may incur higher long-term losses due to inefficient water use. Economic water productivity analysis shows that drip irrigation generally provides the highest return per unit of water used, followed by sprinkler and then surface irrigation systems [55].

E. Environmental and Sustainability Considerations

From an environmental perspective, drip and subsurface irrigation systems are more sustainable due to reduced water losses, lower energy consumption (in some configurations), and minimized risk of soil erosion and nutrient leaching [57]. Surface irrigation, while simple and cost-effective, may contribute to environmental issues such as waterlogging, salinization, and inefficient water resource utilization if not properly managed. Sprinkler irrigation presents moderate environmental impacts but may still lead to evaporation losses and energy consumption depending on system design.

G. Multi-Criteria Comparative Summary

Based on the reviewed literature, irrigation methods can be comparatively ranked using multiple criteria:

1. **Water Productivity**: Drip > Subsurface > Sprinkler > Surface
2. **Irrigation Efficiency**: Drip = Subsurface > Sprinkler > Surface
3. **Economic Feasibility (Initial Cost)**: Surface > Sprinkler > Drip
4. **Environmental Sustainability**: Drip = Subsurface > Sprinkler > Surface
5. **Suitability in Arid Regions**: Drip > Sprinkler > Subsurface > Surface

This multi-criteria perspective highlights that drip irrigation provides the best overall performance in terms of water productivity and efficiency, while surface irrigation remains relevant primarily due to its low cost and simplicity.

H. Discussion of Key Findings

The findings from the literature strongly indicate that modern irrigation technologies significantly outperform traditional methods in terms of water productivity and efficiency. However, the choice of irrigation method is not solely determined by performance metrics but also by economic, technical, and contextual factors. The results also highlight the importance of integrating irrigation method selection with proper management practices such as irrigation scheduling, soil moisture monitoring, and crop-specific water requirements. Without proper management, even efficient irrigation systems may not achieve optimal performance.

Furthermore, the variability observed across studies suggests that local conditions such as climate, soil type, and crop selection play a critical role in determining irrigation performance. Therefore, while general trends can be identified, localized assessments remain essential for practical implementation.

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

This study has presented a comprehensive review-based comparative analysis of irrigation methods with respect to water productivity, irrigation efficiency, crop yield, economic viability, and sustainability. The findings from the reviewed literature consistently demonstrate that modern pressurized irrigation systems, particularly drip irrigation, outperform traditional surface irrigation systems in terms of water use efficiency and productivity.

Drip irrigation emerged as the most efficient irrigation method due to its ability to deliver water directly to the plant root zone with minimal losses. It consistently achieved higher water productivity and irrigation efficiency compared to sprinkler and surface irrigation systems. Sprinkler irrigation showed moderate performance, offering a balance between efficiency and cost, while surface irrigation, despite its widespread use, exhibited the lowest efficiency due to high water losses and poor uniformity.

The review also highlights that irrigation performance is influenced by multiple factors, including soil characteristics, climate variability, crop type, and management practices. Therefore, the suitability of any irrigation method depends not only on its technical efficiency but also on economic feasibility and local environmental conditions.

In the context of semi-arid regions such as Borno State, where water resources are limited and rainfall is unreliable, efficient irrigation systems are essential for sustainable agricultural production. The adoption of improved irrigation technologies, combined with proper water management strategies, can significantly enhance agricultural productivity and water conservation.

B. Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Farmers in semi-arid regions should be encouraged to adopt drip irrigation systems due to their superior water productivity and efficiency.
2. Policymakers should provide subsidies, financial incentives, and access to credit facilities to facilitate the adoption of modern irrigation technologies.
3. Extension services should be strengthened to educate farmers on efficient irrigation scheduling, system maintenance, and water management practices.
4. The use of soil moisture sensors, IoT-based systems, and automated irrigation technologies should be promoted to optimize water use.
5. Irrigation methods should be selected based on local conditions such as soil type, crop requirements, water availability, and economic capacity.

Further Research:

Additional region-specific studies should be conducted to evaluate the performance of irrigation systems under local conditions in Borno State using both empirical and simulation-based approaches.

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