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Analyzing the Challenges and Solutions of Sustainable Groundwater Management using Micro irrigation

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ABSTRACT

Groundwater is essential to the world's water resources because it supports systems for home, industrial, and agricultural water delivery. However, the extensive use of irrigation systems, particularly micro irrigation, is posing an increasing threat to the long-term sustainability of groundwater. A common agricultural practice is micro irrigation, which involves using sprinkler systems and drip irrigation to apply water to crops. This technique's capacity to effectively supply water to crops has led to its widespread use. The present review investigates the effects of micro irrigation on the sustainability of groundwater, with a particular emphasis on the effects on quantity, quality, and overall sustainability. The results show that by lowering water losses, micro irrigation can greatly aid in groundwater conservation. On the other hand, poor management techniques, including excessive irrigation or inaccurate application rates, can result in overuse of groundwater, aquifer depletion, and falling water tables. The use of pesticides and fertilizers in micro irrigation systems can contaminate groundwater, lowering water quality and endangering public health. The need of properly designing, installing, and maintaining micro irrigation systems is emphasized in this review paper in order to reduce any potential negative effects on groundwater. In addition, policies, programs, and regulatory frameworks are essential for encouraging sustainable groundwater management techniques in micro irrigation. In order to guarantee the sustainable use of groundwater resources in micro irrigation systems, the current assessment emphasizes the importance of enforcing pertinent regulations, improving water management strategies, and adopting balanced water use practices.

Key words: *Best management practices, Groundwater sustainability, Irrigation systems, Micro irrigation.*

Introduction

Water scarcity has recently gained significant attention, particularly in light of its vital significance in the agriculture industry. Due to several variables, including population expansion, urbanization, and climate change, the amount of water resources available has been decreasing. The agriculture industry, which depends largely on water for irrigation and other uses, has been greatly harmed by this (Priyan and Panchal, 2017). Lack of water has lowered farmer profitability, raised production costs, and decreased crop yields. Water provision is contingent upon several hydro-meteorological factors; hence,

([1]Assistant Professor, [2,3,4,5,6,7,8,9]B.Sc Agriculture Student) guaranteeing a safe water source for irrigation is critical. As was already mentioned, the situation presents a major challenge. Improving yield is a critical issue in agriculture in order to feed the country's growing population. Given that land holdings are continuing to diminish, and it is becoming more difficult to supply the population's overall food demands, this demographic shift presents a serious problem. Irrigation plays a crucial and indispensable part in achieving the desired outcome.

Ninety-one percent of the water used in India is used for livestock and irrigation, which accounts for a sizeable amount of water consumption. This figure exceeds the global average by a significant margin. India's agriculture is anticipated to be significantly impacted by its reliance on natural water resources, since the country is predicted to be among those experiencing water scarcity by 2025. Because extraction rates are excessive and exceed natural recharge rates, groundwater resources are being depleted. By 2050, average usable water supplies are predicted to drop from 195247 m^3 to 1170 m^3 per capita, from their present level of 1453 m^3 per capita in 1951. Compared to where we are currently, that is a significant decline (Ministry of Jalshakti, 2021). The overall annual recharge of groundwater was estimated to be 437.60 billion cubic meters, according to the Groundwater Dynamics 2022 report. When accounting for a natural outflow, the annual extractable ground water resource comes out to be 398.08 billion cubic meters. The total yearly extraction of ground water was estimated to be 239.16 billion cubic meters as of 2022. An average of 60.08 percent of the ground water resources in the country have been drained, according to calculations. Researchers and policymakers are becoming increasingly concerned about this problem because it has the potential to negatively impact the agriculture industry, which is a vital part of the Indian economy.

Fig. 1. Shows the ground water Resource Assessment (*Source:* as a Glance (2022))

The method used to provide water to the plants called irrigation. India's economy is mostly based on agriculture, hence maintaining agricultural over its enormous land area is mostly dependent on irrigation infrastructure. Different irrigation techniques are required in different sections of the nation due to differences in agro-climatic conditions and water availability. The primary irrigation systems in India consist of tanks, canals, and groundwater. Different approaches are used to supply water to the agricultural land based on these systems. In India, farmers frequently use surface irrigation to disperse water throughout their land. One common technique is flood irrigation, which involves pouring water over the field and allowing it to run off and cover the whole area.

It is necessary to create small, flat pools in the field and fill them with water for basin irrigation. This is an effective way to raise foods like rice. With furrow irrigation, water is moved down crop rows so that it can seep into the soil via tiny channels known as "furrows." When a field is separated into long, thin strips or borders, water runs down the borders and into the soil. This is known as border irrigation. This reduces damage and flow. Taking into account the kind of soil and crop requirements, Indian farmers can employ these various surface irrigation techniques to provide water to their crops as efficiently as feasible. The majority of farmers have embraced drip and sprinkler irrigation systems as micro watering methods in recent years. By supplying water straight to the root zones of plants, these systems improve water consumption and minimize evaporation loss.

A key element in the global production of food is the use of irrigation. It does, however, provide a significant challenge to groundwater supplies, which are typically the main supply of water for irrigation. An essential part of effectively managing water resources and putting sustainable farming methods into practice is looking into the relationship between irrigation systems and groundwater sustainability.

The purpose of this review study is to evaluate how micro irrigation technologies contribute to groundwater management that is sustainable. This objective examines the advantages and disadvantages of micro irrigation methods, including sprinkler systems and drip irrigation, in order to assess how well they minimize water waste, increase water

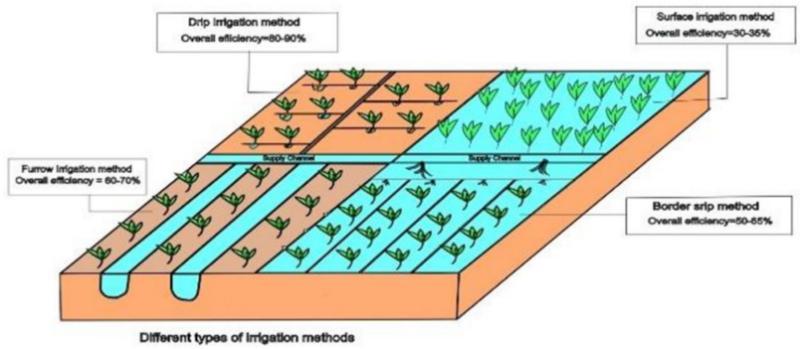

Fig. 2. Type of Irrigation System (Source: Created using Inscape software)

efficiency, and lessen the possibility of adverse effects on groundwater resources. In order to guarantee the long-term sustainability of groundwater, this study report also attempts to determine best practices and suggestions for the effective implementation of micro irrigation systems.

Groundwater resources are difficult to manage and maintain, endangering both their quantity and quality.

Groundwater Sustainability

"Maintaining long-term, dynamically stable storage of high-quality groundwater through inclusive, reasonable, and long-term governance and management" is the definition of groundwater sustainability, (Elshall *et al*., 2020). Where there is substantial groundwater use for domestic, industrial, and agricultural purposes, groundwater sustainability is crucial.

Groundwater resources are under threat from improper management and overexploitation. To meet current and future water needs, groundwater extraction and recharge rates must be balanced. Given how irrigation methods would affect groundwater supplies in the long run, groundwater sustainability is a crucial issue. Because irrigation systems are so important to maintaining agricultural productivity, it is crucial to make sure that they are planned and operated in a way that protects groundwater's long-term sustainability. In debates about irrigation techniques, the sustainability of groundwater with irrigation systems is a crucial but frequently disregarded factor. While crop production improvement and water conservation are the main areas of focus, groundwater reserves' long-term survival requires equal consideration. Food production is possible in areas with low surface water availability thanks to groundwater, which is an essential resource for irrigation. But excessive groundwater extraction and ineffective irrigation methods can cause aquifers to be depleted, which makes it harder for them to naturally refill.

Role of Irrigation systems in groundwater dynamics

Because of their effects on different hydrological cycle processes and interactions, irrigation systems have a considerable impact on groundwater dynamics. Understanding water balance, infiltration, and irrigation return flow all of which have a big impact on sustainable water resource management requires an understanding of the role irrigation systems play in groundwater dynamics. Given that it influences several facets of the hydrological cycle, the effect of irrigation systems on groundwater dynamics is an important field of research. Irrigation systems have a major impact on the different elements of the hydrological cycle. Infiltration, runoff, and irrigation return flow are examples of water balance characteristics that primarily govern how irrigation systems affect groundwater resources. These elements are essential in figuring out how irrigation systems affect groundwater supplies overall. A key idea in hydrology, the water balance represents the equilibrium that exists within a given area between inputs like irrigation and precipitation and outputs like transpiration, evaporation, and runoff. Lun and colleagues (2015); Evans and Zaitchik (2008) Irrigation systems increase the amount of water available for other hydrological processes, which helps maintain the water balance. Groundwater sustainability is greatly dependent on infiltration in the water balance equation. Infiltration is impacted by land management, soil, and irrigation. Infiltration rates and deep percolation losses can be maximized with the use of efficient technologies, water application rates, and irrigation timing. Irrigation return flow can increase groundwater recharge and replenish depleted aquifers if managed appropriately. Water logging, salinity, excessive irrigation return flow, and contamination of groundwater resources can all be results of ineffective irrigation or drainage. In order to maximize water utilization, maintain an ideal water flow, and guarantee long-term groundwater supplies, irrigation systems must be managed effectively.

Micro irrigation

Through a network of pipes with varying sizes known as the main line, the sub-main lines, and the lateral lines, water is made to flow under pressure as part of a coordinated and controlled water management system known as micro irrigation. Some emitters allow water to reach the root zone along the length of the lateral lines. Drip irrigation, sprinkler irrigation, and bubbler irrigation are a few different kinds of micro irrigation systems. The most popular micro irrigation system is drip irrigation. Using emitters or drippers, water is supplied directly to the root zone of the plant in a controlled and metered manner. Water is lost to evaporation and runoff whether it trickles gently over the soil's surface or penetrates it directly. Using tiny sprinklers or sprayers, micro-sprinkler irrigation delivers a very fine mist of water to the earth around a plant. The low-lying position of these sprinklers and the equal and gentle distribution of water over a small area characterize their performance. Their adaptability makes them ideal for watering areas with irregular shapes or little plants. Larger plants or trees, such shrubs or trees that require a greater quantity of water are frequently irrigated with a bubbler. This method requires placing a device, possibly a basin emitter or a bubbler, at the base of the plant. By dispensing the water from the bubbler more gradually, it can seep deeper into the soil and eventually reach the roots of the plant. A specific type of drip irrigation known as subsurface drip irrigation (SDI) involves hiding the drip lines beneath the surface of the ground. Another name for SDI is subsurface drip irrigation. To regulate the water flow, emitters have been placed at regular intervals throughout the subterranean drip lines. By minimizing the growth of weeds and guarding against system damage, SDI lowers the quantity of water lost to evaporation. These micro irrigation systems regulate the supply of water to the root zone, its uniform distribution, and its flow. By directly hydrating plant roots, micro irrigation systems maximize water intake, reduce water stress, and increase agricultural productivity.

Merits and Demerits of micro irrigation systems

Numerous benefits of micro irrigation contribute to its growing acceptance and popularity in agricultural techniques. By delivering water straight to the plant's root zone, this cutting-edge irrigation method reduces water loss from evaporation and deep percolation and guarantees effective water use. In comparison to conventional irrigation techniques, micro irrigation helps preserve water resources by delivering precise and controlled volumes of water, hence reducing overall water use. Additionally, this technique makes it possible to apply nutrients precisely, eliminating leaching and lowering the amount of fertilizer needed, all of which improve nutrient usage efficiency. Additionally, micro irrigation systems are simple to automate and may be fitted with sensors to track soil moisture content and modify water supply as necessary. This enhances irrigation scheduling and maximizes crop productivity.

Moreover, micro irrigation has improved crop health by lowering foliar infections and leaf moisture, which in turn lowers the incidence of disease. Micro irrigation does, however, have some drawbacks to take into account. The initial setup expenses of micro irrigation systems may be higher than those of standard techniques, and continuous maintenance is required to guarantee optimal performance and avoid blockages. For implementation to be successful, technical proficiency and site suitability must also be carefully considered. Notwithstanding these difficulties, micro irrigation is a viable and long-term irrigation strategy for contemporary agriculture because of its advantages in terms of crop output, disease control, water conservation, and nutrient efficiency.

The Department of Agriculture & Farmers Welfare estimates state that in 2020, the penetration rate for the net sown area was almost 9%, up from 5.5% in 2015. Thus, although the penetration of micro irrigation has grown considerably, it is still far lower than in nations like China, the USA, and Israel. The penetration of micro irrigation with regard to net irrigated area and net sowed area is depicted in Fig. 3.

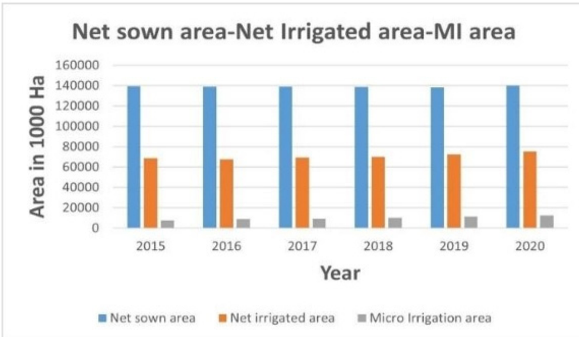

Fig. 3. Net sown area- net irrigated area-Micro Irrigation area (Source: as a Glance (2021)

Groundwater management strategies

In India, groundwater regulation is a complicated matter that is the responsibility of the different states, with federal government oversight. Federal model bills have been developed to incentivize states to enact groundwater regulations based on these models. A framework for regulating and managing ground water resources is provided by the 1970 Model Bill to Regulate and Control the Development and Management of Ground Water. Since it was first drafted, it has undergone a number of adjustments, but it still acts as a guide for efficiently managing ground water resources. Thirteen (out of twenty-nine) states have approved it in various forms (Birkenholtz, 2017). Recognizing the need for increased water production, the government has launched a number of projects to support micro irrigation systems (MIS) in the agricultural sector since 1992. A big turning point was reached in 2006 when the Indian government launched the Centrally Sponsored Scheme (CSS) for micro irrigation. The countrywide promotion and assistance of micro irrigation techniques was the goal of this program. A revised program called the National Mission on Micro Irrigation (NMMI) was put into place by the Ministry of Agriculture and Farmers Welfare in 2013–14. This program was an extension of an earlier plan. The on Farm Water Management (OFWM) component of the plan was used to undertake micro irrigation operations by the National Mission for Sustainable Agriculture (NMSA) once it was operationalized in 2014–2015. A big stride has been taken in the direction of sustainable agriculture in the area with this development. The PMKSY was founded with the goals of "Per Drop More Crop" to boost water use efficiency and "Har Khet Ki Pani" to

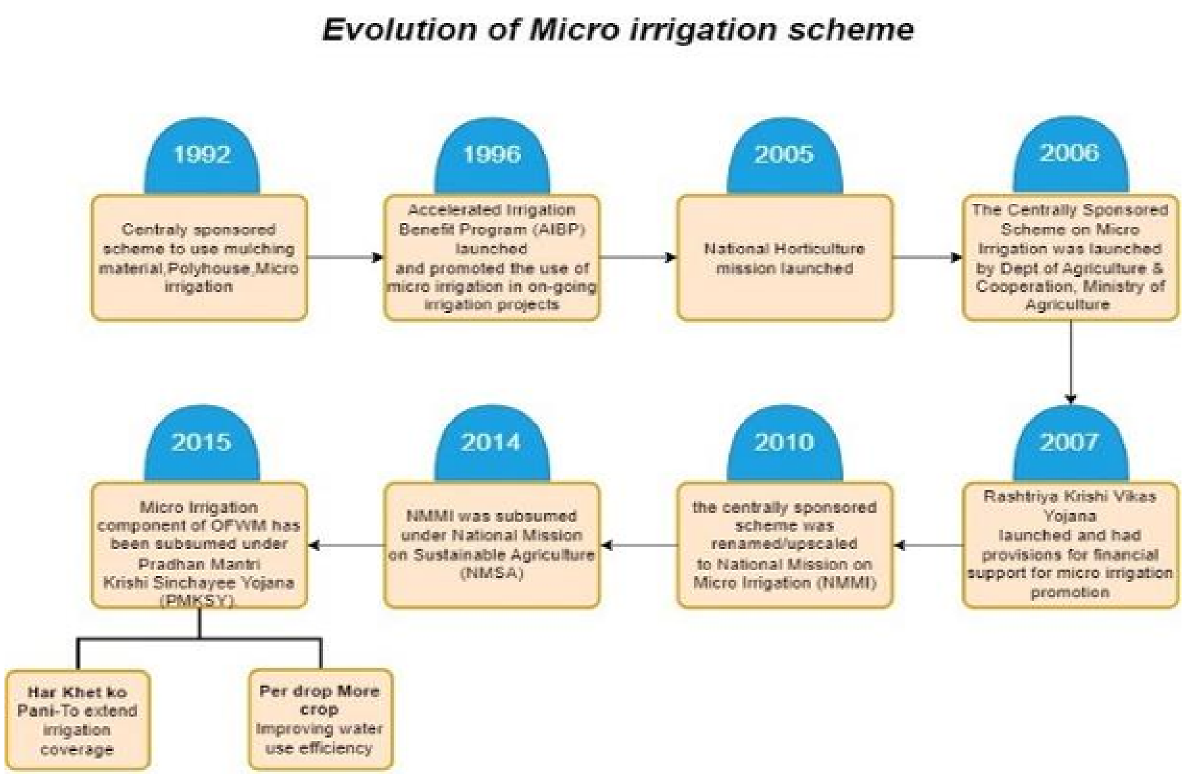

Fig. 4. Evolution of micro irrigation in India (Source: IAI & FICCI, 2016)

expand irrigation coverage.

Methods

A thorough search of scholarly databases such as SCI, Scopus, and Web of Science produced the publications that were included in this analysis. The focus of the chosen search terms is on irrigation systems and how they affect the sustainability of groundwater. Terms like "groundwater," "irrigation," "micro irrigation," and "groundwater sustainability" were used in the first search. There was recent research included. Following their retrieval, the papers underwent a methodical sorting and screening process to ascertain which ones would be incorporated into our investigation. To get rid of duplicates, we first employed reference management software. After that, we selected the papers that were most relevant to our study based on the titles and abstracts. Articles that were obviously outside of their scope were ignored. The remaining papers were screened for compliance with inclusion and exclusion criteria using the full-text screening process. Articles that satisfied the requirements for inclusion-which included being applicable to micro irrigation, irrigation systems, and groundwater sustainability-were accepted. This study concentrates on a limit group of fifty papers that underwent a thorough process of selection, assessment, and synthesis limiting the search to items written in English that have been published during the last 15 years. Furthermore, a manual search was conducted through the reference lists of the retrieved papers to find additional pertinent literature.

Results

This section provides insightful analysis and a summary of the body of research on groundwater management that is sustainable in the context of evolving irrigation techniques. In a nation like India, where groundwater is used for more than 80% of agricultural land, the connection between groundwater uses and irrigation techniques is evident. This section aims to provide a deeper understanding of micro irrigation systems in promoting sustainable groundwater management by highlighting the main advantages and difficulties associated with these techniques through a compilation of research findings from a wide range of books, reports, research articles, and case studies. Our goal in doing this review is to compile up-to-date data from the literature that will be useful for future research on micro irrigation, including benefits, best management practices, economic considerations, obstacles, limitations, and new trends. Micro irrigation has been shown in numerous studies to have a considerable impact on crop productivity and water use efficiency. Plant roots receive precise water delivery from micro irrigation systems, like micro-sprinkler irrigation and drip irrigation. This irrigation technique guarantees that crops get the right amount of oxygen, nutrients, and water, which promotes improved plant development and output. By maximizing fertilizer availability and minimizing water stress, micro irrigation increases yield (Ghazzawy *et al.,* 2022; Assouline *et al*., 2002; Dewedar *et al.,* 2021). In a similar vein, research has shown that, depending on crop variety, soil conditions, and management practices, micro irrigation can raise crop output by 20% to 90% (Assouline *et al*., 2002; Nagaraj and Anitha, 2022). The capacity to customize water and nutrient delivery to individual crop demands in an era of water shortage and climate change makes micro irrigation an invaluable tool for farmers looking to boost crop yields, sustainable resource management, and food supply. By minimizing runoff and evaporation and supplying water directly to the root zone, micro irrigation systems increase the efficiency of water use. These systems maximize fertilizer uptake, minimize water loss, and avoid overwatering thanks to precise control over water administration. By supplying water only where it is required, micro irrigation maximizes crop output per unit of water used, ensuring effective water use. Furthermore, by minimizing deep percolation and promoting soil infiltration, the gradual release of water raises the proportion of applied water that reaches the plants. Micro irrigation's combination of effective irrigation scheduling and tailored water distribution helps preserve water resources while sustaining or even increasing crop output (Fan *et al.,* 2018; Reinders, 2021; Subramanian, 2023). Diverse and insightful conclusions are drawn from an examination of the impacts of micro irrigation on crop output, quality, and water use efficiency in various locations. (Khor and Feike, 2017) found that drip irrigation significantly increased cotton productivity in China. Concerns are raised, nevertheless, about its long-term viability and ability to save water, particularly for farmers who use less water. In the meantime, a study carried out in India by Nagaraj and Anitha shows that the use of micro irrigation promotes water saving while increasing output and profitability. Nevertheless, the overall net returns decrease when one takes into account the costs related to irrigation and its external consequences (Nagaraj and Anitha, 2022).

The switch from traditional to precise irrigation is emphasized by Fishman *et al*. (2015), who also show how this reduces water runoff, which affects soil moisture and the connectivity of root zones. When there are no regulations controlling the use of groundwater, farmers in the Indian state of Rajasthan opt to employ drip irrigation to produce their crops. This emphasizes the significance of putting in place an efficient groundwater policy and has the potential to exacerbate the issue of excessive groundwater extraction (Birkenholtz, 2017). Research has shown that micro irrigation has positive consequences. It has also highlighted increased productivity, improved water efficiency, and the promise of drip irrigation in regions with limited water resources (Abou *et al*., 2019). Similar research in areas with salinized soils showed that drip irrigation increases cotton yield (Khamees *et al*., 2023). In their 2015 study, Saxena and Purohit investigate how varying salinity levels in water affect okra crop yields. Furthermore, research done in Israel by Assouline *et al.* (2002) shows that using micro drip irrigation systems increases maize yields while reducing water waste.

The collective results improve our knowledge of how microirrigation affects sustainable agriculture. This emphasizes how important responsible behaviour and context-specific components are to long-term success.

Case studies showing best management practices

In Almería, Spain, Martínez and Reca (2014) carried out experimental research to compare a surface drip irrigation system with a different subsurface drip irrigation system. They examined the efficiency of water consumption for three different irrigation water supplies: 100%, 80%, and 60%. Randomized block design served as the foundation for the study. There were six treatments total, with three duplicates of each treatment. Regardless of the year or irrigation volume, the subsurface drip irrigation approach produced more olive oil in an experiment than the drip irrigation system.

The effects of partial root-zone drying (PRD) on the development and growth of potato crops were examined by Liu *et al.* (2006). There were two treatments used, and PRD showed a noticeably better water use efficiency than FI. According to the findings, PRD-treated plots considerably decreased water consumption and raised water use efficiency by 60%.

The performance of maize (SC 704) under drip irrigation (by strip method) with varying densities and row planting patterns has been studied by Amini *et al.* (2023). Applying drip tapes and other surface treatments along with soil and water monitoring, according to the results, decreased water use by 81%, 71%, 61%, 52%, and 36%.

At the Water Management Farm in Himachal Pradesh, Kumar *et al.* (2022) carried out a study to look at the effects of different irrigation levels and weed control techniques on cauliflower. The impact of four different weed management strategies on overall crop health as well as three different irrigation levels on crop growth and production were assessed using a split plot design. Cauliflower productivity increases significantly when black polythene mulch is used and watering is done at 0.9 PE level, according to the data.

In contrast to once-daily irrigation time-based treatments (TIME), Dukes *et al.* (2007) examined a number of irrigation treatments that permitted up to five watering events per day. With SMS irrigation management, tomato plant yield was similar across all treatments but significantly higher on TIME treatments. Pepper plants used 37%- 66% less water, and tomato plants used 29%-44% less water.

A meta-regression analysis of crop water use efficiency (WUE) based on 52 instances from 49 empirical research published between 1986 and 2012 was reported by Fan *et al.* (2018). The analysis looks for patterns and trends using a meta-regression technique. To obtain insights on agricultural practices and patterns of water usage in wheat and cotton, an extensive database was assembled. The findings indicated that a loss of 14.8% in grain production can lead to a reduction of 31.4% in water usage for wheat, whilst a decrease of 51.7% can result in a reduction of 51.4% in water use. Although micro irrigation is a more effective technique for growing wheat, the yield is also lower (Dewedar *et al.,* 2021) assessed how been was affected by various irrigation techniques, including surface and subsurface drip irrigation. They discovered that subsurface irrigation produced somewhat more yield and water productivity than surface drip irrigation. The effects of different drip irrigation treatments on rice physiology and water productivity were studied by Parthasarathi *et al.* (2018). These treatments comprised changes to dripper discharge rates (0.6 and 1.0 Lph), irrigation techniques (surface and subsurface), lateral distances (0.6, 0.8, and 1.0 m), and the traditional aerobic rice production system (control).

The subsurface drip irrigation system used in the aerobic rice production system, which has drippers/ laterals spaced 0.8 m apart and a 1.0 Lph flow rate, is economical and can save 27% of water without compromising grain yield.

The case studies and research findings presented here demonstrate the tremendous potential that micro irrigation systems and best management practices (BMPs) have to increase agricultural output and water usage efficiency. Numerous studies have demonstrated the advantages of micro irrigation over traditional methods, including increased crop yields, reduced water consumption, and enhanced water-use efficiency. Additionally, cutting-edge techniques like precise irrigation scheduling and partial root-zone drying have demonstrated notable benefits in terms of water conservation. As part of Best Management Practices (BMP), sensor-based and mobile app technologies are being investigated for water application during the entire sowing and harvesting process. Farmers who want to be able to use these instruments effortlessly need to undergo specific training and skill development. By enhancing water management strategies through knowledge and proficiency with sensor-based technologies and mobile applications, farmers can raise overall agricultural production. Overall, if these strategies are successfully applied and managed, the use of micro irrigation technologies in conjunction with best management practices (BMPs) offers a potential path to sustainable agriculture and water resource management, despite issues and limitations.

Challenges and limitations

The Jevons Paradox, sometimes referred to as the rebound effect, is a phenomena where the projected decrease in the use of a natural resource is unexpectedly reversed when a more technically efficient solution, such drip irrigation, is implemented. This contradiction has been noted in a number of situations and has important ramifications for resource management that are sustainable (Birkenholtz, 2017). Although micro irrigation offers many advantages, there are several difficulties and restrictions with it. The Indian green revolution exemplifies the Javon paradox perfectly. The 1960s saw the start of India's Green Revolution, a momentous time when the nation's agricultural sector evolved into an industrial system. The main reason for this change was the use of contemporary techniques and equipment, such as tractors, fertilizers, herbicides, irrigation systems, high-yielding variety (HYV) seeds, and irrigation facilities (Aheeyar *et al.,* 2005). India's agriculture benefited greatly from the Green Revolution in terms of higher crop yields, food security, and economic expansion. The Green Revolution brought about numerous benefits, but it also brought about certain problems, most notably with groundwater. The top beneficiary states in India, Punjab, Haryana, and Uttar Pradesh, experienced excessive groundwater extraction due to high-yielding crop types, intensive irrigation, and inadequate water management. Because of poor water resource management, the nations that benefited most from the green revolution are currently overexploited (Bashir *et al*., 2022). The practical implications of the research findings are significant in areas where groundwater conditions are not constant. It highlights how important it is for politicians to support and encourage the adoption of efficient micro irrigation technologies, like sprinklers and drip irrigation, as these systems have the potential to help conserve precious water resources. In India's modern agricultural setting, limited landholdings and the socioeconomic status of farmers are two important challenges. Small-scale farmers account up 89.4% of farmers' landholdings, which makes it challenging for them to invest in micro irrigation technology (PIB Delhi, 2022). The increased cost of micro irrigation exacerbates the issue, especially for those who depend on rainfall yet lack access to it. While financial difficulties are meant to be alleviated by subsidies, actually using and spending the money is difficult. Affordability remains a challenge even with discounted rates, highlighting the struggles small-scale farmers face. Fordability remains an issue, highlighting the challenges small-scale producers confront. The Minimum Support Price (MSP), on the other hand, is necessary to preserve economic sustainability. To solve these problems, a comprehensive plan is required to increase the accessibility and affordability of essential agricultural technologies. It could be advantageous for administrators of water resources to create legislation and educational initiatives that ensure these systems are implemented and maintained correctly. Micro irrigation can help farmers, especially those in water-stressed areas, increase crop yields while using less water. By enhancing both agriculture and the long-term management of groundwater supplies, this approach makes everyone's future access to water more secure (Anjum, 2023).

Barriers to adoption of micro irrigation

The broad use of micro irrigation techniques, like sprinkler systems or drip irrigation, may encounter a number of obstacles. The following are typical obstacles to micro irrigation adoption: i) The initial cost of micro irrigation is a major barrier. Small-scale farms in particular would require assistance in order to purchase drip lines, emitters, filters, and control systems. ii) Widespread adoption may be restricted by the initial outlay. In order to invest in micro irrigation systems, many farmers could require additional financial resources or financing availability. iii) To ensure optimal performance, micro irrigation systems need to be maintained and operated on a regular basis. Farmers may encounter difficulties if they require additional time, finances, or skills to efficiently manage and operate their farms.iv) Farmers frequently are unaware of the benefits and inducements of microirrigation. Under the PDMC (per drop more crop) program, the government has made steps to remove all of these obstacles (Indian Government Report, 2023).

Economic considerations

Micro irrigation systems are common and extensively used because they are economical in a number of ways, similar to drip and sprinkling systems. Firstly, these technologies save water use and expenses by enabling farmers to apply water precisely. Food may be grown in regions with limited water supplies thanks to the direct delivery of water to the root zone of plants, which also conserves water (Priyan and Panchal, 2017). Additionally, micro irrigation systems provide the automation of watering procedures, reducing the associated expenses and labor required. Farms can increase their revenue by controlling water and nutrients to improve the growth and quality of their produce. In general, farmers should consider micro irrigation systems due to their financial advantages. They increase farming's productivity and profitability while assisting farmers in managing water responsibly (Singh and Sharma, 2013).

Emerging trends and innovation in micro irrigation

To improve efficiency, efficacy, and sustainability, micro irrigation has been integrated with cutting-edge trends and innovations. Many cutting-edge developments and trends are currently being seen in the micro irrigation sector with the goal of maximizing efficacy, sustainability, and efficiency. In today's agriculture, precision irrigation techniques have become a major trend. According to Suresh and Samuel (2020), this method makes use of cutting-edge technology like automation, remote sensing, and sensors to precisely monitor and control water applications in relation to crop water requirements and soil conditions. Farmers are able to maximize agricultural yields, minimize waste, and optimize water usage through the integration of this technology. Critical goals for farmers include maximizing agricultural yield, cutting waste, and reducing water usage. The use of efficient tactics and technologies is necessary to meet these goals. Precision agriculture is one such technique that has grown in popularity recently. With data-driven methods, precision agriculture helps farmers maximize crop yield, minimize waste, and manage water. Using sensors, drones, and other cutting-edge technologies, farmers may get information on temperature, moisture content in the soil, and other environmental aspects. The ideal amount of water needed for each crop is then determined by analyzing this data, which lowers waste and increases output. According to Durukkar and Poonia (2018), precision agriculture is a potential technology that can support sustainable agricultural practices while assisting farmers in achieving their goals. With the integration of cutting-edge technologies like Internet of Things (IoT) devices, data analytics, and mobile applications to enable remote monitoring and control of irrigation operations, the adoption of creative irrigation systems is increasing (Keswani *et al.,* 2019; Laphatphakkhanut *et al*., 2020; Obaideen *et al*., 2022; Anagha *et al.,* 2023). It has been discovered that putting such systems in place makes it easier for farmers to access data in real time, provides timely notifications, and gives them the power to schedule irrigation effectively. This has thus resulted in lower labor costs and more effective water utilization. This has thus resulted in lower labor costs and more effective water utilization. In addition to improving crop yields and resource efficiency, these new developments in micro irrigation show considerable potential for agriculture's sustainable use of water (Mohammed *et al.*, 2023).

Conclusion

Numerous research and case analyses are used to investigate the impact of micro irrigation on agricultural productivity and water use efficiency. Micro irrigation, which involves methods like drip and micro-sprinkler systems, is a crucial tool for precisely supplying water to plant roots, encouraging better crop yield and growth. Micro irrigation has been directly linked to increased crop productivity, as evidenced by numerous studies, with yield improvements ranging from 20% to 90%. The kind of crop, the state of the soil, and management practices are some of the variables that determine how strong this connection is. Micro irrigation is a useful technique in nations where there is a shortage of water and growing challenges due to climate change. Tight control over water distribution not only saves water but also improves nutrient uptake, cutting down on overwatering and increasing efficient water use. More case studies that highlight the intricate and nuanced effects of micro irrigation are available from locations including China, India, and the Middle East. While drip irrigation increases cotton productivity in China, there are concerns about its long-term sustainability and water-saving efficacy. In India, micro irrigation boosts profitability and production. Nevertheless, the net profits decrease when the associated costs are taken into account. In some places, the application of targeted irrigation techniques reduces runoff, which influences soil moisture dynamics. However, the problem of excessive water extraction is made worse by the use of drip irrigation in Rajasthan without groundwater legislation, emphasizing the significance of carefully crafted groundwater policies. Reductions in irrigation, fertilizer, and energy costs are associated with significant improvements in farmers' income and savings, according to an Indian NMMI study. Micro irrigation is economically beneficial, as evidenced by studies done in Egypt and the United States that show increased crop yields and improved financial advantages. To maximize the advantages of micro irrigation, the best management practices must be put into place. Key Best Management Practices (BMPs) include constant maintenance and an irrigation schedule that is in line with the unique needs of the plants and the current environmental conditions. Other BMPs include the thoughtful selection, proper spacing, and methodical positioning of emitters. Case studies attest to the strategies' ability to maximize agricultural productivity while minimizing resource consumption.

It is acknowledged that there are difficulties and limitations, like the Jevons Paradox and socioeconomic limitations. According to the Jevons Paradox, while micro irrigation may increase efficiency, the ensuing increase in demand may outweigh the goal of resource conservation. The problem of small-scale farmers not being able to afford micro irrigation because of their small landholdings and rising costs is one of the socioeconomic concerns.

The financial ramifications highlight the effectiveness of micro irrigation devices, which reduce water usage, automate tasks, and enhance total agricultural productivity. The best possible system functioning is ensured by implementing technological and maintenance standards, emphasizing the need of employing premium parts and monitoring systems. Efficiency, sustainability, and efficacy might all be increased with the help of micro irrigation innovations like precision farming, Internet of Things connectivity, and data analytics. Real-time data monitoring is made possible by these technical advancements, which also enable timely notifications and well-informed decision-making. Thus, labor costs are decreased and more efficient water management techniques are encouraged to be adopted.

The thorough analysis of micro irrigation emphasizes how important it is to advancing sustainable agriculture. Even if there are challenges and limitations, the patterns and developments that are emerging show that micro irrigation is a revolutionary force in the management of water resources, with long-term benefits that include increased crop productivity, resource efficiency, and sustainable agriculture.

Discussion

The research findings have significant practical consequences for politicians, water managers, and farmers who operate in regions with diverse groundwater conditions. Policymakers can set restrictions that are directly targeted, but water managers can build strategic plans for the sustainable use of resources. Farmers may use resources more effectively by optimizing irrigation operations with the help of our results. Effective management of water resources is encouraged by this integrated strategy, which empowers stakeholders to make informed decisions. Water managers can implement targeted conservation measures, policymakers can create more impactful regulations to improve the sustainability of water resources in a variety of geographical settings, and farmers can adopt sustainable groundwater use practices by tailoring their approaches to particular regional contexts. This study provides a thorough examination of how irrigation systems, and particularly micro irrigation systems, affect the sustainability of groundwater resources. This study looks at the several ways that groundwater resources are being depleted and how irrigation systems are making the problem worse. By means of an extensive analysis of extant literature and case studies, the paper offers valuable perspectives on the possible advantages and disadvantages of micro irrigation systems with respect to groundwater sustainability. The results of this study advance knowledge of the intricate connection between irrigation systems and groundwater supplies. They can help with policy choices that support environmentally friendly methods of managing water resources. This study focuses on the economic effects of micro irrigation, namely the advantages of increased crop output and water-use efficiency. The technological and maintenance requirements required to achieve maximum performance of micro irrigation systems are the main subject of this study. Moreover, it offers a series of suggestions meant to improve the efficiency of their deeds. One big concern is the problem of over-extraction of groundwater, which is linked to electricity subsidies. The study suggests a progressive elimination of these subsidies in order to encourage the use of sustainable water management techniques in order to address this problem. The review paper's conclusions are very valuable to scholars and decision-makers since they clarify the potential and difficulties of implementing micro irrigation systems as well as how they affect the sustainability of groundwater.

Conflict of Interest- None

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