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A Review of Sustainable Irrigation Practices and Technologies in India

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ABSTRACT

Sustainable irrigation is the intelligent use of watering plants in landscapes and agriculture to help satisfy their basic needs for survival and well-being. More than 80% of the freshwater withdrawals in the country result from irrigation, which is essential to agricultural output. However, traditional irrigation techniques have led to salinization, soil deterioration, and a shortage of water, endangering agriculture's long-term sustainability. Despite being vital to the country's economy, India's agricultural industry confronts obstacles in its pursuit of sustainable growth because of the negative effects of traditional irrigation techniques. In order to maximize resource efficiency and reduce environmental degradation, this study looks into sustainable irrigation techniques including micro-irrigation, solar-powered irrigation, and precision agriculture using AI and IoT technology. In line with the concepts of efficiency, ecological preservation, and ergonomics, the study investigates these sustainable practices in Uttar Pradesh and Punjab through primary research that includes farmer surveys and secondary data analysis. The study leads to an understanding that while addressing urgent environmental issues, sustainable irrigation techniques have enormous potential to stimulate agricultural expansion in India.

Key Words: Micro Irrigation, Sustainable Irrigation, Precision Irrigation, Solar Powered Irrigation, Uttar Pradesh, Punjab, India

LIST OF ABBREVIATIONS

1) **PMKSY** - Pradhan Mantri Krishi Sinchai Yojana
2) **ABY** - Atal Bhujal Yojana
3) **PMKUSUM** - Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan
4) **MNRE** - Ministry of New and Renewable Energy
5) **NABARD** - National Bank for Agriculture and Rural Development
6) **SPIS** - Solar-Powered Irrigation Systems
7) **UP** - Uttar Pradesh
8) **IoT** - Internet of Things
9) **EOSDA** - EOS Data Analytics
10) **PVC** - Polyvinyl Chloride
11) **LRDU** - Last Regular Drive Unit
12) **VAC** - Volts Alternating Current
13) **KW** - Kilowatt
14) **IWMI** - International Water Management Institute
15) **RBI** - Reserve Bank of India
16) **PMKSY** - Pradhan Mantri Krishi Sinchayee Yojana
17) **HKKP** - Har Khet Ko Pani
18) **GIS** - Geographic Information System

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1. INTRODUCTION

India has an extensive legacy of agricultural methods that have been inherited by successive generations. Since a large portion of Indian agriculture depends on irrigation to guarantee crop yields, irrigation is essential to the country's agricultural sector. Water shortages, soil erosion, and water pollution are just a few of the environmental and social issues that have been brought on by the adoption of unsustainable irrigation techniques and technology. In India, the use of sustainable irrigation techniques and technology has grown in popularity recently (D'Odorico et al., 2020). Sustainable irrigation techniques and technology are becoming more popular in India. Drip irrigation, sprinkler irrigation, lateral move irrigation, and centre pivot irrigation are a few amazing methods and strategies. According to Aznar-Sánchez et al. (2019), irrigation is essential for Indian agriculture since this is the main crop industry in the nation. Irrigation practices and technologies that are unsustainable have caused several environmental and social problems, including water scarcity, soil degradation, and water pollution. In recent years, there has been a surge in interest in sustainable irrigation techniques and technology in India. Some of the sustainable irrigation strategies and technologies that are gaining momentum in India (Michailidis et al., 2011). Over the years, made considerable progress in improving access to irrigation. According to Reserve Bank of India (2022a) and Reserve Bank of India (2022b), the Table 1 shows that India's net irrigated area in 1970-71 (311 Lac hectares), 1990-91 (480.2 Lac hectares), 2005-06 (608.4 Lac hectares), and 2019-20 (754.6 Lac hectares). This has increased from 311 Lac hectares in 1970-71 to 754.6 Lac hectares in 2019-20, an overall increase of 142.9%.

Table 1: India's net irrigated area (in Lac hectares)

YEAR	India's net irrigated area (in Lac hectares)
1970-71	311
1980-81	387.2
1990-91	480.2
2000-01	569.4
2005-06	608.4
2010-11	638.7
2015-16	677.7
2019-20	754.6

Source: (Reserve Bank of India, 2022)

Table 2: Sources of Irrigation and Net Area Irrigated in India

Sources of Irrigation	Net area irrigated in India (in %)
Well and tube wells	62 %
Canals	26 %
Tanks	3 %
Others	9 %

Source: (LotusArise, 2021)

The increase in net irrigated area is likely due to a number of factors, such as government policies, increased investment, changes in cropping pattern, climate change, various government schemes, like Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Per Drop More Crop (Micro Irrigation), Har Khet Ko Pani (HKKP), etc. This has increased the pressure on groundwater resources. water reserves and increased the energy required to extract simultaneously, many of the previous efficient and sustainable infrastructure, such as tanks and ponds, are becoming obsolete. Second, there is a large variety among states in terms of inexpensive irrigation accessible, based on ground water supply and the level of subsidy granted by state governments in agricultural electricity costs (Almutairi et al., 2020, pp. 17-20). The sources of irrigation and net area irrigated in India are mentioned in the Table 2, which are well and tube-wells (62%), canals (26%), tanks (3%), and others account for (9%) (LotusArise, 2022). There are also substantial differences across states in terms of the quality of energy supply, the level of the water table, and the proportions of deep wells powered by cheaper electricity and more expensive diesel pumps. In Punjab and Uttar Pradesh, for example, ground water extraction exceeds replenishable levels (Schmitt et al., 2022).

2. REVIEW OF LITERATURE

As it can be seen in Table 3, this literature review has conducted a thorough study and synthesis of the body of knowledge about sustainable irrigation methods and technology in India. Because it enables researchers to discover gaps in the present understanding of sustainable irrigation practices and technologies in India, place their own work within the larger framework of previous research, and comprehend the current level of knowledge in these areas.

Table 3: Key Findings of the Sustainable Irrigation Practices

References	Key Findings
D'Odorico et al. (2020)	- 20% of all cultivated land is on irrigated ground, although same acreage produces 40% of all agricultural output.
Sirimewan et al. (2020)	- Irrigation involves complex infrastructure projects with significant environmental implications.
Ministry of New and Renewable Energy (2022)	- The program aims to promote the use of solar energy among farmers to enhance agricultural productivity, reduce dependency on diesel pumps, and contribute to sustainable development.
Athwani & Pandey (2020)	- This research paper analyzes the trends and patterns of rainfall in Uttar Pradesh over a specific period and compares them with other states in India.
Ravindra (2021)	- Uttar Pradesh's Situation Analysis of Groundwater: A Critical Overview and Sustainable Solutions.

Shah et al. (2009)	- Small-holder irrigation is being forced out of the large and impoverished Indo-Gangetic basin due to the high cost of substitute water.
Quintana-Ashwell et al. (2020)	- Farmers are hesitant to adopt new practices due to perceived use of all viable water-saving practices.
Aznar-Sánchez et al. (2019)	- Sustainability in irrigation research is increasingly important.
Gimpel et al. (2021)	- Proposes an intelligent irrigation system for urban trees using design science research and IoT sensors.
Glória et al. (2020)	- Combines IoT, sustainability, and machine learning algorithms for more efficient irrigation procedures and resource consumption reduction.
Institute for Energy Economics and Financial Analysis (2018)	- This study looks at the potential and difficulties that come with solar-powered irrigation systems being adopted in India.

References	**Key Findings**
Ali et al. (2022)	- Describes a smart irrigation system in Pakistan that runs on solar power to cut down on water waste and solve electrical issues.
LotusArise (2022)	- Provides insights into determinants of agriculture and irrigation.
Bwambale et al. (2022)	- Examines new developments in remote sensing, GIS (Geographic Information System), and precision irrigation management.

Aznar-Sánchez et al. (2019)	- Analyzes global research on sustainable irrigation in agriculture.
Wichelns et al. (1996)	- Farmers explain irrigation costs, pointing out that labour expenses might outweigh sprinkler system water savings.
Chikabvumbwa et al. (2021)	- Conducts a geophysical investigation of dumbo groundwater reserves for sustainable irrigation in Linthipe Sub-basin.
Mitra (1997)	- Discusses irrigation management and pricing of irrigation water.
Alberts (1998)	- The Indo-Dutch Tubewell Project, which sought to encourage the use of tubewells for irrigation in Uttar Pradesh, is examined in this paper.
Rosa (2022)	- Investigates the biophysical potentials and feedbacks for using sustainable irrigation to adapt agriculture to climate change.
Garg (2018)	- Examines India's enormous potential for solar-powered irrigation.

References	**Key Findings**
Rutledge et al. (2022)	- Provides information on irrigation.
Michailidis et al. (2011)	- Investigates the adoption of sustainable irrigation practices in water-scarce areas.
Almutairi et al. (2020)	- Carries out a cost study of farms' micro-irrigation systems.
International Water Management Institute (2006)	- Promotes micro-irrigation technologies to reduce poverty.

Schmitt et al. (2022)	- Examines the global expansion of sustainable irrigation limited by water storage.
Mehta & Masdekar (2018)	- Discusses precision agriculture as a modern approach to smart farming.
Punjab Energy Development Agency (2023)	- Provides information on solar power projects related to irrigation.
Smith et al. (2010)	- Reviews precision irrigation technologies and their application.
RBI (2022)	- Discusses irrigation management for sustainable agriculture in RBI Bulletin.
Sergieieva (2022)	- Explores precision irrigation methods and their management.
Statistsa (2022)	- Presents estimated cultivation area in Uttar Pradesh in the financial year 2022 by crop type.
Yao et al. (2017)	- Describes China’s water-saving irrigation management system, its policy, implementation, and challenges.
Cline (2007)	- Estimates the impact of global warming on agriculture by country.

References	Key Findings
Bera (2015)	- Discusses a government-approved irrigation package to boost agriculture in India.
Ashraf & Jamil (2022)	- Investigates solar-powered irrigation as a nature-based solution for sustaining agricultural water management in the upper Indus Basin.
Reserve Bank of India (2022a)	- Pattern of land use and net irrigated land in India.

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In summary, a thorough literature review enables researchers to place their work in the larger context of existing knowledge, spot gaps in the field and opportunities for new research, and make sure their work advances and adds to our understanding of the subject.

3. OBJECTIVES OF THE STUDY

- To explore the sustainable irrigation process and methods and the factors responsible for the adoption of these practices.
- To study the cost-effectiveness of each of these methods and the reasons why they are sustainable
- To study the indigenous sustainable irrigation know-how.

4. RESEARCH METHODOLOGY

For Indepth anaylsis of Sustainable irrigation practices, secondary data collection method is used. The data collected in this paper is from authentic sources and is reliable. The statistical data was collected from Statista, IWMI (International Water Management Institute), website of RBI and Government of India. Government publications, articles, journals, books and company websites were used to collect data. In this study descriptive research method is being used.

For effective analysis of Sustainable Irrigation practices research papers from the late 1990s to 2023 was used.

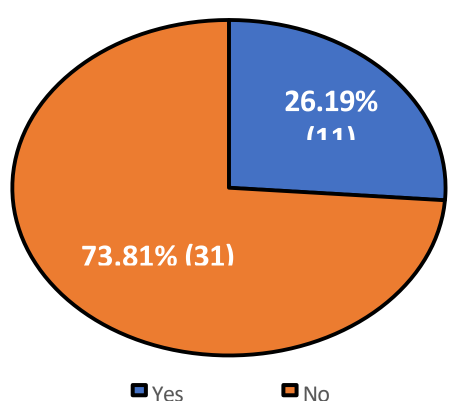
For the purpose of this study, a quantitative research approach was adopted, and data was collected through an online survey. The survey instrument was developed using Google Forms, a widely used and accessible platform for creating and distributing surveys. The sample size is 87 wherein 42 responses are from Uttar Pradesh and 45 responses are from Punjab. The survey consisted of questions, including a combination of multiple-choice, open-ended questions, etc. The questions were carefully designed to address the research objectives and gather relevant information from the participants. The survey items were informed by existing literature and theoretical frameworks related to sustainable irrigation practices and technologies in India.

5. FINDINGS AND DISCUSSION

The research includes findings and discussions of Punjab and Uttar Pradesh. This basically talks about their land holdings, climate, cropping pattern, methods of irrigation used, etc. With the help of these findings and discussions, one will get to know about the irrigation system of Punjab and Uttar Pradesh. All data will be taken from the authorized sources so that the authenticity of the research will be maintained. The key findings from the surveys through Google Forms, are as follow:

Figure 1 explicates that the pie chart shows that **26.19% (11 out of 42)** of the Uttar Pradesh population surveyed are aware of sustainable irrigation. The remaining **73.81% (31 out of 42)** are not aware of sustainable irrigation practices. This finding highlights a significant knowledge gap that may impede the adoption of resource-efficient irrigation methods, consequently hindering efforts to conserve water resources for future generations.

Figure 1: Percentage of Uttar Pradesh Population (42) who are Aware About Sustainable Irrigation



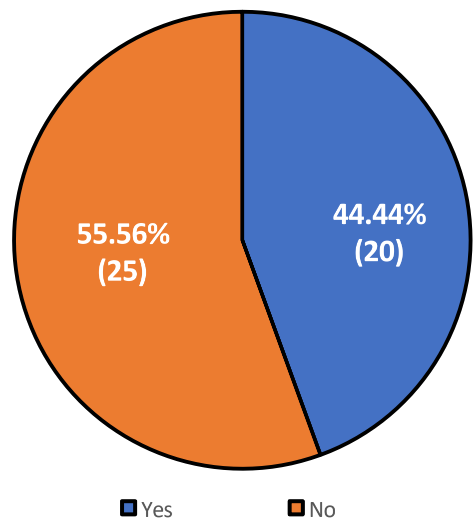
Data: Table based on primary survey

The survey results, as depicted in Figure 2, revealed that **44.44% (20)** of the respondents from the Punjab population (out of 45) and above were aware of sustainable irrigation practices. However, a significant proportion, **55.56% (25)**, indicated a lack of awareness regarding such practices. The aforementioned results highlight the necessity of focused awareness efforts and educational programmes aimed at closing the knowledge gap within this particular population.

Data: Table based on primary survey

A large portion of the population and above may not be aware of certain things due to a variety of reasons, including poor information availability, insufficient training and extension services, or reluctance to accept new technology. It is critical to acknowledge that within their homes or communities, this population frequently assumes a vital position in decision-making processes pertaining to agricultural techniques.

Figure 2: Percentage of Punjab population (45) who are aware about sustainable irrigation



The focus should be on developing awareness campaigns and educational initiatives that are specifically tailored to the requirements and preferences of this age group. Collaborations between key stakeholders, local community organizations, and agricultural extension agencies might make it easier to effectively disseminate knowledge through accessible and culturally acceptable channels.

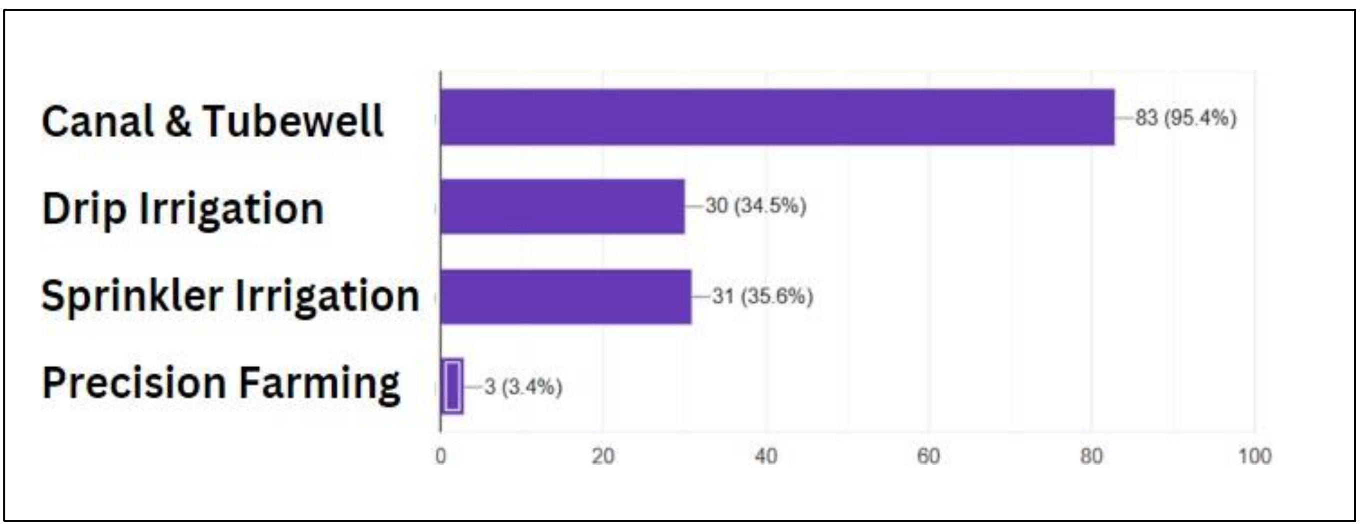


Figure 3: Different methods (or techniques) of irrigation

Data: Figure based on primary survey

Figure 3 depicts the percentage of farmers using different irrigation systems in a survey. These all numbers are out of 87 responses. The insights from the figure 3 are as follow:

- **Canal & Tubewell (Canal and Well)** is the most popular irrigation system, used by 83 farmers (**95.4%** of those surveyed). Canal irrigation involves diverting water from rivers or streams into canals for distribution to fields. Tubewell irrigation uses wells to pump groundwater for irrigation.
- **Drip Irrigation** is used by 30 farmers **(34.5%)**. Through a system of emitters and tubes, drip irrigation provides water straight to the roots of plants. Water may be saved by using this highly effective strategy.
- **Sprinkler Irrigation** is used by 31 farmers (**35.6%**). Sprinkler irrigation systems spray water onto crops through sprinklers in a way that simulates rainfall.
- **Precision Farming** is used by only 3 farmers (**3.4%**). Precision farming is an agricultural technology that uses data to manage crops and livestock. It can include using sensors to monitor soil moisture and irrigation systems that apply water only where and when it is needed.

The study arrives at the result that canal and tubewell irrigation are the most widely employed irrigation technologies in this area, despite the fact that they may not be the most water-efficient methods. Precision farming and drip irrigation, which can use less water, are used by fewer farmers. Despite having a lower water efficiency than methods like drip irrigation and precision farming, canal and tubewell irrigation are nevertheless widely used in the region. A number of variables, including infrastructure availability, historical habits, and early investment costs, can be blamed for this tendency.

5.1 IRRIGATION IN PUNJAB

Irrigation is a major factor in Punjab's agricultural production, making it one of the most agriculturally affluent states in India. Notwithstanding these initiatives, the overuse of groundwater supplies and the requirement for environmentally friendly irrigation techniques remain problems for Punjab's agricultural industry. Addressing these issues is crucial for ensuring the long-term sustainability of agriculture in the state. There are distinct parameters in which the irrigation system of Punjab has been discussed and those are as follow:

LAND HOLDINGS

With 2,933,000 hectares of forest area, Punjab has a total geographical area of 5.036 million hectares. Cultivable land covers 4.20 million hectares, or 83.4% of the total land area. 4.019 million hectares are under irrigation (26.2% through canals, 72.5% through tube wells, and 1.3% through other means) (Punjab Energy Development Agency, 2023).

CLIMATE

The north of Punjab receives an average of 1250 mm of rain annually, whereas the south-west receives 350 mm. From July through September is when the monsoon season occurs, accounting for almost 70% of the yearly precipitation. Although it might get below freezing at night, January's average temperature is 13° C (55° F) (Punjab Energy Development Agency, 2023).

CROPPING PATTERN

Punjab is one of the world's most fertile areas. It has been dubbed the "Food Basket of the Country" and the "Granary of India," supplying 40% of the nation's rice and 50% to 70% of its wheat during the past 20 years. Punjab's agriculture is extremely demanding in terms of resources, including water, fertilisers, agricultural inputs, capital, and land (Punjab Energy Development Agency, 2023).

5.2 METHODS OF IRRIGATION USED IN PUNJAB

Punjab's primary irrigation sources are canals and tube wells. Punjabi agriculture mostly grows two crops: Rabi and Kharif. Maize, cotton, rice, sugarcane, pulses, bajra, peas, jowar, and vegetables including gourds, onions, and chilies are among Punjab's Kharif crops. Almost all of Punjab's agricultural land is under-irrigated, with groundwater pumped from tube wells serving as the major supply (Punjab Energy Development Agency, 2023). Groundwater tube wells irrigated 88.3% of working property, whereas canal water irrigated only 1.7% as shown in Table 4. Nearly 10% of the operational properties in the area were watered by tube wells and canals. Despite minor discrepancies in irrigation sources throughout the three districts, canal water was available to 14.7% of farms in Amritsar, 19.5% in Jalandhar, and 18.5% in Ludhiana. 53% were near the head of the canal, 46% towards the tail, and 25% thought the canal water was insufficient for agriculture. The farmers near the canal's end were particularly hard hit (Reserve Bank of India, 2022a; Reserve Bank of India, 2022b; Statista, 2023).

Table 4: Sources of Irrigation in Punjab

Source of Irrigation	Amritsar (%)	Jalandhar (%)	Ludhiana (%)	Overall (%)
Canal	1.4	0.6	2.9	1.7
Tube well	84.1	95.2	85.8	88.3
Both	14.5	4.1	11.3	10.0
% of farmers having access to canal water	19.5	2.0	18.5	14.7

Source: (Statista, 2023)

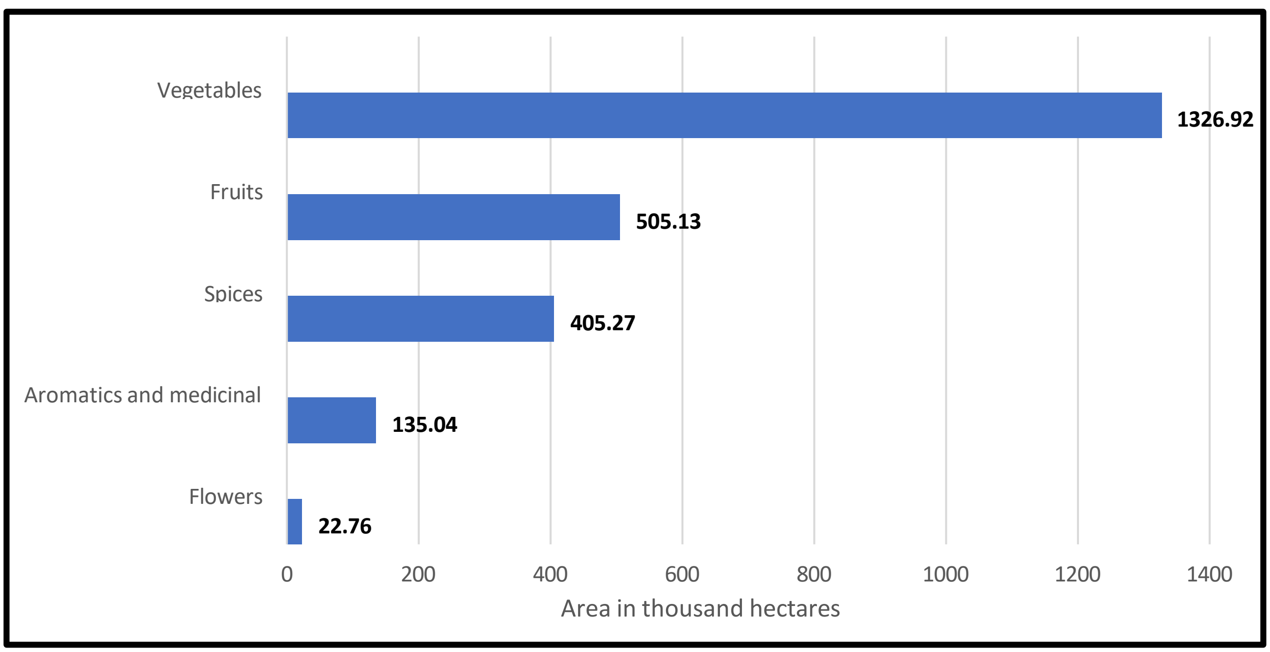
5.3 IRRIGATION IN UTTAR PRADESH

Uttar Pradesh is one of the major agricultural states in India and irrigation plays a crucial role in its agricultural productivity. The over-extraction of groundwater and inefficient use of surface water are major challenges that need to be addressed through sustainable irrigation practices and cropping pattern changes in Uttar Pradesh to ensure long-term agricultural growth. There are distinct parameters in which the irrigation system of Uttar Pradesh has been discussed and those are as follow:

AGRICULTURE LAND AREA

With 16,57,023 hectares of forest, Uttar Pradesh has a total land area of 29.44 million hectares. A net seeded area of 1,65,73,478 hectares (68.5% of the cultivable area) make up the cultivable area of 2,41,70,403 hectares (82.1% of the entire geographical area) (Statista, 2022).

Figure 4: Uttar Pradesh's estimated cultivation area in India in fiscal year 2022, by crop type (in 1,000 hectares)



Source: (Statista, 2022)

According to **Statista (2022)**, in Uttar Pradesh, the main engine of economic growth is the agriculture industry. The bulk of people residing in the state depend nearly exclusively on agriculture for their livelihood. The agriculture industry employs a significant number of people. About half of Uttar Pradesh's workforce works in agriculture, either directly or indirectly. By 2022, the state government hopes to treble farmers' earnings. The agriculture of Uttar Pradesh is incredibly varied. It yields several crops due to the comparative benefit of a broad range of agro-climatic changes. It is one of the country's largest grain-producing states. Uttar Pradesh had approximately 16.8 million hectares of agricultural land available (Alberts, 1998).

Here's a breakdown of the area occupied by different plant types as shown in Figure 4:

- **Vegetables:** This category has the largest area at 1326.92 thousand hectares.
- **Fruits:** Fruits occupy the second largest area at 505.13 thousand hectares.
- **Spices:** The area occupied by spices is 405.27 thousand hectares.
- **Aromatics and medicinal:** This category occupy 135.04 thousand hectares.
- **Flowers:** Flowers occupy the least area at 22.76 thousand hectares.

In conclusion, vegetables occupy the largest area among the five plant types included in this graph. This suggests that the land area represented by this graph is cultivated primarily for vegetable production. It is important to note that without knowing the scale of the graph or the total area it represents, it is difficult to draw any strong conclusions from this data (Statista, 2022).

CLIMATE

Uttar Pradesh has year-round warmth because to its tropical monsoon environment. The east of the state receives 40–80 inches (1,001–2,000 mm) of rain annually, while the west receives 24–40 inches (600–1,000 mm). About 90% of the rainfall is caused by the south-west monsoon, which runs from June to September. Since most of the state's rainfall occurs during those four months, flooding is a common issue there, particularly in the eastern portion of the state where it often results in fatalities as well as considerable damage to property and crops. The monsoons' cyclical failure is what causes drought conditions (Athwani & Pandey, 2020).

CROPPING PATTERN

Alluvium-derived soils, mainly khaddar (recent alluvium) and hangar (ancient alluvium), make up the soils of Agroclimatic Zone IV. Certain places have very calcareous soil. The loamy soil has a high organic matter content. Rice, maize, moong beans, and pigeon peas are popular crops during the kharif season. Remaining soil moisture is used to grow wheat, lentils, Bengal gramme, peas, sesame, and in some regions, groundnuts. One or two more irrigations are also given during the post-rainy (rabi) season. The main economic crops in the area are sugarcane, potatoes, tobacco, chillies, turmeric, and coriander, all of which require additional irrigation. The technique of rice- wheat cultivation is increasingly widely used. Softly to very gently sloping fields are the predominant soil landscapes of the northern plains. Certain places have very calcareous soil. In general, soils contain a low level of organic carbon, a neutral reaction, and a moderate clay concentration (Ravindra, 2021). Rainfed and irrigated agriculture has been the norm in agriculture. The main crops planted in the kharif season include wheat, betel gramme, green peas, rapeseed, mustard, lentil, rice, sorghum, maize, pigeon pea, pearl millet, and moong beans. The most significant cash crop is sugarcane. The technique of rice-wheat cultivation is increasingly widely used.

6. MAJOR SOURCE OF IRRIGATION IN UTTAR PRADESH

Canals were the most essential source of irrigation until the 1960s, when they were surpassed by wells and tube wells to become the second most significant method of irrigation in India. The proportion of canal irrigation area to irrigated land area in the country has decreased from approximately 39.77% in 1950-51 to 29% in 2000-01. Canals can be an efficient source of irrigation in areas with a low elevation, deep fertile soils, a constant source of water, and a large command area (Statista, 2022).

Therefore, Canals are a significant source of irrigation in Uttar Pradesh. The state is drained by perennial rivers that originate in the snow-capped Himalayan ranges and has fertile soils. However, the intensity of rain, particularly in the state's western regions, is insufficient to sustain agricultural growth. As a result, a huge number of canals have indeed been built to ensure that crops receive a consistent supply of sufficient water. Uttar Pradesh has approximately 3,091 thousand hectares under canal irrigation, accounting for 30.91 percent of the country's total canal irrigated area. Canals irrigate more than one-fourth of the state's net irrigated area (Statista, 2022). Table 5 depicts the major canals in Uttar Pradesh and the area irrigated by them are given below in the table:

Table 5: Name of The Canals and Their Area Irrigated

Serial No.	Name of the Canals	Area irrigated (in hectares)
1.	Upper Ganga Canal	7 Lac
2.	Lower Ganga Canal	4.6 Lac
3.	Sharda Canal	8 Lac
4.	Eastern Yamuna Canal	2 Lac
5.	Agra Canal	1.5 Lac
6.	Betwa Canal	1.2 Lac

Source: (Statistsa, 2022)

7. PROBLEMS FACED BY UTTAR PRADESH FARMERS IN IRRIGATION

Lack of funding for adopting sustainable irrigation is the main issue facing framers in Uttar Pradesh. Due to the inconsistent and insufficient power supply to the agricultural sector, the farmers must continue to utilise the diesel pump. The state is experiencing droughts and water shortages as a result of the careless usage of water resources (Athwani & Pandey, 2020). Flood irrigation is preferred by farmers who have access to a sufficient supply of water, as is the case with sugarcane farming. However, long-term use of this flood irrigation harms the soil, and occasionally it even has an impact on the crops. This disrupts the environment as a whole. Lack of education is a further element that is significant in the adoption of sustainable irrigation systems. The majority of these farmers are illiterate and lack the means to use these methods (Ravindra, 2021). As a result, they need to receive sufficient instruction in how to use these tactics and benefit from them in the long run. To help farmers adopt these sustainable irrigation practises, the government should develop programmes that give them access to sufficient resources and supplies of water. Corruption in Uttar Pradesh's irrigation department is another factor. The government funds allocated for the improvement of farmers are directly going into the pockets of the bureaucrats' holding positions in these departments due to their extreme corruption (Alberts, 1998).

8. SOLUTIONS FOR ADOPTING SUSTAINABLE IRRIGATION

The following recommendations are hereby put out in an effort to improve the effectiveness of Uttar Pradesh's irrigation department. The use of more sprinklers, drip irrigation, underground irrigation, and techniques to reduce salination. These are only a few examples of the new scientific irrigation technologies that are sustainable and must be increased in usage in order to improve water consumption (LotusArise, 2022). However, this necessitates intensive study and advancement in this field. Using water-saving irrigation is another approach to expand the area that is irrigated. Here, it is imperative to use as much of the water that is often drained away as waste for irrigation. The usage of irrigation water from the kitchen, drainage system, and RO plant is a well-known illustration to illustrate this idea. So that the water that is naturally accessible in the form of rain does not go to waste, water storage capacity must also be increased. Science-based water storage methods, such as rainwater collecting, can help with this. Farmers must be able to purchase solar tube well sets from the government at a reduced cost (Bwambale et al., 2022). This will lower the cost of operating tube wells that are powered by either fuel or electricity.

Additionally, strong regulations must be put in place to control theft. It is necessary to digitise the entire process for this to become a reality. The times of the water release from canals and the permitted time for irrigation should be communicated to farmers via SMS. Additionally, those caught stealing water and engaging in illicit activity must face severe punishment. In their community and surrounding places, their names must be made known. This is anticipated to put social pressure on those people. Since most illegal acts are carried out at night, there is a need to lengthen the duration and frequency of night patrols. By eliminating the corruption that exists within the irrigation department and implementing a transparent system, water usage may be maximised. Overall, there is no need for new policies, but there is a critical need for the effective execution of existing ones (Chikabvumbwa et al., 2021).

9. 3 Es OF GROWTH

The 3 Es of Growth - Ergonomics, Efficiency, and Ecology - refer to the three pillars of sustainable development that need to be balanced and optimized. By aligning irrigation practices with the 3 Es, the agricultural sector can achieve holistic sustainable growth that balances economic progress with social equity and environmental preservation. Increased farmer well-being, optimal water use efficiency, and minimized ecological degradation can collectively contribute to long-term agricultural sustainability and food security.

EFFICIENCY

Efficiency in farming is a very foremost thing since there are scarce resources in our economy and farmers are not utilizing them efficiently. If they are utilized efficiently, then there are a lot of resources (water) which could be saved so that future generation can utilize those resources in an optimal manner. In the states of India, such as, Punjab, Haryana, Uttar Pradesh, Bihar, Tamil Nadu, West Bengal, etc. They widely use canals and tube wells to irrigate their vegetation which can damage the crops and lead to soil erosion as well. Soil with an excess of water has a lower total pH. As a result, its acidity rises, and a low pH may inhibit plant growth. Over-irrigation creates an oxygen deficit in the soil near the root zone (Yao et al., 2017).

ERGONOMICS

Ergonomics plays a vital role in using today’s sustainable irrigation practices and techniques since it requires hard efforts of farmers to put in as they have to operate that techniques and practices whatever they are using to utilize their resources efficiently. Ergonomics is related to that thing, measuring of a person’s efficiency in the working environment. There are a lot of practices and techniques in sustainable irrigation farming viz., drip irrigation, sprinkle irrigation, center pivot irrigation, lateral move irrigation, etc. These all techniques require human intervention so that it can effectively operate and produce tremendous results (Glória et al., 2020). The purpose of this research is to examine farmers' historical, current, and projected behavior when it comes to adopting sustainable irrigation systems, which is a determining productivity cause, especially in water-stressed areas. More than fifty percent of total workforce in the country (India) are engaged in agriculture sector, but very few of them are utilizing their resources efficiently since they are not interested in adopting sustainable irrigation practices and techniques to improvise their farming and save a lot of resources.

ECOLOGY

According to Aznar-Sánchez et al. (2019), irrigation is the process of giving crops water through sprinklers, canals, pipelines, or other man-made channels as opposed to only relying on rainfall. In regions where rainfall is sporadic or unpredictable, irrigation is essential for agricultural purposes. In areas with unpredictable precipitation, irrigation improves agricultural growth and quality. Because irrigation allows farmers to cultivate crops on a regular schedule, it also contributes to the production of a more consistent food supply. During the 20th century, the irrigated area of the world doubled in size (Rutledge et al., 2022). Nowadays, over 18% of agriculture worldwide uses irrigation. The regions most affected by this rise include South America, Africa, and Asia. Desert ecosystems, like those in Jordan, need irrigation. Groundwater from wells and aquifers is used in Jordan for a number of irrigation techniques.

10. PRECISION IRRIGATION

Mehta & Masdekar (2018) described that Precision irrigation is a cutting-edge approach to sustainable agriculture that allows water and nutrients to be applied to plants in small, regulated doses at the right times and places to provide them the greatest growing conditions. When desired, precision irrigation delivers moisture effectively to crops in small amounts, precisely meeting their demands. When fertiliser and irrigation are coupled, this technique also supplies nutrients to plants (fertigation). Precision irrigation allows farming operations to use less water and chemical resources, which is good for both the environment and the economy (Sergieieva, 2022).

This entails giving their crops the appropriate quantity of fertiliser and water. It is crucial to have high spatial resolution data about the health or status of the crop during the growing season. Regardless of the data source, the primary objective of precision irrigation is to support farmers in managing their operations (Smith et al., 2010). Precision irrigation makes use of data from several sources to improve agricultural yields and the capital adequacy of crop management strategies, such as fertiliser inputs, irrigation management, and pesticide use.

Bwambale et al. (2022) conducted an analysis on how Internet of Things (IoT)-based technology has changed precision irrigation. Smart homes, smart grids, smart health, and smart cities are a few examples of IoT. IoT data analytics and machine learning will be employed in the agriculture sector to increase crop yield and quality in order to meet the growing demand for food. The most amazing prospects are being created by such revolutionary breakthroughs that are upending conventional agricultural approaches (Yao et al., 2017).

TECHNOLOGIES INVOLVED IN PRECISION IRRIGATION

Sergieieva (2022) outlined several technologies related to precision farming, such as EOSDA (EOS Data Analytics) crop monitoring, precision surface irrigation, precision sprinkler irrigation, precision trickle (drip) watering systems, and precision irrigation management.

(A) Precision Surface Irrigation

Water spreads across the field spontaneously and according to the rule of gravity. It is justified when soil penetration is poor even if it does not use any cutting-edge agriculture methods. Clay soils are a good fit for this precise irrigation technique, while sandy soils will make it more challenging to use. Sergieieva (2022) described the following procedures are used to apply the surface method:

- The basin technique limits the area with bunds and floods it. Long-lasting water is present there. This is a common method for cultivating rice, however wheat may also be grown in this way. With extra levelling if necessary, the procedure is used on flat terrain.

- The furrow technique entails creating furrows, which are lengthy water-filled trenches. The water drains naturally through syphon tubes or gates or through furrows that are higher than the crop rows.

- The border method provides water in the spaces between land strips. It makes use of syphons or gates, much as the prior kind.

(B) Precision Sprinkler Irrigation

Machinery or manually operated tools that can be permanently or temporarily placed, move ahead, or spin spray water through them. Depending on their guns and nozzles, sprinklers produce different pressures and sizes of droplets.
All crops are not ideal for this type of precise irrigation since large drops and strong pressure harm the plant. Pollination would be eliminated, and it would destroy flowers in blooming plants. Additionally, any insoluble particles that get lodged inside the system will render the device inoperable. Another problem is that winds have a significant impact on moisture distribution.

(C) Precision Trickle (Drip) Watering System

Precision drip irrigation is sometimes referred to as drip tape or drip line watering since moisture is distributed through small pipes that are positioned in lines. Low pressure droplets are directed to the crop itself, while the absence of water around prevents the growth of weeds. As a result, one of the key advantages of drip watering systems is that it significantly decreases the amount of water required while also preventing plant famine caused by weeds.

(D) Precision Irrigation Management With EOSDA Crop Monitoring

Dr. Max Polyakov created EOS Data Analytics (EOSDA), a global provider of AI-driven satellite imagery analyses. Accurate and trustworthy information about the current state of the field is necessary for rational and justifiable planning of precision irrigation events, as it is a precipitation forecast that will indicate the need for extra soil moisture supply. It is advised to undertake precise irrigation, that is, to water crops only when necessary, because each watering activity entails additional expenditures and too much moisture might cause more harm than benefit.

Figure 5: Forecast market value of precision agriculture worldwide from 2021 to 2025 (in billion U.S. dollars)

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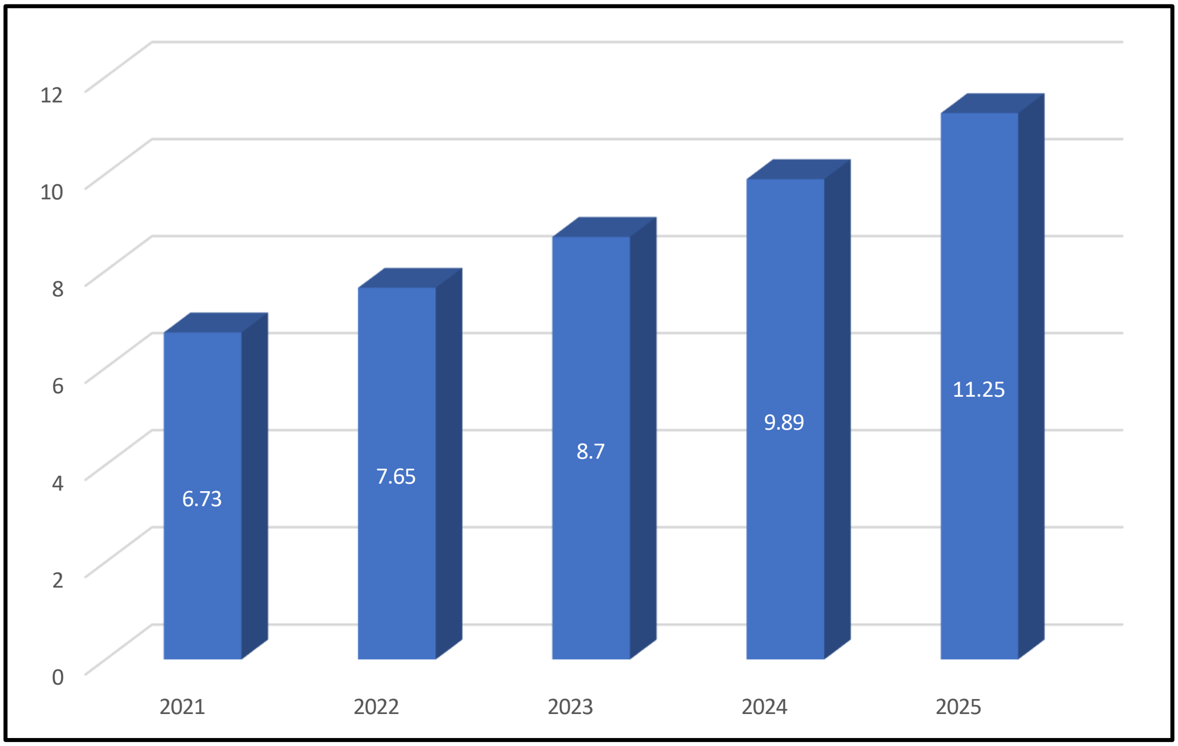


Source: (Statista, 2023)

From the above Figure 5, it can be analyzed that in 2021, the forecasted market value of precision farming was 6.73%, in 2022, it was 7.65%, in 2023, it is projected to rise to 8.7%. Precision farming's market growth is projected to rise from around 6.73 billion dollars in 2021 to 11.25 billion dollars by 2025 (Shahbandeh, 2023). This suggests that the precision farming is going to rise in the future as year-by-year the market value is increasing which ultimately helps farmers to enhance their crop productivity and efficient management of the crop production system. This also helps in better irrigation management system which ultimately helps in saving the resources (water) for the future generations so that they can utilize the resources efficiently and with the best of their requirement.

11. MICRO-IRRIGATION TECHNIQUES

According to a research by International Water Management Institute (2006), micro-irrigation technologies (along with costing in Table 6) are one such approach that can use water more effectively in irrigated agriculture. They are frequently used in water-scarce areas of developed countries. These innovations can boost family food security, increase crop yields and outputs, and increase productivity. Many studies have demonstrated the benefits of adopting micro-irrigation, and a number of public and private groups are actively promoting the technologies. There are distinct techniques which are as follow:

(A) Drip Irrigation:

Applying little amounts of fertiliser and water on a regular basis to a designated area is known as drip irrigation. Since fertiliser and water are delivered straight to the crop root zone, runoff, evaporation, and drift are minimized. Drip irrigation systems that are well-planned and maintained provide the highest uniformity and application efficiency, saving farmers time, effort, and water while increasing yields. The cost of drip irrigation for crops grown in a 6X6 pattern is around Rs. 35,000 per acre. In India, drip irrigation now costs around $1,412 per acre, as Table 6 (Almutairi, et al., 2020) illustrates.

Pros:

- Reduces nutrient losses from leaching.
- Helps conserve water by reducing evaporation.
- Land grading is not necessary.
- May be applied in unconventional domains.

Cons:

- The method cannot be used with water containing high iron content due to clogged emitters.
- System maintenance is necessary to keep it running.
- Insects and rodents chewing on tubing can cause leaks.
- Tubing can be sliced by mowers and trimmers.

(B) Sprinkler Irrigation:

The technique of simulating rainfall using irrigation water is known as sprinkler irrigation. One method for moving water via a system of pipes is pumping. The entire soil surface is then irrigated by spraying it into the air, which causes tiny water droplets to fall to the ground. Spray heads are used for this purpose. Sprinklers cover small to large areas efficiently and are perfect for use on all types of farms. It is also adaptable to practically all types of irrigable soils because sprinklers come in a variety of discharge capabilities. For an acre of land, as seen in Table 6, sprinkler irrigation kits cost about Rs 19,000 each. There is a sprinkler cost of Rs. 3,500 per head and an installation cost of $187.5 per acre (including the installation of three-inch PVC (Polyvinyl Chloride) main pipe and riser pipe). One acre can be irrigated within one hour and fifteen minutes (Dennis, et al., 1996).

Pros:

- It grows well on soils with medium and coarse textures.
- Watering it costs little (less than 0.1 acres-inches).
- Middle pivot constructions may be set to start and stop at specific angles or times.
- Fertigation and chemigation are methods that inject chemical compounds into irrigation water for the purpose of controlling pests or providing plant nutrients.

Cons:

- Center pivot tires can cause deep ruts on clay soils.
- Frequent sprays may be required to replenish crop-depleted soil.
- Poor quality water can clog sprinkler nozzles.
- Crop leaves can become scalded.

(C) Center Pivot Irrigation

Most of the machine's operations are managed by the pivot's control panel. The pivot will function in the same manner regardless of the control panel that it is equipped with, however the controls will vary. Once a command is typed into the control panel, an electrical signal is routed down the pivot until it reaches the Last Regular Drive Unit. 480 VAC, or voltage-alternating current, is sent from the tower box to the engine via a motor lead line. The Last Regular Drive Unit (LRDU) moves in either direction, depending on what the control panel indicates. According to specifications, Table 6 shows that a Centre Pivot irrigation system may be purchased and installed at about $712 per acre (Almutairi, et al., 2020).

Advantages:

- Water is directed to areas of the farm where it is most needed using the centre pivot irrigation system. This lessens the likelihood of erosion and runoff. Additionally, this kind of irrigation system ensures that the earth absorbs the water.
- The typical lifespan of a centre pivot is twenty years. A centre pivot irrigation system is unlikely to need to be replaced for at least 20 years. This has the potential to significantly reduce agricultural operating costs.

- The use of a central pivot enables for the application of nutrients to plants via Fertigation. Fertigation may drastically improve crop output.

Disadvantages:

- The cost of purchasing a centre pivot irrigation system is usually high. A single centre pivot in Nigeria might set you back as much as N30 million.
- Just like an electric motor, the centre pivot needs electricity to function. A centre pivot irrigation system might be expensive due to its high KW (kilowatt) consumption.
- One very advanced type of irrigation system is the centre pivot system. Acquiring the technical expertise needed to operate the centre pivot might prove to be challenging.

(D) Lateral Move Irrigation

Similar to the centre pivot irrigation system, the linear move irrigation system (also called lateral move) has moving towers and pipe spans linking the towers. The main difference is that every tower moves at the same speed and in the same direction. Water is injected into one of the ends or the centre. Water may be supplied to the linear system by connecting and disconnecting from hydrants or by dragging a supply hose that is attached to a main line across the field. Table 6 illustrates the approximate cost per acre for the delivery and installation of a lateral move irrigation system (Wichelns, D., et al., 1996).

Advantages:

- To satisfy agricultural water requirements, the systems may deliver a fixed amount of water. Surface runoff and groundwater recharge are less likely if the system is designed to match soil infiltration characteristics.
- Generally speaking, manpower requirements for surface irrigation are higher; however, this might vary depending on the system and/or level of machine automation.
- Fertigation makes it possible to supply precise doses of nutrients with high consistency and little risk of nutrient loss. The irrigation system may also be used to apply pesticides and herbicides.

Disadvantages:

- In comparison to surface irrigation systems, the systems have a relatively high capital cost unless extensive land shaping is required for optimal surface system performance.
- In order to prevent silt accumulation in the system, water may need to be filtered before use. Irrigation infrastructure might have a shorter lifespan due to poor water quality.
- These systems will require different expertise than surface irrigation systems to operate and maintain.

Table 6: Micro-Irrigation Techniques and their costs

	MICRO-IRRIGATION TECHNIQUES	COST (per acre)
1)	Drip Irrigation	$1,412
2)	Sprinkler Irrigation	$187.5
3)	Center Pivot Irrigation	$712.54
4)	Lateral Move Irrigation	$1000 - $2000

Source: (Wichelns et al., 1996); (Almutairi et al., 2020)

12. SOLAR POWERED IRRIGATION

According to Institute for Energy Economics and Financial Analysis (2018), it delineates that the solar-powered irrigation is generation of electricity from solar panels. All the three aspects of sustainability are catered i.e., Economic, Social, Environmental. The prudent use of water because of subsidized electricity provided to the farmers affects all the three aspects. To reduce this effect and help India maintain emission levels, solar-powered irrigation policies and practices can be followed, as seen in Figure 6.

Figure 6: Advantages of Solar-Powered Pumps in Place of Conventional Pumps

Additional power generated with 3-horsepower solar pumps	**66.8 GW**
Percentage of government renewable energy (RE) target of 175 GW by 2022 (Solar target of 100 GW)	38.1% (66.8%)
Reduction of coal use annually	141 million tonnes
Reduction of diesel use annually	4 billion litres
Fuel cost savings – coal[7]	INR 105 billion per year (US$1.5 billion)
Fuel cost savings – diesel	INR 272 billion per year (US$3.9 billion)
Agriculture electricity government subsidy savings	INR 228 billion per year (US$3.3 billion)
Cross electricity subsidy savings	INR 300 billion per year (US$4.3 billion)
Forex savings – reduction of coal import	INR 479 billion per year (US$6.9 billion)
Forex savings – reduction of oil import	INR 400 billion per year (US$5.8 billion)
CO2 emission reduction from reduction in use of coal	52.5 million tonnes
CO2 emission reduction from reduction in use of diesel	224 million tonnes

Source: (Institute for Energy Economics and Financial Analysis, 2018)

India's farmers have access to a more affordable and environmentally friendly option for meeting their irrigation needs: Solar-Powered Irrigation Systems (SPIS). The application of SPIS has significantly increased agricultural output and water usage efficiency in states like Uttar Pradesh (UP) and Punjab, where agriculture is the main driver of the economy (Garg, 2018).

The government of Uttar Pradesh has initiated the "Solar Powered Irrigation Pumps Scheme" to encourage farmers to utilize SPIS. Farmers that participate in this programme receive fuel-free solar-powered pumps that run on renewable energy. As a result, farmers are now less reliant on diesel-powered pumps, which has decreased fuel expenses significantly.

Similar to this, the Punjab government has encouraged farmers to use SPIS by introducing the "Punjab Agriculture Export Promotion Solar Scheme". Farmers who install solar panels and pumps can get incentives from this programme, which has increased the uptake of solar-powered irrigation systems (Punjab Energy Development Agency, 2023).

Using SPIS is an environmentally friendly option since it has not only helped farmers save money on irrigation, but it has also significantly decreased carbon emissions. Furthermore, increased crop yields and enhanced agricultural production have resulted from the provision of a consistent and dependable electricity supply (Schmitt et al., 2022).

In conclusion, the agriculture industry has seen a radical transformation with the introduction of solar-powered irrigation systems in areas like Punjab and Uttar Pradesh. In addition to giving farmers an affordable and sustainable irrigation option, it has helped the nation get closer to its goals of sustainable development and food security.

Advantages:

- The environmental impact will be less as compared to the electricity generated from coal and other fossil fuels.
- The surplus power that farmers have can be given out to the distribution companies (DISCOMs) which will help farmers diversify and expand their income.
- The globally acceptable emission levels will be maintained easily if shifted to solar- powered irrigation.

Disadvantages:

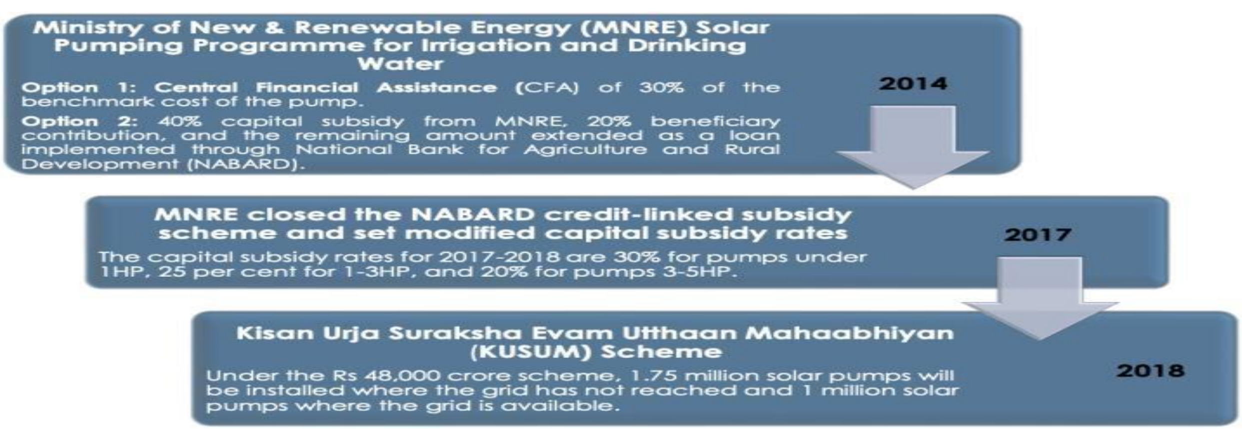
- Farmers may be discouraged from switching to solar due to a lack of knowledge about the advantages of solar and inadequate after-maintenance support. They will continue to use less effective, non-sustainable watering methods.
- Due of their high setup costs, solar-powered irrigation systems presented a significant hurdle.
- In order to overcome the various obstacles preventing the broad use of solar-powered irrigation systems, a significant amount of area is needed to set up solar panels.

13. GOVERNMENT INITIATIVES

The Indian government has launched programmes like the Pradhan Mantri Krishi Sinchai Yojana (PMKSY), the Atal Bhujal Yojana (ABY), the Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PMKUSUM), and the Micro Irrigation Fund, as shown in Figure 7 (Pradhan Mantri Krishi Sinchayee Yojana, 2022) to promote sustainable irrigation practices and technologies throughout the nation.

These schemes seek to raise farmers' earnings, promote water efficiency, and guarantee that future generations have access to clean water.Solar-powered irrigation systems are becoming a practical and ecologically friendly alternative to traditional irrigation methods. The Indian government has started a variety of initiatives to promote the use of solar-powered irrigation technology by farmers. In this article, it will discuss some of the most significant rules relating to solar-powered irrigation.
Garg (2018) states that the Ministry of New and Renewable Energy (MNRE) launched the Solar Pumping Programme in 2014 to promote the usage of solar-powered irrigation pumps. The plan aims to construct one million solar pumps by 2021. Under the project, the government provides a subsidy that can amount to as much as 30% of the benchmark cost of the solar pumping equipment. Thanks to the project, thousands of farmers around the country now have access to consistent and fairly priced irrigation. However, the MNRE ended the NABARD credit scheme in 2017 due to a lack of transparency about the allocation of subsidies. Previous releases from NABARD and MNRE said that the latter would give a 50% subsidy while the former would cover 30% of the cost of the solar-powered irrigation system. Farmers' concern about the exact amount of the subsidy they would get caused a delay in the installation of solar-powered irrigation equipment (National Bank for Agriculture and Rural Development, 2016).

Figure 7: Schemes Supporting Solar-Powered Irrigation



Source: (Ministry of New and Renewable Energy, 2022)

The Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PMKUSUM) was created in 2019 to promote the use of renewable energy for irrigation. By 2022, 25,750 MW of solar energy will be installed for agricultural usage as part of the programme. In order to prevent animals from getting near their crops, farmers can construct solar-powered pumps, fences, and cold storage units as part of the initiative (Ministry of New and Renewable Energy, 2022).

To conclude, the Indian government has started a variety of initiatives to persuade farmers to employ solar-powered irrigation technology. These rules aim to promote environmentally friendly farming practices, reduce dependency on groundwater, and improve irrigation system performance. The MNRE Solar Pumping Programme (2014), the Pradhan Mantri Krishi Sinchai Yojana (PMKSY), the Atal Bhujal Yojana (ABY), the Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PMKUSUM), and the MNRE closing the NABARD credit scheme due to unclear subsidy allocation are a few of the significant government initiatives pertaining to solar- powered irrigation (Pradhan Mantri Krishi Sinchayee Yojana, 2022).

14. USAGE AND COSTING

Examining the costs and application of sustainable irrigation systems can provide valuable insights into the current state of affairs and highlight the advantages as well as the drawbacks of using these approaches. In the end, by offering focused strategies to support the widespread adoption of these sustainable practices by policymakers, agricultural extension services, and other stakeholders, this information can aid in the efficient management of water resources and the long-term sustainability of agriculture.

Sergieieva (2022) illustrates how these contemporary technologies are used and priced. These technologies are essential to sustainable irrigation practices and technologies, but most farmers in Punjab and Uttar Pradesh may find it challenging to put these strategies into practice because they own small or marginal holdings that prevent them from installing these strategies on their land. In addition, farmers are not given enough direction or mentoring, which makes it harder for them to use and maintain these contemporary methods and procedures.

Table 7: Usage and costing of distinct methods of sustainable irrigation.

STATUS OF SUSTAINABLE IRRIGATION PRACTICES IN INDIA			
	Precision Surface Irrigation	**Micro-Irrigation Techniques**	**Solar- Powered Irrigation**
Total Irrigated land	140.13 Million Hectares	140.13 Million Hectares	140.13 Million Hectares
Percentage of land using	10.013 Million Hectares	12.90 Million Hectares	16.95 Million Hectares
Cost of cultivation/Ha	Rs. 1,50,000 – Rs. 3,00,000	Rs. 1,00,000 – Rs. 2,00,000	Rs. 4,00,000 – Rs. 5,00,000

Source: (Agriculture Industry Market Reports, 2022)

Furthermore, the cost of irrigation using flood irrigation **Rs. 42,653**. That is why the farmers do not adopt the modern technologies since there is a cost factor which restrict the farmers to implement those techniques as there is lack of guidance and support regarding the operation and maintaining of these techniqiues. As illustrated in Table 7, Bera et al. (2015) have analyzed that the total irrigated land in precision surface irrigation is 140.13 million hectares, in micro-irrigation techniques is 140.13 million hectares, and in solar-powered irrigation is also same as 140.13 million hectares. In the 2020-21, the net irrigated area is 68.6 million hectares. The percentage of land using in precision surface irrigation is 10.013 million hectares, in micro-irrigation technique is 12.90 million hectares, and in solar-powered irrigation is 16.95 million hectares. Talking about the cost factor of each technique, the cost of cultivation per hectare in precision surface irrigation is Rs. 1,50,000 to Rs. 3,00,000, in micro-irrigation technique, it is Rs. 1,00,000 to Rs. 1,20,000, and in solar powered irrigation, it is Rs. 4,00,000 to Rs. 5,00,000, as illustrated in Table 7 (Ashraf & Jamil, 2022). Costing is one of the main concern of the farmers of the Uttar Pradesh and Punjab due to which they are unable to afford the modern techniques and they are continuing with their farming in the traditional way, such as flood irrigation, canal, tubewells, etc. This will lead to excess use of the natural resources (water) due to which future generation will suffer since they will not have the adequate amount of resources to use or to utilize. That's why it is necessary to provide them with the right mentorship regarding the modern technologies viz., operations of the modern techniques or machnines, systematic use of the machines, proper maintenance of the machines, etc. By doing this, Gradually, farmers will get to know how to operate those modern techniques and how to use them efficiently and effectively (International Water Management Institute, 2006).

15. CONCLUSION

Irrigation systems are designed and maintained in a way that maximises crop water utilisation while reducing waste. Precision irrigation, micro-irrigation, and solar-powered irrigation are modern methods that can help significantly minimise water waste while enhancing agriculture productivity (Ali et al., 2022). The 3 E's of growth—Ergonomics, Efficiency, and Ecology—assist in raising knowledge of sustainable irrigation practises in addition to this. With the purpose of promoting India's economy's sustainable growth, the government has implemented a variety of initiatives and provided farmers with subsidies (LotusArise, 2022). The Indian government has also developed programmes like the Micro Irrigation Fund, Atal Bhujal Yojana, Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan, and Pradhan Mantri Krishi Sinchai Yojana to encourage sustainable irrigation practises and technology throughout the nation. These programmes are designed to raise farmers' income, promote water usage efficiency, and assure water supply for future generations (Gimpel et al., 2021). This will aid in disseminating awareness of government subsidy programmes to encourage farmers to adopt better techniques, better maintenance support for farmers after irrigation systems are installed, and education and training programmes for irrigation system operators will encourage the adoption of sustainable irrigation practices and enhance water management. In the end, this helps to ensure that the resources are used as efficiently as possible with the use of technology and appropriate farmer mentoring. The majority of farmers in Punjab and Uttar Pradesh find it difficult to put these strategies into practise since they have tiny and marginal holdings, which hinders them from doing so on their agricultural land. Utilization and cost analysis of these contemporary technologies are therefore crucial to developing sustainable irrigation practises and technology (Rosa, 2022). In conclusion, the high cost associated with modern irrigation techniques such as precision surface irrigation, micro- irrigation, and solar-powered irrigation has hindered their widespread adoption among farmers. Due to the high expense of these technologies and the dearth of assistance and knowledge regarding their use and upkeep, farmers in Punjab and Uttar Pradesh are still using antiquated techniques including tubewells, flood irrigation, and canal irrigation. Regrettably, this dependence on traditional methods leads to an overuse of natural resources, especially water, raising worries about potential shortages in future generations. Giving farmers the required guidance and instruction on how to utilise and maintain contemporary technology is essential to resolving this problem (Michailidis et al., 2011). Farmers may maximise the efficiency and usefulness of these approaches in agricultural activities by progressively adopting them and receiving knowledge on their operations and methodical utilisation. In addition to encouraging sustainable resource management, this strategy will provide farmers the tools they need to increase production and advance the agricultural industry as a whole. In states like Uttar Pradesh (UP) and Punjab, the use of solar-powered irrigation systems (SPIS) has shown to be a viable and economical way to meet farmers' demands for irrigation. Farmers have been encouraged to embrace SPIS by the development of programmes like the "Punjab Agriculture Export Promotion Solar Scheme" in Punjab and the "Solar Powered Irrigation Pumps Scheme" in Uttar Pradesh, which offer solar- powered irrigation pumps and financial incentives for solar panel installation. Significant fuel cost reductions have resulted from this move away from diesel-powered pumps and towards renewable energy (Reserve Bank of India, 2022a; Punjab Energy Development Agency, 2023; Sergieieva, 2022; Quintana-Ashwell et al., 2020). Furthermore, because SPIS provides a consistent and dependable power source, it has not only reduced the carbon emissions linked to irrigation but also raised crop yields and enhanced agricultural production (Cline, 2007). In addition to providing farmers with financial benefits, the implementation of SPIS has helped the nation achieve its goals of sustainable development and food security. Overall, solar-powered irrigation systems have emerged as a game-changer for the agriculture sector in Uttar Pradesh and Punjab, providing farmers with an environmentally sustainable solution for irrigation (Shah et al., 2009).

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