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Comparative analysis of irrigation technologies and their impact on water use efficiency in northeast India

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Abstract

Water scarcity has emerged as a critical challenge for global agriculture, which accounts for nearly 70.00 per cent of total freshwater withdrawals. Increasing pressure from population growth, urbanization, and climate change necessitates the adoption of efficient and sustainable irrigation technologies. This review paper examines the impact of both modern and traditional irrigation systems including smart irrigation systems, drip irrigation, sprinkler irrigation, jalkund irrigation, and bamboo drip irrigation on water use efficiency, crop productivity, environmental sustainability, and economic feasibility. A systematic review of literature published between 2010 and 2025 was conducted using major scientific databases.

The findings indicate that drip irrigation achieves the highest water use efficiency (80 to 95%) by delivering water directly to the root zone, thereby minimizing losses. Smart irrigation systems further enhance efficiency through real-time monitoring and automated decision-making. Sprinkler irrigation is effective in uneven terrains but may experience water losses due to environmental factors. In contrast, traditional systems such as jalkund irrigation and bamboo drip irrigation play a significant role in rainwater harvesting and gravity-based water distribution, particularly in the North Eastern Himalayan region of India, offering low-cost and sustainable alternatives.

Despite their advantages, the adoption of advanced irrigation technologies is constrained by factors such as high initial investment, limited awareness, and unsustainable groundwater extraction. The study concludes that integrating modern technologies with indigenous practices, along with supportive policies and farmer training, is essential for achieving sustainable agricultural water management, especially in ecologically sensitive regions like North East India.

Keywords: Irrigation technologies, water use efficiency, drip irrigation, smart irrigation, sustainable agriculture

Introduction

From global freshwater resource, agriculture consumes approximately 70.00 per cent of that fresh water and that making it as largest consumer of worldwide water.

As the population grows, urbanization and industrialization, water scarcity due to climate changes has impacted in the agricultural sector. Flood irrigation, run off and loss of water through evaporation creates an urgent need for new and more efficient technologies for irrigation.

Several advanced irrigation technology has been developed to minimize the water loss. The new technology focuses on delivering water directly to the plant root zone which reduces run off losses.

Types of technology irrigation

1. **Smart irrigation system:** Also known as digital irrigation or precision irrigation. They rely on fixed schedules and this technology use real time data to determine when, where and how much water is needed, it helps reduce water wastage also improve efficiency. This method is good for the places/regions which face water scarcity or the weather pattern is unpredictable.
2. **Drip irrigation:** This is also known as micro or trickle irrigation, it is considered as highly efficient method of

irrigate ion which allows the water to drip in the root zone of plants, say below or above the surface of side. Drip irrigation method minimizes evaporations and run off and ensures that water and nutrients are used effectively which could increase crop yields and reduce the environmental impact.

3. **Sprinkler irrigation:** It is a kind of method applying water to the crops like an artificial rain and sprinkler/pipes are used in this method so that water is distributed evenly over the soil surface. The sprinkler sprays the water into air through nozzles creating a mist which falls to the ground. This method is suitable and effective in area where traditional surface irrigation is impractical due to uneven terrain or soil conditions.
4. **Jalkund irrigation:** Jalkund water irrigation is a low cost rainwater harvesting method that helps farmers in the North Eastern Himalayan region of India to store rainwater for use during the dry month.

Bamboo drip irrigation: Bamboo pipes are used to divert perennial springs on the hilltops to the lower reaches by gravity. The channel sections, made of bamboo, divert and convey water to the plot site where it is distributed without leakage into branches, again made and laid out with different forms of bamboo pipes. Manipulating the intake

pipe positions also controls the flow of water into the lateral pipes. Reduced channel sections and diversion units are used at the last stage of water application. The last channel section enables the water to be dropped near the roots of the plant. About four to five stages of distribution are involved from the point of the water diversion to the application point. The water for betel leaf plants is diverted from streams by temporary diversions into very intricate bamboo canal systems. Betel leaf is planted in March before the monsoon. It is only during winter that irrigation water is required, and the bamboo pipe system is used. Hence, these bamboo systems are made ready before the onset of the winter, and during the monsoon no water is diverted into them.

Methodology

This review article is based on a comprehensive analysis of published literature on irrigation technologies and their impact on water use efficiency and agricultural sustainability. Relevant research articles, review papers, and reports were collected from major scientific databases, including Google Scholar, Scopus, Web of Science, and Science Direct.

The literature search was conducted using keywords such as “irrigation technologies,” “drip irrigation,” “smart irrigation systems,” “water use efficiency,” “precision agriculture,” and “sustainable irrigation.” Studies published between 2010 and 2025 were primarily considered to ensure the inclusion of recent advancements and findings.

The selected studies were screened based on relevance, methodological rigor, and focus on water-saving technologies in agriculture. Both qualitative and quantitative studies were included to provide a comprehensive understanding of the impacts of irrigation technologies. Data from the selected studies were analyzed and synthesized under key themes such as water use efficiency, crop productivity, environmental impact, and economic feasibility.

Results

The review of existing literature indicates that modern irrigation technologies significantly improve water use efficiency and agricultural productivity compared to traditional irrigation methods.

1. Water Use Efficiency

Studies consistently show that drip irrigation systems achieve the highest water use efficiency, ranging between 80.00 to 95.00 per cent, compared to 30.00 to 50.00 per cent in conventional flood irrigation (Postel *et al.*, 2001; FAO, 2017) ^[19, 10]. Smart irrigation systems further enhance efficiency by optimizing irrigation scheduling based on real-time data (Evans & Sadler, 2008) ^[9].

Jalkund had helped improve water management, cropping intensity and livelihood security in hill ecosystems. It acts as a supplemental irrigation during the rabi season and it also enhances the agricultural productivity.

In Meghalaya, an ingenious system of tapping of stream and spring water by using bamboo pipes to irrigate plantations is widely prevalent. It is so perfected that about 18-20 litres of water entering the bamboo pipe system per minute gets

transported over several hundred metres and finally gets reduced to 20-80 drops per minute at the site of the plant. The tribal farmers of Khasi and Jaintia hills use this harvesting system to drip irrigate their black pepper cultivation (Agarwal, A. and Narain, S., 1997 ^[1], Dying Wisdom: Rise and Fall of India's Traditional Water harvesting System. Centre for Science and Environment. New Delhi. p. 64)

2. Crop Productivity

The adoption of advanced irrigation technologies has been associated with increased crop yields. Drip irrigation improves yield by 20.00 to 50.00 per cent due to precise water and nutrient delivery (Feres & Soriano, 2007) ^[11]. Similarly, precision irrigation techniques contribute to improved plant growth and uniformity (Gebbers & Adamchuk, 2010) ^[12].

3. Reduction in Water Loss

Modern irrigation systems significantly reduce water losses due to evaporation, runoff, and deep percolation. Micro-irrigation systems minimize surface evaporation, while smart irrigation systems prevent over-irrigation (Dukes *et al.*, 2010) ^[8].

4. Environmental Impact

Efficient irrigation technologies contribute to reduced soil erosion, minimized nutrient leaching, and prevention of waterlogging (Tilman *et al.*, 2002) ^[22]. However, excessive groundwater extraction associated with automated irrigation systems has been reported in some regions (Rodell *et al.*, 2018) ^[20].

The ability of Jalkund to store water mitigates the impact of water scarcity and helps climate change. Jalkund helps in sustainable development of hill ecosystems in North Eastern Himalayas, ensuring food security, improved livelihood and environmental sustainability.

5. Economic Impact

Although the initial investment in technologies such as drip and smart irrigation systems is high, long-term benefits include reduced water and labor costs and increased profitability (Narayanamoorthy, 2007) ^[17].

The demand has been increased for micro irrigation and low cost water harvesting system. So low cost water harvesting is found suitable for the farmers of the hilltop for small scale agricultural activities. Jalkund is found acceptable and economical for those who live in hill top. (Bhakta, D., *et al.*, 2019) ^[3]

6. Adoption and Constraints of Irrigation Technologies

Despite the proven benefits of modern irrigation technologies, their adoption remains uneven across regions. Factors such as high initial investment, lack of technical knowledge, limited access to credit, and inadequate extension services hinder widespread adoption (Kumar *et al.*, 2018) ^[15]. Small and marginal farmers, particularly in developing countries, face greater challenges in adopting these technologies.

7. Role of Government Policies and Subsidies

Government interventions play a crucial role in promoting

irrigation technologies. Schemes such as micro-irrigation subsidies and water conservation programs have significantly increased adoption rates in countries like India (PMKSY scheme). According to FAO (2017) ^[10], policy support and financial incentives are essential to encourage farmers to shift from traditional to modern irrigation methods.

8. Climate Change and Irrigation Technologies

Climate variability, including irregular rainfall and increasing temperatures, has increased the importance of efficient irrigation systems. Smart irrigation technologies help farmers adapt to climate change by enabling precise and timely water application (Rodell *et al.*, 2018) ^[20].

Table 1: Comparison of irrigation technologies based on water use efficiency, suitability, advantages, and limitations in Northeastern climate

Irrigation Technology	Water Use Efficiency (%)	Suitability in NE Climate	Advantages	Limitations for Northeastern states
Drip Irrigation	80-95% (Postel <i>et al.</i> , 2001; FAO, 2017) ^[19, 10]	Very High	Precise water delivery to root zone, minimal runoff, ideal for slopes and horticulture crops	High initial cost, maintenance required
Smart Irrigation Systems	70-90% (Evans & Sadler, 2008) ^[14]	High	Real-time monitoring, efficient scheduling, climate adaptive	Expensive, requires technical knowledge
Sprinkler Irrigation	60-75% (Dukes <i>et al.</i> , 2010) ^[8]	Moderate	Suitable for uneven terrain, uniform distribution	Evaporation and wind losses in humid conditions
Jalkund (Rainwater Harvesting)	Depends on storage efficiency	Very High	Stores excess rainfall, supports irrigation in dry periods, low-cost	Limited water capacity, requires maintenance
Bamboo Drip Irrigation	~70-80% (Agarwal & Narain, 1997) ^[1]	Very High	Indigenous, low-cost, eco-friendly, gravity-based	Limited scalability, traditional knowledge dependent
Flood Irrigation	30-50% (FAO, 2017) ^[10]	Low	Simple and low-cost	High runoff, soil erosion, water wastage (not suitable for slopes)
Canal Irrigation	40-60%	Low	Large-scale irrigation possible	Not feasible in hilly terrain, high infrastructure cost
Tube Well Irrigation	50-70%	Moderate (plains only)	Reliable water source	Groundwater depletion risk, limited in hills

Discussion

The findings of this review highlight the significant role of advanced irrigation technologies in enhancing water use efficiency and promoting sustainable agriculture. Drip irrigation emerges as the most efficient method, as supported by studies conducted by Fereres and Soriano (2007) ^[11], who reported substantial improvements in both water savings and crop yield. Similarly, Postel *et al.* (2001) ^[19] emphasized that micro-irrigation systems can drastically reduce agricultural water consumption while maintaining productivity.

Smart irrigation systems represent a major advancement in irrigation management. According to Evans and Sadler (2008) ^[9], the integration of sensors and real-time data enables precise water application, thereby minimizing wastage. However, the effectiveness of these systems largely depends on technological accessibility and farmer awareness, which remains a challenge in developing regions.

While sprinkler irrigation offers advantages in terms of uniform water distribution, studies by Dukes *et al.* (2010) ^[8] indicate that environmental factors such as wind speed and temperature can lead to considerable evaporation losses, reducing overall efficiency.

From an environmental perspective, efficient irrigation technologies contribute to sustainable resource management. Tilman *et al.* (2002) ^[22] highlighted that improved irrigation practices can reduce environmental degradation by minimizing nutrient runoff and soil erosion. However, Rodell *et al.* (2018) ^[20] raised concerns regarding increased groundwater depletion due to the overuse of advanced irrigation systems, particularly in regions lacking proper regulation.

Economically, the adoption of modern irrigation technologies is often constrained by high initial costs.

Narayanamoorthy (2007) ^[17] noted that small and marginal farmers may face difficulties in adopting these technologies without institutional support or subsidies. Despite this, long-term benefits in terms of water savings and increased productivity make these technologies a viable option for sustainable agriculture.

In addition to technological efficiency, the success of irrigation systems depends heavily on socio-economic and institutional factors. Studies by Kumar *et al.* (2018) ^[15] emphasize that farmer awareness, training, and access to extension services significantly influence the adoption of modern irrigation technologies. Without adequate capacity building, even highly efficient systems may fail to deliver expected outcomes.

Furthermore, the integration of irrigation technologies with climate-resilient agricultural practices is becoming increasingly important. As highlighted by FAO (2017) ^[10], sustainable water management requires a combination of efficient irrigation systems, crop diversification, and improved soil management practices.

Another critical aspect is the long-term sustainability of water resources. While technologies such as drip and smart irrigation improve water use efficiency, their unregulated use may lead to increased groundwater extraction, as noted by Rodell *et al.* (2018) ^[15]. Therefore, proper monitoring and policy regulation are essential to ensure sustainable water use.

Conclusion

The present review clearly demonstrates that advancements in irrigation technologies play a pivotal role in enhancing water use efficiency, agricultural productivity, and environmental sustainability in the face of increasing water scarcity and climate variability. Among the various methods, drip irrigation emerges as the most efficient

system, achieving substantial water savings and yield improvements, as supported by studies such as Elias Fereres and María A. Soriano (2007)^[11] and Postel *et al.* (2001)^[19]. Smart irrigation systems further strengthen water management through real-time monitoring and precision application, aligning with modern climate-resilient agricultural practices.

In contrast, while sprinkler irrigation provides flexibility in uneven terrains, its efficiency is often constrained by environmental factors such as evaporation and wind drift (Dukes *et al.*, 2010)^[8]. The review also highlights the continued relevance of low-cost and indigenous technologies such as Jalkund and bamboo drip irrigation systems, particularly in the North Eastern Himalayan region. These systems not only enhance water availability during dry periods but also contribute significantly to livelihood security and sustainable ecosystem management (Ansari *et al.*, 2020; Bhakta *et al.*; 2019 Agarwal & Narain, 1997)^[1, 2, 3].

Despite the proven benefits, the adoption of modern irrigation technologies remains limited due to high initial investment costs, inadequate technical knowledge, and insufficient institutional support, especially among small and marginal farmers (Kumar *et al.*, 2018; Narayanamoorthy, 2007)^[15, 17]. Furthermore, the risk of groundwater over-extraction associated with advanced irrigation systems underscores the need for proper regulation and sustainable water governance (Rodell *et al.*, 2018)^[20].

Therefore, the future of sustainable irrigation lies in an integrated approach that combines advanced technologies with traditional knowledge systems, supported by strong policy frameworks, financial incentives, and farmer capacity building. As emphasized by the Food and Agriculture Organization (2017)^[10], achieving long-term water sustainability requires not only technological innovation but also effective management practices and institutional support.

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