SUSTAINABLE GROUNDWATER MANAGEMENT THROUGH MICRO IRRIGATION: A CRITICAL REVIEW ON CHALLENGES AND SOLUTIONS

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ABSTRACT

Groundwater plays a vital role in global water resources, supporting agricultural, industrial, and domestic water supply systems. However, the long-term sustainability of groundwater is increasingly threatened due to the widespread adoption of irrigation systems especially micro irrigation. Micro irrigation is a widespread agricultural technique that involves water application to crops through drip irrigation and sprinkler systems. This method has gained widespread adoption due to its ability to deliver water efficiently to crops. This review paper examines the impacts of micro irrigation on groundwater sustainability, focusing on its effects on groundwater quantity, quality, and overall sustainability. The findings reveal that micro irrigation can significantly contribute to groundwater conservation by reducing water losses. However, improper management practices, such as over-irrigation or incorrect application rates, can lead to excessive groundwater extraction, depletion of aquifers, and declining water tables. Applying fertilizers and pesticides in micro irrigation systems may lead to groundwater pollution, thereby affecting water quality and posing a risk to human health. This review article emphasizes the significance of appropriate design, installation, and upkeep of micro irrigation systems to minimize potential adverse effects on groundwater. Furthermore, regulatory frameworks, policies, and educational programs are crucial in promoting sustainable groundwater management practices in micro irrigation. The present review highlights the significance of adopting balanced water use practices, enhancing water management techniques, and implementing relevant regulations to ensure the sustainable utilization of groundwater resources in micro irrigation systems.

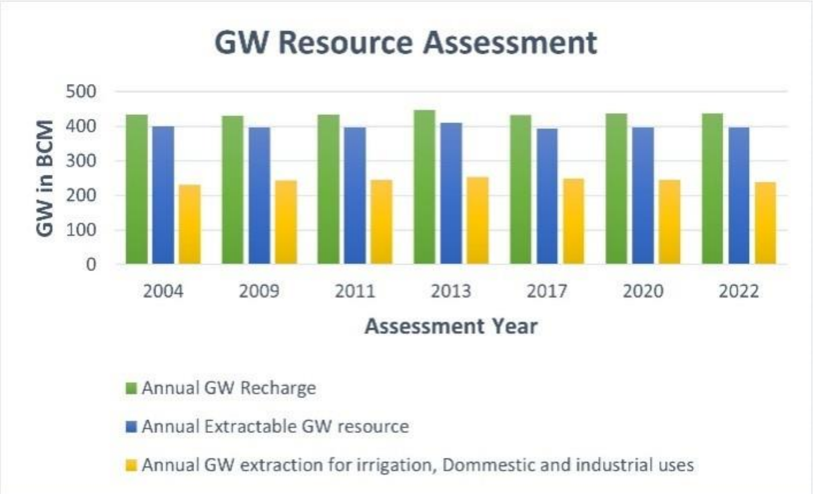
Keywords: Best management practices, groundwater sustainability, irrigation systems, micro irrigation.

INTRODUCTION

Water scarcity has become a pressing concern recently, especially considering its crucial role in the agricultural sector. The availability of water resources has been declining due to various factors such as climate change, population growth, and urbanization. This has significantly impacted the agricultural sector, which is heavily dependent on water for irrigation and other purposes (Priyan & Panchal, 2017).Water scarcity has reduced crop yields, increased production costs, and decreased farmer profitability. The provision of water is subject to a range of hydro-meteorological variables therefore, ensuring a secure water supply for irrigation is of utmost importance. The circumstance, as mentioned earlier, poses a significant obstacle. The pressing concern in agriculture is the need to enhance yield to sustain the nation's increasing population. This demographic shift poses a significant challenge as land holdings continue to shrink, making it increasingly difficult to meet the food demands of the overall population. The role of irrigation is of utmost importance and critical to accomplishing the intended purpose.

In India, irrigation and livestock sectors are responsible for a significant proportion of water withdrawal, accounting for 91 % of the total water usage. This value is considerably higher than the global average. The dependence on natural water resources is expected to have a significant impact on Indian agriculture, given that India is projected to be one of the countries facing water scarcity by 2025. The depletion of groundwater resources is due to extraction rates that are unsustainable and surpass natural recharge rates Average usable water resources are expected to decline from their current level of 1453 m^3 per capita to 1170 m^3 by 2050, down from 195247 m^3 in 1951. That is a drastic drop from where we are now (Ministry of Jalshakti, 2021).As per the report of dynamics of groundwater 2022, The total amount of yearly ground water recharge was calculated to be 437.60 billion cubic meters. The yearly extractable ground water resource comes out to be 398.08 billion cubic meters when considering an allocation for natural discharge. As of the year 2022, the total annual ground water extraction was calculated to reach 239.16 billion cubic meters. It has been calculated that around 60.08 percent of the nation's ground water resources have been extracted on average. This issue has been a growing concern for researchers and policymakers alike, as it has the potential to severely affect the agricultural sector, which is a critical component of the Indian economy.

Fig. 1: Groundwater Resource Assessment

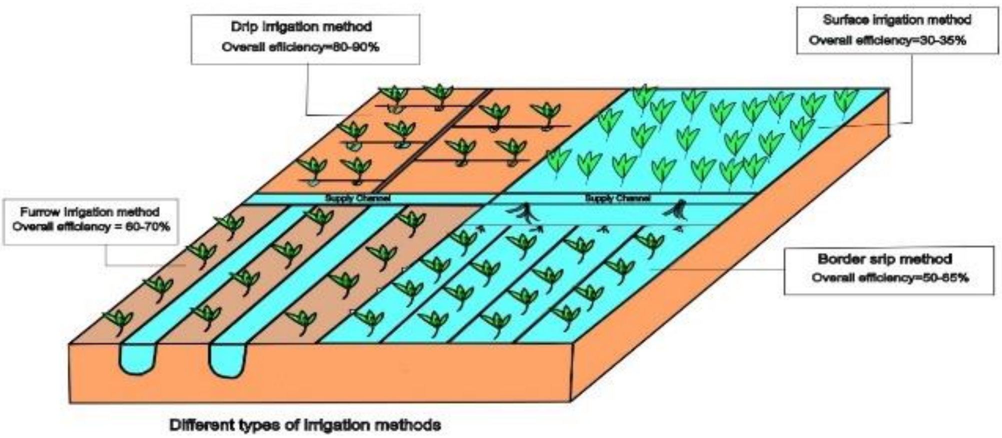


Source: as a Glance (2022)

Irrigation is the process that delivers water to the plants. India's economy depends mainly on farming, so it relies heavily on irrigation systems to keep farming across its colossal land area. Different parts of the country have different agroclimatic conditions and water availability, so they need different irrigation methods. India's main irrigation system are canals, tanks, and groundwater. Depending upon these systems, different types of methods are adopted to supply water in the agriculture field. Surface irrigation is a common way for farmers in India to spread water across their areas.

Flood irrigation is a popular way in which water is dumped on the field and left to run and spread over the area. For basin irrigation need to make small, level pools in the field and put water in them. This method works well for growing foods like rice. Furrow irrigation uses small pathways called "furrows" to move water along the rows of crops so it can soak into the soil. Border irrigation is when the field is divided into long, thin strips or borders, and water flows down the borders and into the soil. With contour irrigation, water is spread along the natural lines of the land using canals. This cuts down on flow and damage. Farmers in India can use these different surface irrigation methods to get water to their crops in the best way possible, considering the soil type and crop needs. In recent years, most farmers have adopted micro irrigation systems like drip and sprinkler irrigation. These systems deliver water directly to plants' root zones, reducing water loss from evaporation and making better water use.

Fig. 2: Types of Irrigation systems



Source: Created using Inkscape software

The utilization of irrigation is a vital component in food production on a global scale. However, it presents a considerable obstacle to groundwater resources, which frequently serve as the primary source of irrigation water. Investigating the correlation between irrigation systems and groundwater sustainability is a crucial aspect of proficient water resource management and implementing sustainable agricultural practices.

This review paper aims to assess the role of micro irrigation systems in promoting sustainable groundwater management. By analysing the benefits and challenges associated with micro irrigation techniques, such as drip irrigation and sprinkler systems, this objective seeks to evaluate their effectiveness in minimising water wastage, improving water-use efficiency, and reducing the potential negative impacts on groundwater resources. Additionally, this research paper also aims to identify best practices and recommendations for successfully implementing micro irrigation systems to ensure long-term groundwater sustainability.

There are many problems with managing and keeping groundwater supplies in good shape, threatening its availability and quality.

Groundwater Sustainability

Groundwater sustainability is "maintaining long-term, dynamically stable storage of high-quality groundwater through inclusive, reasonable, and long-term governance and management"(Elshall *et al.*, 2020). Groundwater sustainability is essential where agricultural, household, and industrial groundwater usage is significant.

Groundwater resources are threatened by overexploitation and mismanagement. Groundwater extraction and recharge rates must be balanced to fulfil present and future water needs. Groundwater sustainability is a critical concern in the context of the long-term impact of irrigation systems on groundwater resources. As irrigation systems play a vital role in supporting agricultural productivity, it becomes essential to ensure that these systems are designed and managed to safeguard the long-term sustainability of groundwater. The sustainability of groundwater with irrigation systems is an essential yet often overlooked aspect in discussions surrounding irrigation practices. While the focus primarily centres on crop yield optimization and water conservation, the long-term viability of groundwater reserves demands equal attention. Groundwater serves as a crucial resource for irrigation, enabling food production in regions with limited surface water. However, excessive groundwater extraction and inefficient irrigation techniques can lead to the depletion of aquifers, compromising their ability to replenish naturally.

Role of Irrigation systems in groundwater dynamics

Irrigation systems significantly impact groundwater dynamics due to their impact on various hydrological cycle processes and interactions. The role of irrigation systems in groundwater dynamics is crucial for understanding water balance, infiltration, and irrigation return flow, which have significant implications for sustainable water resource management. The impact of irrigation systems on groundwater dynamics is a critical area of study as it affects multiple aspects of the hydrological cycle. The use of irrigation systems significantly influences the various components of the hydrological cycle. The impact of irrigation systems on groundwater resources is determined mainly by water balance parameters like infiltration, runoff and irrigation return flow. These factors play a crucial role in determining the overall impact of irrigation systems on groundwater resources. The water balance is a fundamental concept in hydrology that describes the equilibrium between inputs, such as precipitation and irrigation, and outputs, such as evaporation, transpiration, and runoff, within a specified area. (Leng *et al*., 2015; Evans & Zaitchik, 2008) Irrigation systems contribute to the water balance by increasing the water available for other hydrological processes. In the water balance equation, infiltration plays a very crucial role in groundwater sustainability. Irrigation, soil, and land management affect infiltration. Proper irrigation scheduling, water application rates, and effective technologies may optimise infiltration rates and deep percolation losses. If handled properly, irrigation return flow may boost groundwater recharge and restore depleted aquifers. Inefficient irrigation or drainage may cause excessive irrigation return flow, waterlogging, salinity, and groundwater resource pollution. So, effective management of irrigation systems is essential to make the best use of water, keep an optimal water flow and ensure that groundwater availability will last for a long time.

Micro irrigation

Micro irrigation is a coordinated and controlled water management system in which water is forced to flow under pressure through a network of pipes with different diameters called the main line, the sub-main lines, and the lateral lines. Along the length of the lateral lines, some emitters allow water to flow to the root zone. Different types of micro irrigation systems include drip irrigation, sprinkler irrigation and bubbler irrigation system. Drip irrigation is the most used micro irrigation technology. It is accomplished by applying water in a measured and controlled manner straight to the plant's root zone using emitters or drippers. The water trickles gently over the soil surface or enters the soil directly, reducing the amount of water lost to evaporation and runoff. Micro-sprinkler irrigation employs miniature sprinklers or sprayers to provide water to a plant's soil in a very thin mist. These sprinklers are positioned low to the ground, and the water they provide is dispersed in a manner that is both soft and even throughout a minimal area. They are suited for watering regions with uneven forms or little plants because of their versatility. Irrigation with a bubbler is often used for larger plants or trees that demand a more significant amount of water, such as shrubs or trees. Putting a device at the base of the plant that may be either a bubbler or a basin emitter is required for this method. The water is dispensed from the bubbler at a more measured pace, which enables it to go greater distances into the soil and ultimately reach the plant's root system. Subsurface Drip Irrigation is a specialised kind of drip irrigation in which the drip lines are hidden under the earth's surface. SDI is also known as subsurface drip irrigation. Emitters have been strategically positioned along the underground drip lines at regular intervals to control the water flow. SDI minimises the development of weeds and prevents the system from being damaged, hence reducing the amount of water lost due to evaporation. These micro irrigation systems control water flow, uniform distribution, and root zone supply. Micro irrigation systems optimise water consumption, alleviate water stress, and boost agricultural output by directly watering plant roots.

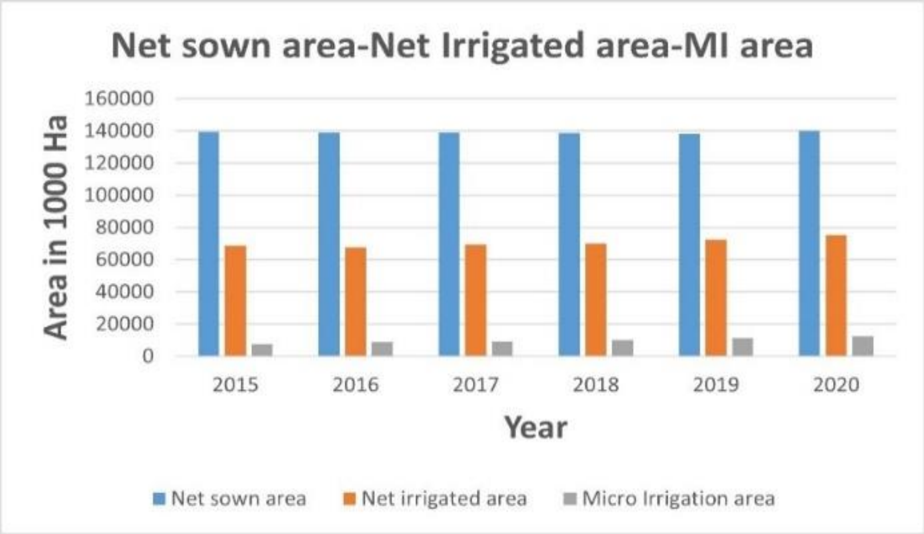
Merits and Demerits of micro irrigation systems

Micro irrigation offers several merits contributing to its increasing popularity and adoption in agricultural practices. This innovative irrigation technique delivers water directly to the root zone of plants, minimizing losses due to evaporation and deep percolation, thus ensuring efficient water usage. By providing precise and controlled amounts of water, micro irrigation helps conserve water resources and reduce overall water consumption compared to traditional irrigation methods. This technology also enables precise nutrient application, preventing leaching and reducing fertilizer requirements, leading to enhanced efficiency of nutrient use. Moreover, micro irrigation systems can be easily automated and equipped with sensors to monitor soil moisture levels and adjust water delivery accordingly, improving irrigation scheduling and optimizing crop yield.

Furthermore, micro irrigation has positively impacted crop health, reducing disease incidence by minimizing leaf wetness and foliar diseases. However, micro irrigation does have certain demerits to consider. Micro irrigation systems' initial setup costs can be higher than traditional methods, and ongoing maintenance is necessary to ensure proper functioning and prevent clogging. Additionally, technical expertise and site suitability must be carefully evaluated for effective implementation. Despite these challenges, the benefits of micro irrigation in terms of water conservation, nutrient efficiency, crop productivity, and disease control make it a promising and sustainable irrigation approach for modern agriculture.

According to reports of the Department of Agriculture & Farmers Welfare, the penetration for the net sown area was approximately 9 % in 2020, which was 5.5 % in 2015. So here we can observe good growth in the micro irrigation penetration, but which is significantly less compared to the countries like Israel, the USA and China. In Fig 3, we can see the penetration of micro irrigation concerning net sown area and net irrigated area.

Fig. 3: Net sown area-Net irrigated area-Micro irrigated (MI) area



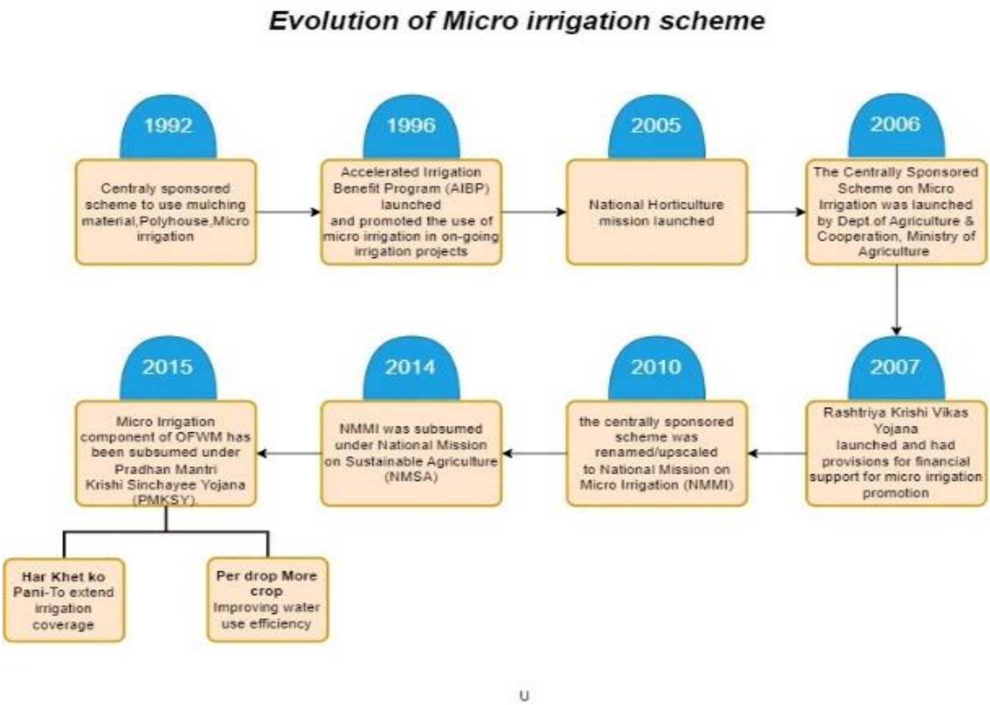
Source: as a Glance (2021)

Groundwater management strategies

Groundwater regulation in India is a complex issue that falls under the jurisdiction of individual states, with the central government providing guidance. Model bills have been created at the federal level to encourage states to implement some form of groundwater regulation based on these models. The Model Bill to Regulate and Control the Development and Management of Ground Water dates to 1970 and is designed to provide a framework for regulating and managing ground water resources. It has undergone several revisions since its initial drafting and continues to serve as a guiding document for effectively managing ground water resources. Various forms of it have been adopted by 13 (of 29) states (Birkenholtz, 2017).

Since 1992, the government has implemented various initiatives to promote micro irrigation systems (MIS) in the agriculture sector, in recognition of the need for improved water productivity. In 2006, the Government of India initiated a Centrally Sponsored Scheme (CSS) for micro irrigation, which marked a significant turning point. This scheme aimed to promote and support micro irrigation practices throughout the country. The National Mission on micro Irrigation (NMMI) was an upgraded scheme that was implemented by the Ministry of Agriculture & Farmers Welfare in the year 2013-14. This initiative was a continuation of a previous scheme. In 2014-15, the National Mission for Sustainable Agriculture (NMSA) became operational and began implementing micro irrigation activities through the On Farm Water Management (OFWM) component of the scheme. This development marks a significant step towards achieving sustainable agriculture in the region. The PMKSY was established with two mandates: "Har Khet Ki Pani" to increase irrigation coverage and "Per Drop More Crop" to increase water use efficiency.

Fig. 4: Evolution of micro irrigation in India



Source: IAI & FICCI (2016)

METHODS

A comprehensive literature search of academic sources like SCI, Scopus and Web of Science gathered the publications included in this study. The selected search words emphasize irrigation systems and their impacts on groundwater sustainability. The initial search included terms like "groundwater," "irrigation," "micro irrigation," and "groundwater sustainability". Recent research was included. After papers were retrieved, they were sorted and screened systematically to determine which ones would be included in this study. At first, we used reference management software to eliminate duplicates. After that, we used the titles and abstracts to determine which publications were most pertinent to our study. Articles that were blatantly out of scope were disregarded. The full-text screening was used to evaluate whether the remaining articles met inclusion and exclusion criteria. Articles were included if they met the inclusion criteria, which included their applicability to irrigation systems, micro irrigation, and groundwater sustainability. This review focuses on a limited group of 50 articles subjected to a rigorous selection, evaluation, and synthesis process. Restricting the search to English-language articles published in the last fifteen years. In addition, the reference lists of the retrieved papers were manually searched for more relevant articles.

RESULTS

This section describes valuable insights and synthesis of existing literature on sustainable groundwater management in relation to changing irrigation practices. The relationship between groundwater uses and irrigation practices is noticeable in the context of a country like India where more than 80 % of agricultural land depends on groundwater. By collecting findings from a diverse variety of research articles, reports, books, and case studies, this section seeks to highlight the key benefits and challenges associated with micro irrigation techniques that contribute to a deeper understanding of micro irrigation systems in promoting sustainable groundwater management. Through this review, we aim to synthesize current information of existing literature based on benefits, best management practices, economic considerations, challenges, limitations, emerging trends etc. on micro irrigation that help in future research. Numerous studies demonstrated that micro irrigation significantly influences crop yield and water use efficiency. Micro irrigation systems, such as drip irrigation and micro-sprinkler irrigation, deliver water precisely to the root zone of plants. This method of watering ensures that crops receive the proper quantity of water, nutrients, and oxygen, resulting in enhanced plant growth, development, and yield. Micro irrigation improves yield by reducing water stress and maximising nutrient availability (Ghazzawy *et al*., 2022; Assouline *et al*., 2002; Dewedar *et al*., 2021).

Similarly, (Assouline *et al*., 2002; Nagaraj & Anitha, 2022) have demonstrated that micro irrigation can increase crop yield by 20 % to 90 %, depending on crop type, soil conditions, and management techniques. In an era of water scarcity and climate change, the ability to tailor water and nutrient delivery to specific crop needs makes micro irrigation a valuable tool for producers seeking to increase crop yields, sustainable resource management, and food production. Micro irrigation systems improve water use efficiency by delivering water directly to the root zone, minimising evaporation, and runoff. With precise control over water application, these systems reduce water losses, optimise nutrient uptake, and prevent overwatering. Micro irrigation ensures efficient water utilisation by providing water only where needed, maximising crop yield per unit of water consumed. Additionally, the slow release of water enhances soil infiltration and minimises deep percolation, increasing the percentage of applied water available to plants. The combination of targeted water delivery and efficient irrigation scheduling in micro irrigation contributes to sustainable water management, conserving water resources while maintaining or even improving crop productivity (Fan *et al.*, 2018; Reinders, 2021; Subramanian, 2023).

An analysis of the effects of micro irrigation on water use efficiency, crop output, and quality in different locales produces varied and enlightening findings. In China, (Khor & Feike, 2017) discovered that drip irrigation had a substantial positive impact on cotton productivity. However, concerns arise regarding its long-term sustainability and effectiveness in conserving water, especially for farmers who use less water. Meanwhile, a study conducted by Nagaraj and Anitha in India reveals that the implementation of micro irrigation leads to higher levels of output and profitability, while also promoting water conservation. However, when considering the expenditures associated with irrigation and its external effects, the overall net returns fall (Nagaraj & Anitha, 2022).

Fishman *et al.* (2015) emphasize the transition from conventional to accurate irrigation, demonstrating a decrease in water runoff that has ramifications for soil moisture and the interconnectedness of root zones. In the state Rajasthan (India), farmers choose to use drip irrigation for crop production when there are no rules regulating groundwater usage. This could worsen the problem of excessive groundwater extraction and highlights the importance of implementing effective groundwater policy (Birkenholtz, 2017). The beneficial effects of micro irrigation have been demonstrated in research highlights the enhanced water efficiency, heightened productivity, and the potential of drip irrigation in areas with limited water resources (Abou *et al.*, 2019). Similarly study in salty soil locations revealed that drip irrigation leads to higher cotton yield (Khamees *et al*., 2023). The study conducted by (Saxena & Purohit, 2015) examines the impact of different levels of salinity in water on the yield of okra crops. Moreover, studies conducted in Israel by (Assouline *et al*., 2002) provide evidence that the implementation of micro drip irrigation techniques results in higher maize yields and less water wastage.

The combined findings enhance our understanding of the implications of micro irrigation for sustainable agriculture. This highlights the significance of context-specific elements and responsible behaviours for achieving long-term success.

Case studies supporting benefits of micro irrigation

The National Mission on Micro irrigation (NMMI) recently conducted a study based on a survey of 5,892 beneficiaries who had availed themselves of the mission's services. The objective of the study was to evaluate the effectiveness of the NMMI's micro irrigation programs and to identify areas for improvement. In 2014, a study was conducted on behalf of the government of India. The findings of the study indicate a significant increase of 42 % in the income and savings of farmers. This increase is attributed to reduced irrigation, fertiliser, and energy consumption costs. The findings revealed a significant increase in productivity by 40-50 per cent upon further consumption of fruits and vegetables (IAI & FICCI, 2016).

A study was conducted in California to collect information on irrigation methods used by growers to irrigate their crops in 2010. The results showed that the planted area has increased for orchards and vineyards, while the planted with vegetables has decreased. Low-volume irrigation has increased while surface irrigation has decreased (Tindula *et al.,* 2013). Similar kind of study was conducted at Washington State University's Irrigated Agriculture Research and Extension Centre for 2 years to determine the effect of different water stress levels applied at different times during the growth period on the yield quantity, quality, and production costs of drip-irrigated native spearmint. The findings shown that a 60 % irrigation shortage in native spearmint may conserve water, increase water usage efficiency, and lower production costs while maintaining oil yields and quality comparable to fully watered plants (Nakawuka *et al*., 2014).

(Aydinsakir *et al*., 2022) carried out the research on the effect of deficit irrigation on yield and quality parameters in 20-year-old Star Ruby grapefruit trees. Three different treatments (100 %, 67 % and 33 % irrigation was tested for executing research. Different irrigation levels of drip irrigation had statistically significant impacts on yield, fruit weight, breadth, length, juice production, total soluble solid, pH, titratable acidity, total dry matter, total flavonoids, total phenols, and ascorbic acid. In Egypt research evaluates investment profitability and economic efficiency of the drip irrigation system for producing tomatoes. Researchers have surveyed 100 tomato producers. The drip irrigation system estimated tomato growing's economic efficiency using financial discounted criteria and data envelopment analysis. Compared to non-drip irrigation, drip irrigation investment increased net return per hectare by 67 % and benefit–cost was 1.35 (Ali *et al*., 2020).

According to the findings of the research conducted by (Suresh & Palanisami, 2010) the use of drip irrigation technology has resulted in a rise in both the net seeded area and the net irrigated area, which has contributed to the achievement of greater cropping intensity and irrigation intensity. It has been found that there is a significant shift towards annual crops like vegetables and sugarcane and toward perennial crops like coconut, grapes, and bananas.

In south korea, researchers have compared the efficiency of sprinkler, surface drip and subsurface drip irrigation methods on water use efficiency, tree growth, yield, and canopy volume. Results showed that subsurface drip irrigation method consumed 37 % and 27 % less irrigation water to maintain the same matric potential compared to sprinkler and surface drip irrigation methods, respectively. Researcher concluded that that subsurface drip irrigation can be used as an efficient method to reduce irrigation water and reduce weed growth in apple orchards (Han *et al*., 2018).

Best management practices for implementing micro irrigation.

The use of micro irrigation systems in agriculture has the potential to save water while increasing agricultural production. To optimize the advantages of these systems, best management practices (BMPs) must be highlighted throughout their design, installation, and maintenance. The proper selection, spacing, and arrangement of emitters is critical to maintaining uniform water distribution and guaranteeing system efficiency. Regular maintenance and monitoring are essential BMPs for preventing problems and ensuring optimum system operation. Irrigation scheduling that is based on plant demands, soil moisture monitoring, and meteorological conditions reduces under- and over-irrigation, resulting in increased crop growth and production. Furthermore, providing water in modest doses over time increases greater water penetration and reduces runoff, which is especially important in water-stressed areas.

Micro irrigation combined with proper fertilizer management minimizes nutrient leaching and assures plant nourishment. The effectiveness of these initiatives, however, is dependent on farmer training and education programs that disseminate key information and skills for efficient, sustainable agricultural production while conserving resources and reducing environmental consequences.

Case studies showing best management practices.

Martínez & Reca (2014) have conducted experimental research in Almería, Spain, to evaluate a surface drip irrigation system to an alternate subsurface drip irrigation system. They have analysed water use efficiency under three distinct irrigation water supplies 100 %, 80 % and 60 %. The research was based on a randomised block design. Six treatments and three replicates for each treatment were carried out. Experimentally, the subsurface drip irrigation method yielded more olive oil than the drip irrigation system, regardless of year or irrigation volume.

Liu *et al.* (2006) investigated the effects of partial root-zone drying (PRD) on the growth and development of potato crops. Two treatments were implemented, with PRD exhibiting significantly higher water use efficiency than FI. Results showed that PRD-treated plots significantly reduced water usage and increased water use efficiency by 60 %.

Amini *et al*. (2023) have tested the performance of corn (SC 704) in drip irrigation (by strip method) with a different density and different row planting pattern. Results showed that applying drip tapes and different surface treatments with soil and water monitoring reduced water consumption by 81 %, 71 %, 61 %, 52 % and 36 %.

Kumar *et al*. (2022) Have conducted a study at the Water Management Farm in Himachal Pradesh to investigate the impact of various irrigation levels and weed management practises on cauliflower. A split plot design was employed to evaluate the effects of three different irrigation levels on crop growth and yield, as well as four distinct weed management practises on overall crop health. The findings revealed that utilisation of black polythene mulch and irrigation at 0.9 PE level leads to a significant increase in cauliflower productivity.

Dukes *et al*. (2007) have conducted an experiment tested several irrigation treatments that allowed up to five watering episodes per day, compared to once-daily irrigation time-based treatments (TIME). SMS irrigation control utilised 29 %-44 % less irrigation water on tomato plants and 37 %-66 % less water on pepper plants, and tomato output was comparable across all treatments but considerably greater on TIME treatments.

Fan *et al*. (2018) have presented a meta-regression analysis of crop water use efficiency (WUE) based on 52 cases from 49 empirical studies published between 1986 and 2012. The analysis uses a meta-regression approach to identify patterns and trends. A comprehensive database was compiled to gain insights into agricultural practices and water usage patterns in wheat and cotton. Results showed that a reduction of 30.4 % in water use for wheat can be achieved with a decrease of 14.8 % in grain yield, while a reduction of 51.4 % in water use can be achieved with a decrease of 51.7 %. Micro irrigation is a more efficient method for wheat cultivation but has also decreased yield. (Dewedar *et al*., 2021) have evaluated the effect of different irrigation systems (surface and subsurface drip irrigation) on Been. They found that Yield and water productivity under subsurface irrigation was slightly higher than under surface drip irrigation.

Parthasarathi *et al*. (2018) investigated the effects of various drip irrigation treatments on rice physiology and water productivity. These treatments included variations in lateral distances (0.6, 0.8, and 1.0 m), dripper discharge rates (0.6 and 1.0 Lph), irrigation methods (surface and subsurface), and the conventional aerobic rice production system (control). The aerobic rice production system's subsurface drip irrigation system with drippers/laterals 0.8 m apart and 1.0 Lph flow rate is cost-effective and can save 27 % of water without affecting grain output.

The case studies and research results provided here highlight the enormous potential of micro irrigation systems and best management practices (BMPs) in improving water usage efficiency and agricultural output. Several studies have shown that micro irrigation has benefits over conventional approaches, such as greater crop yields, lower water use, and improved water-use efficiency. Furthermore, novel technologies like as partial root-zone drying and precision irrigation timing have shown significant advantages in terms of water conservation. Sensor-based and mobile app technologies are being explored for water application during the whole sowing and harvesting process as part of Best Management Practices (BMP). Farmers must receive specialized training and skill development to prepare for them to be able to operate these tools with ease. Farmers can improve overall agricultural productivity by optimizing water management techniques through education and skill in using sensor-based technologies and mobile applications.

Overall, although there are problems and limits, the use of micro irrigation technologies in conjunction with best management practices (BMPs) provides a potential road to sustainable agriculture and water resource management, provided that these techniques are successfully implemented and controlled.

Challenges and limitations

The Jevons Paradox, also known as the rebound effect, is a phenomenon in which implementing a more technically efficient natural resource technology, such as drip irrigation, results in an unexpected increase in the utilization of that natural resource rather than the intended decrease. This paradox has been observed in various contexts and has significant implications for sustainable resource management (Birkenholtz, 2017). Micro irrigation has numerous benefits, it also faces specific challenges and limitations. The perfect example of the Javon paradox is the green revolution in India. The Green Revolution in India in the 1960s denotes a significant period when the country's agricultural sector transformed into an industrial system. This transformation was primarily attributed to adopting modern methods and technology, including using high-yielding variety (HYV) seeds, tractors, irrigation facilities, pesticides, and fertilizers (Aheeyar *et al*.,2005) The Green Revolution's impact on Indian agriculture profoundly led to increased crop yields, food security, and economic growth. Despite its many advantages, the Green Revolution also caused challenges, notably with groundwater. High-yielding crop types, intense irrigation, and poor water management caused excessive groundwater extraction in Punjab, Haryana and Uttar Pradesh, the highest beneficiary states of India. The states which were the most beneficiary of the green revolution are now overexploited due to improper water resource management (Bashir *et al*., 2022). The results of this research have important practical relevance in locations with variable groundwater conditions. It emphasizes the need of promoting and driving the use of effective micro irrigation systems, such as drip irrigation and sprinklers, for policymakers, since these systems may assist save valuable water supplies. The socioeconomic position of farmers and small landholdings are major difficulties in India's contemporary agricultural environment. 89.4 % farmers have minimal areas of land with small scaled farmers which makes it difficult for them to invest in micro irrigation techniques (PIB Delhi, 2022). The problem is made worse by the growing expense of micro irrigation, particularly for people who rely on rainfall but do not have well access. Even though subsidies are supposed to help with money issues, the actual spending and use of the subsidies are challenging. Even with subsidized rates, affordability is still a problem, underscoring the hardships faced by small-scale farmers. On the other hand, Minimum Support Price (MSP) is essential for maintaining economic sustainability. A comprehensive strategy to improve the affordability and accessibility of crucial agricultural technologies is needed to address these issues. Water resource managers may benefit from developing laws and training programs to guarantee that these systems are properly installed and maintained. Micro irrigation may boost the yield of crops while reducing water waste for farmers, particularly those in water-stressed regions. This method improves agriculture as well as the long-term management of groundwater resources, creating a more secure water future for everybody (Anjum, 2023).

Barriers to adoption of micro irrigation

Adopting micro irrigation techniques, such as drip irrigation or sprinkler systems, can face several barriers that hinder its widespread implementation. Common barriers to adopting micro irrigation are i) The initial cost of micro irrigation is a significant obstacle. Farms, mainly small-scale farms, may need help to afford drip lines, emitters, filters, and control systems. ii)The initial expenditure might limit broad adoption. Many farmers may need more financial resources or access to credit to invest in micro irrigation systems. iii) Micro irrigation systems require regular maintenance and operation to ensure optimal performance. The ongoing maintenance and operation requirements can be a barrier if farmers need more skills, time, and resources to carry out these activities effectively. iv) Micro irrigation advantages and incentives are often unknown to farmers. To overcome all these barriers government has taken initiatives under PDMC (per drop more crop) scheme. (Government of India Report, 2023)

Economic considerations

Micro irrigation systems, like drip and sprinkling systems, are popular and widely used because they are cost-effective in several ways. First, these systems allow farmers to apply water in an exact way, which cuts down on water use and costs. The direct transfer of water to the root zone of plants saves water and makes it possible to grow food in areas with low water supplies (Priyan & Panchal, 2017). Also, micro irrigation systems make it easier to automate watering processes, which cuts down on the amount of work needed and the costs that come with it. Better food growth and quality from managing water and nutrients also help farms make more money. Overall, the economic benefits of micro irrigation systems make them a good choice for farmers. They help farmers handle water sustainably while making farming more productive and profitable (Singh & Sharma, 2013).

Emerging trends and innovation in micro irrigation

Emerging trends and innovations have been incorporated into micro irrigation to enhance efficiency, efficacy, and sustainability. The micro irrigation field is currently experiencing various novel trends and innovations geared towards optimising its efficiency, sustainability, and efficacy. Precision irrigation techniques have emerged as a significant trend in modern agriculture. This approach utilises advanced technologies such as sensors, remote sensing, and automation to accurately monitor and manage water applications based on crop water requirements and soil conditions (Suresh & Samuel, 2020). The integration of these technologies enables farmers to optimise water usage, reduce waste, and enhance crop yields. The optimisation of water use, reduction of wastage, and enhancement of crop productivity are critical objectives for farmers. Achieving these objectives requires the implementation of effective strategies and technologies. One such technology that has gained popularity in recent years is precision agriculture. Precision agriculture enables farmers to optimise water use, reduce waste, and enhance crop productivity by using data-driven approaches. Farmers can collect data on soil moisture, temperature, and other environmental factors through sensors, drones, and other advanced technologies. This data is then analysed to determine the optimal water required for each crop, reducing wastage, and enhancing productivity. Precision agriculture is a promising technology that can help farmers achieve their objectives while promoting sustainable agriculture practices (Durugkar & Poonia, 2018). The adoption of innovative irrigation systems is on the rise, with the integration of cutting-edge technologies such as Internet of Things (IoT) devices, data analytics, and mobile applications to facilitate remote monitoring and control of irrigation operations (Keswani *et al*., 2019; Laphatphakkhanut *et al*., 2020; Obaideen *et al*., 2022; Anagha *et al*., 2023). The implementation of such systems has been found to facilitate real-time access to data, offer timely alerts, and empower farmers to make informed decisions regarding irrigation scheduling. This, in turn, has led to a reduction in labour costs and more efficient water use. These emerging trends and innovations in micro irrigation hold great promise for sustainable water management in agriculture and contribute to improved crop yields and resource efficiency (Mohammed *et al*., 2023).

CONCLUSION

The examination of micro irrigation's influence on water use efficiency and agricultural productivity is conducted through a variety of studies and case analyses. Micro irrigation, which includes techniques like as drip and micro-sprinkler systems, is an important instrument for accurately delivering water to plant roots, promoting improved growth and crop yield. Multiple studies have demonstrated a direct relationship between micro irrigation and enhanced crop productivity, with yield increases ranging from 20 % to 90 %. The extent of this link depends on factors such as the type of crop, soil conditions, and management techniques. Micro irrigation is an effective method in countries experiencing water scarcity and the increasing difficulties posed by climate change. The rigorous regulation of water distribution not only conserves water but also enhances nutrient absorption, reducing excessive watering and boosting effective water consumption.

Case studies conducted in various regions such as China, India, and the Middle East provide more examples that demonstrate the subtle and detailed effects of micro irrigation. Although drip irrigation in China has a good impact on cotton yield, there are issues regarding its long-term durability and effectiveness in conserving water. Micro irrigation in India results in increased productivity and profitability. However, when factoring in the related expenses, the net returns decline. The use of precise irrigation techniques in certain areas leads to a decrease in water runoff, which in turn affects the dynamics of soil moisture. Nevertheless, the implementation of drip irrigation without groundwater laws in Rajasthan worsens the problem of excessive water extraction, highlighting the importance of well-designed groundwater policies. The NMMI study conducted in India reveals noteworthy enhancements in farmers' income and savings, which can be linked to the reduction in irrigation, fertilizer, and energy expenses. Studies conducted in both the United States and Egypt demonstrate the economic effectiveness of micro irrigation, highlighting higher crop yields and enhanced financial gains. Implementing optimal management strategies for micro irrigation is essential for optimizing its benefits. Key Best Management Practices (BMPs) include the careful selection, appropriate spacing, and systematic placement of emitters, as well as consistent maintenance and irrigation schedule that aligns with the specific requirements of the plants and the prevailing environmental circumstances. Case studies confirm the effectiveness of these approaches in enhancing agricultural output while limiting resource utilization.

The existence of challenges and constraints, such as the Jevons Paradox and socioeconomic restrictions, is recognized. The Jevons Paradox posits that whereas micro irrigation may lead to improvements in efficiency, the resulting rise in demand could counterbalance the intended conservation of resources. The socioeconomic challenges encompass the issue of small-scale farmers facing difficulties in affording micro irrigation due to their restricted landholdings and increasing costs.

The economic implications emphasize the efficiency of micro irrigation systems, which decrease water consumption, automate operations, and improve overall agricultural output. Implementing technological and maintenance standards guarantees the best possible functioning of the system, highlighting the significance of using top-notch components and monitoring systems. The advancements in micro irrigation, including precision agriculture, integration of Internet of Things (IoT), and utilization of data analytics, offer potential for improving efficiency, sustainability, and effectiveness. These technological improvements facilitate the monitoring of data in real-time, allowing for prompt notifications and enabling well-informed decision-making. As a result, this leads to a reduction in labor expenses and promotes the adoption of more effective water management practices.

The comprehensive investigation of micro irrigation highlights its crucial significance in promoting sustainable agriculture. Despite recognizing obstacles and constraints, the developing patterns and advancements establish micro irrigation as a revolutionary influence in the management of water resources, leading to improved crop production, efficient use of resources, and sustainable agriculture in the long run.

DISCUSSION

The practical implications of our research findings are noteworthy for policymakers, water managers, and farmers operating in regions with varying groundwater conditions. While water managers can create strategic plans for the sustainable use of resources, policymakers can create regulations that are specifically focused. Using our findings to optimize irrigation operations helps farmers use resources more efficiently. By enabling stakeholders to make knowledgeable decisions, this integrated strategy promotes efficient management of water resources. Policymakers can enhance the sustainability of water resources in diverse geographical settings by implementing regulations that are more impactful, water managers can implement targeted conservation measures, and farmers can adopt sustainable groundwater use practices by customizing their strategies to specific regional contexts.This research article presents a comprehensive analysis of the effects of irrigation systems, specifically on micro irrigation systems, on the sustainability of groundwater resources. The study examines the various factors that contribute to the depletion of groundwater resources and the role that irrigation systems play in exacerbating this issue. Through a thorough review of existing literature and case studies, the article provides insights into the potential benefits and drawbacks of micro irrigation systems regarding groundwater sustainability. The findings of this research contribute to a better understanding of the complex relationship between irrigation systems and groundwater resources. They can inform policy decisions aimed at promoting sustainable water management practices. This research article focuses on the economic implications of micro irrigation, precisely the benefits of enhanced water-use efficiency and crop yield. This study focuses on the technological and maintenance requirements necessary for achieving optimal performance of micro irrigation systems. Further it also provides a set of recommendations aimed at enhancing the effectiveness of their actions. The issue of excessive groundwater extraction, attributed to subsidized electricity, has been identified as a significant concern. To address this issue, the paper recommends a gradual reduction in these subsidies to promote the adoption of sustainable water management practices. The findings of this review paper are of great value to researchers and policymakers alike, as they shed light on the challenges and opportunities associated with using micro irrigation systems and their impact on groundwater sustainability.

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