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Tracking the Green Irrigation Technologies in Agricultural Sectors for Sustainable Groundwater Conservation.

[1]**Dr. Pulak Dey**
Assistant Professor, Department of Chemistry, Sukanta Mahavidyalaya, Dhupguri, Jalpaiguri, Mail Id: pulakchem24@gmail.com

Abstract: Agriculture is responsible for about 70% of worldwide freshwater usage, making sustainable water management essential for both food security and environmental protection. Irrigation efficiency in the field of agriculture acts as central role to sustainable water management. As population growth, changes the underground water-level toward depleted, irrigation systems have changed significantly in terms of technology and structure. This article explores the history of modern irrigation technologies, focusing on how they help save water in farming communities. The study starts with the shift from traditional surface irrigation to mechanized and pressurized systems. It examines important technological milestones such as sprinkler irrigation, drip and subsurface irrigation, automation, sensor-based control, and digital irrigation platforms in account of water use efficiency. It addresses to evaluate methods for water conservation, enhancements in efficiency, and sustainable management approaches. Significant results demonstrate that contemporary irrigation technologies can lower water usage by 36-61% while also boosting crop yields by 12-49%. In addition to technological advancements; the document explores the socio-economic factors, policy structures, and environmental consequences that have influenced the progress of irrigation across various regions. It also highlights future directions such as climate-adaptive irrigation, improved precision technologies, and complete watershed management approaches. However, technological progress alone is not enough to ensure sustainability. Integrated water governance, institutional reform, and building farmer capacity are essential for turning efficiency gains into long-term water conservation.

Keywords: Irrigation systems, water conservation, sustainable agriculture, precision irrigation, drip irrigation, smart irrigation, water management, agricultural technology.

INTRODUCTION

Irrigation is the process of applying water to soil, primarily to meet the water needs of growing plants. Water from rivers, reservoirs, lakes, or aquifers is pumped or flows by gravity through pipes, canals, ditches or even natural streams. Applying water to fields enhances the magnitude, quality and reliability of crop production. The lack of water in the soil impairs the correct plant development and its excess can reduce root respiration, affect the root growth to plant productivity of plant (Bhattacharya. A., 2021). Soil water is balanced by irrigation involves applying the right amount of water at the right time to maintain optimal soil moisture for crop growth. Soil moisture ensures the healthy growth of the roots and the overall development of the plant (Paul, et al. 1944). Irrigation decisions in agriculture depend on how much water the crop of a particular species requires and how much water is available from local sources. Effective irrigation replenishes moisture lost by evapotranspiration (Viets, F.G., (1966) avoids water stress, and prevents losses from runoff and deep drainage. According to irrigation efficiency (Israelsen, O.W., 1950) the dimensionless ratio of the irrigation water consumed by the crops of an irrigated farm or supplied by an irrigation system to the water diverted from a river or other natural water source into the irrigation system. Good soil-water management (Bouwer. H., (2000) & Gusev et al. 2007) leads to healthier crops, higher yields, and efficient water use and also active involvement in controlling soil water content for long-term sustainability. Endeavors to maintain soil water balance in agriculture have a long tradition and have been performed in many parts of the world with irrigation. At its core Irrigation is a strategy that allows for stable food production even in dry or unpredictable climates by overcoming the limitations of natural rainfall.

Irrigation has played a central role in the rise and development of human civilization. In ancient times, irrigation transformed agriculture from simple rain-fed farming to controlled water management with using canals, basins, wells, and terraces, early societies could grow enough food to support large populations, form cities, and develop the foundations of civilization (Roux, G., 1992). The irrigation schemes of the Mesopotamian plain are a well-documented example in ancient time (Kuiper, K., 2010 & Manish, D., 2011). Its history begins in the world's earliest agricultural societies, where controlling water meant controlling survival. Around 6000–3000 BCE, farmers in Mesopotamia created some of the first organized irrigation systems by diverting the Tigris and Euphrates Rivers through canals and basins. Similar early innovations appeared along the Nile in Egypt, where basin irrigation captured seasonal floodwaters, and in the Indus Valley, which developed carefully planned canals and reservoirs (Larry, W. M. 2010). Almost of agriculture were done by irrigation system which was surface irrigation. These systems allowed communities to grow surplus food, supporting population growth and urbanization. The impact of irrigation extends beyond farming: It has contributed to the development of complex societies and influenced settlement patterns, and it continues to be crucial in modern economics and environmental management.

The development of civilizations led to the advancement of irrigation methods. Advanced technology has had a profound influence on human population growth. Throughout history, technological progress has consistently enabled societies to support larger populations by improving food production, health, economic opportunities and living conditions such as environmental sustainability. In the 20th century the Industrial Revolution changed agriculture by introducing machines, improving transportation, promoting scientific methods, and increasing productivity (Joel, M., 1998 & Mohajan, H., 2019). These changes allowed farmers to produce more food with less labor, supported population growth, and helped build the foundation of modern industrial societies. Global agriculture has steadily produced impressive increases in crop yield. The Industrial Revolution transformed traditional irrigation system to modern/Green irrigation system like sprinkler irrigation, drip irrigation, smart irrigation through mechanical pumps, dams, and pressurized systems (Vibeke, et al., 2010). In the 20th century, technologies like sprinkler and center-pivot irrigation spread globally, and the invention of drip irrigation dramatically increased water efficiency to higher production. Agriculture by use of irrigation allowed communities to grow surplus food by providing a reliable water source for crops, enabling larger harvests and food storage. Surplus food supported population growth and freed people to take on specialized roles, which led to economic complexity and the rise of towns and cities.

Efficient use of water resources in the agricultural sector has been a great concern of water managers around the world (IFAD, 2014, Peasants et al. 2021 & Iván, 2018). Proper water management to agriculture balances human needs with environmental sustainability. World is much concern today on water crisis problem (Jury et al., 2007, Debaere et al. 2017, & WEF., 2019) by huge population through exceeding the planetary carrying capacity as there was in the days immediately prior to the water management revolution. The reason for the concern is that the global population has vaulted upward to 6.5 billion in 2006, and for some time has been increasing at a rate which outpaces gains in food production. The best current population forecasts are that the world will have 7.9 billion people by 2025 and 9.2 billion by 2050 (WEF., 2019). World population growth and economic development increase competition for water and exacerbate waters scarcity- and drought-related losses, resulting in the identification of water crises as the greatest global societal threat (Burek., et al. 2016 & G.O.I., 2013). Over-extraction from underground water due to excessive pumping by irrigation, often driven by unregulated agricultural practices and increasing water demands, has led to a decline in water resources. Unconscious irrigation practice in agriculture sector by farmers for high crop productivity to intensified the stress on groundwater resources. As resulted today the global have gotten another big problem on Ground water depletion (Ananda, et al., 2020, Chindarkar., et al., 2019 & Mukherjee., et al., 2016).Groundwater over-extraction is a major concern in agriculture, especially in regions relying on tube wells and pumps. Sustainable water requirement ensures that water is used wisely and responsibly to meet human, agricultural, industrial, and environmental needs without harming future availability. It is essential for long-term water security, food production, ecosystem health, and overall societal well-being. Changing irrigation systems can reduce water use, recharge aquifers, and ensure long-term water sustainability**.** By switching from flood irrigation to drip and sprinkler systems, carefully scheduling irrigation, harvesting rainwater, and managing crops wisely, groundwater depletion can be slowed. These changes make agriculture more sustainable, ensuring water availability for future generations while maintaining crop productivity. For several decades, various water conserving technologies have been studied in order to significantly increase water use efficiency (WUE) and Water Productivity (WP) are used to ensure support sustainable agricultural water management(Zhou et al., 2021, Vincent et al., 2012 & Kambou, et al., 2014). Efficiency improvements in agricultural water management for sustainable development of ground water are aimed at conserving water tend to be formulated in two ways: (1) by increasing allocative efficiency through water conservation policies (WCPs) (Pigou et al., 1932 & Knapp et al., 1992) and (2) by increasing physical irrigation efficiency through water conservation technologies (WCTs) (Molden, et al., 1997).This paper showed that sustainable development of irrigation system in cultivation in order to contribute water saving practices on the field. Irrigation water conservation technologies have been categorized starting from surface irrigation to modern irrigation technology for minimizing the groundwater depletion by water saving concern.

2. Globally Shifting to Green Irrigation:

Earth is a planet with 71% of its surface covered by water, of which 68% of this fresh water. 0.3% of the worlds freshwater are contained by lakes and rivers (El-Ghonemy, A., 2012). In addition to these two available main freshwater sources; groundwater is another huge potential freshwater source for human survival (Wada, et al., 2010). About 2.5 billion people depend on this ground water source only to satisfy the requirement of their fresh water (Shaji, et al., 2021). Globally, the largest abstractor and predominant consumer of groundwater resources, is agriculture sector (Siebert, et al., 2010). An estimated 70% of all global groundwater use goes to irrigated farms (Siebert, et al., 2010 & Misstear, et al., 2017). Nature Conservancy, also state that in some arid countries, agricultural use can be as high as 90% of groundwater use (Wada, Y. et al. 2010).For example, agriculture consumes the largest share of groundwater in India - the biggest user of groundwater in the world (Minderhoud, et al., 2017 & Singh. Et al., 2018). According to (Misstear, D et al. 2017), above 70% of the groundwater is used to agriculture through irrigation and India, China and USA are the major leading countries in use of this water source. While almost half of the agricultural area cultivating food grains in India depends on irrigation, as high as 65 percent of these irrigated land holdings depend on groundwater to meet their water needs (Bahinipati, et al., 2019). India is one of those countries. It uses 30% of the world's irrigated land and consumes the largest volume of groundwater in the world, but its water is becoming harder to access (Soumendra, N. B., et al., 2017 & Goldin, 2016).On the other hand, day to day enhancing world population is big serious issued to compensate the food demand. According to the United Nations World Water Development Report, the ability of a population to provide sustainable access to sufficient amounts of water of acceptable quality is already in jeopardy for many, and the situation is expected to worsen over the coming decades (Alberto, B et al., 2019). The lack of clean water is a significant problem in the 7.7 billion-person globe of today. By 2050, when there will be between 9.4 and 10.2 billion people on the planet—a 22–34% increase—the water system will be under more stress (UNWWD, 2018). Increasing population is leading to increase in demand of food and as well as demand of agriculture. As know that agriculture uses a considerable portion of the ground water, we can say that the demand of water is increasing contentiously with the demand of food. Therefore, huge change of water withdrawal is expected to come due to the stated changes of living style and population. Excessive groundwater withdrawals can cause groundwater levels to decline and environmental degradation. The annual withdrawal of freshwater in the world has been found increasing(UNESCO, 1999 & FAO, 2016) . This withdrawal of freshwater in the world has increased from 3790 (in 1995) to 4430 (in 2000) and is expected to reach 5240 (in 2025) in kilometer cube.(UNESCO, 1999).

According to sustainable development, to saving earth groundwater many developed countries has been changed conventional irrigation practice for reduce the ground water consumption. Irrigation is not inherently sustainable, but water-saving micro-irrigation systems as green irrigation system like modern, efficient drip or subsurface irrigation technologies make it one of the best tools for sustainable groundwater management (Sara S. F., et. al., 2022). Therefore Irrigation can be a sustainable technology for groundwater management — but only when it's used efficiently and with proper techniques. Simply saying "irrigation is the best sustainable technology for groundwater" isn't entirely accurate, because some irrigation methods can waste water and even deplete groundwater reserves. Therefore, by providing the proper amount of water directly to plant roots, sophisticated irrigation technologies like drip irrigation, sprinkler systems, and smart irrigation scheduling assist farmers in using water more effectively. In order to benefits of Groundwater Sustainability, green irrigation system is to be more essential Instead of traditional or poorly managed irrigation (like flood irrigation) due to sustainable of green irrigation in the following point as (1). *Efficient water use*: Reduces wastage and minimizes over-extraction of groundwater (2). *Recharge management*: Combining irrigation with groundwater recharge systems (like recharge pits or check dams) helps replenish aquifers (3). *Crop-water matching*: Modern irrigation systems allow farmers to grow crops suited to local water availability (4). *Monitoring and automation*: Sensors and IoT-based irrigation systems optimize water use in real-time (Levidow, L., et al., 2014). The researchers observed that, a sustainable transition to a less water-intensive in agriculture by regulating the irrigation system that will help in conserving water and also been linked to an increase in the yield of crops. For this situation green revelation on irrigation technique in cultivation field is highly necessary to fulfillment of water requirement of plant roots to keeping with higher cultivation production by minimizing the wastage of ground water and it significantly minimized the ground Water Depletion. Farmers are aware of the current and the upcoming competition for water so they know that the adoption of efficient irrigation systems is beneficial for them.

3. Traditional and Ancient Irrigation Technology:

Surface irrigation methods: Irrigation has been integral to agriculture since ancient times. This section explores the historical evolution of irrigation practices, beginning with early civilizations in Mesopotamia, Egypt, and the Indus Valley. It highlights the use of basic methods like flood irrigation along the Nile River, the development of sophisticated canal systems in ancient Persia, and the terraced farming of the Inca civilization. Different type of surface irrigation is explained in (**Figure. 1**) (Raveendra, K. R., 2017). Surface irrigation technology one of the earliest and simplest forms of irrigation was performed in ancient time (Larry W. M., 2010). It refers to as traditional yet evolving method of applying water to crops by allowing it to flow over the soil surface under the influence of gravity. It's one of the oldest and most common irrigation techniques in the world, especially in regions where water is relatively abundant and land is relatively flat. Surface irrigation is a method where water is distributed across agricultural fields by flowing over the soil surface. Unlike pressurized systems (like sprinklers or drip irrigation), surface irrigation relies on gravity flow rather than mechanical pumps to distribute water. Surface irrigation is the traditional water application method in the world. About 84% of the world uses the surface irrigation method to irrigate the crops (FAO., 2011 & USDA, 2019). This can be accomplished by flooding the entire field at once (basin irrigation), putting water into small channels (furrows), or flooding the land surface strips (borders) until the entire field is covered.

Surface irrigation depends mainly on surface water sources like rivers, canals, lakes and reservoirs. It requires large volumes of water because of natural losses, making it less efficient but still practical in regions with abundant surface water and gravity-fed systems. The availability of surface water in any system at any given time depends on many factors, that is storage capacity of lakes, wetlands and artificial reservoirs, soil type and local surface and soil evaporation rates. In water-short and low-rainfall regions of the Middle East, Northern Africa and Central Asia, most of the exploitable water is already withdrawn, with 90% of that going to agriculture. Therefore, the rivers and aquifers of these regions have been depleted beyond sustainable levels (Oweis, T., 2018). Even today, many regions around the world (Cui, Z.J., 2019) still depend heavily on surface irrigation — especially where traditional farming, canal systems, and gravity-fed water distribution are dominant. Regions like South Asia, East Asia, the Middle East, North Africa, and parts of Africa and Latin America still depend on surface irrigation because it's affordable, traditional, and supported by large river and canal systems, even though it is less efficient than modern methods (Jagermeyr, J., 2015). Surface irrigation became the most popular irrigation method historically and still remains widely used today — for several practical and socio-economic reasons. Historically, civilizations developed along rivers and floodplains (e.g., Nile, Indus, Tigris-Euphrates). These areas naturally favored gravity-fed water distribution, so surface irrigation evolved organically. Farmers can construct and maintain systems without needing complex equipment or technical skills (Wang, C. et al., 2021).

Despite its extensive application, surface irrigation is often criticized for its low efficiency with uses of large volumes of water, even when crops need much less water. Excessive withdrawals from rivers and canals reduce water available for ecosystems, wildlife, and communities downstream. Surface irrigation methods, such as flood and furrow irrigation, are generally considered inefficient compared to modern methods like drip or sprinkler irrigation and consequently result in the significant wastage of fresh water. It is estimated that 40 to 50% or more of the water applied can be lost at the field level (Fadul, E., et al., 2020). Unconstructed water in surface irrigation technologies, like flood irrigation, contribute to groundwater depletion through high water loss due to evaporation (Fuentes, et al., 2020 & Yin et al., 2020), seepage, and runoff (Wang, Z.H., 2019). This non-uniform irrigation stresses crops and lowers productivity (Salmerón,Y.F., 2012). These methods require high water volumes that exceed natural replenishment rates, and the wasted water puts extra pressure on already stressed aquifers, especially when combined with excessive pumping for irrigation. Surface irrigation is not sustainable today (Oster, J.D., 2006). due to significant water waste and associated environmental problems such **as** soil degradation**,** increases pollution, and cannot adapt to modern climate and efficiency demands. In arid areas, agricultural production was limited by water validity, it is very important to use the production systems to accelerate water-use efficiency and improve the grain yield (Ma et al., 2020).As a result of the water-saving campaign in recent years, many water-saving irrigation techniques have been researched to replace traditional flooded irrigation to achieve high water-efficient as well as eco-friendly irrigation in crop production.

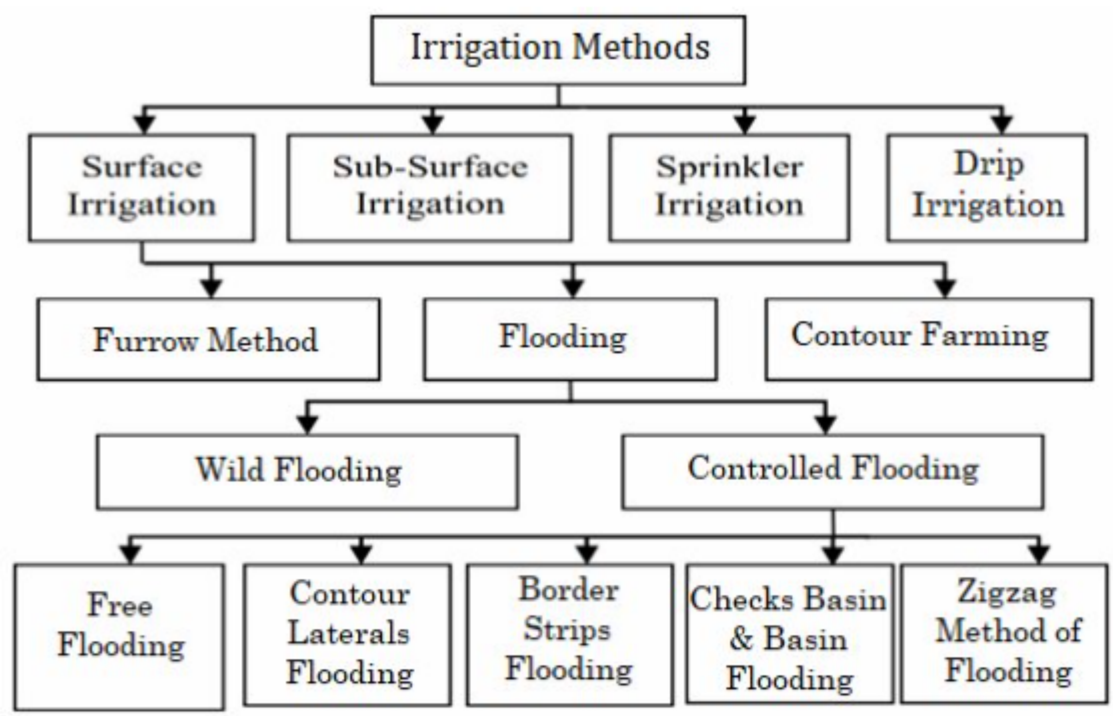

Figure 1. Various type of irrigation technology (Raveendra, K. R., 2017),

4. Ground Water Depletion by Conventional Irrigation System (Surface, Flood Sprinker Irrigation):

Groundwater depletion is mostly caused by excessive water extraction for ineffective and inappropri ate traditional irrigation techniques in the agricultural sector. For many important agricultural production areas, groundwater will remain the ultimate source of freshwater when surface water sources have been depleted. Traditional irrigation method (e.g., flood irrigation**,** furrow irrigation**,** or basin irrigation) uses river water or canal water, but in many regions, farmers pump groundwater to supply surface irrigation when surface sources are unavailable (Scanlon, et al. 2012).The aquifers that host groundwater are the primary buffers against drought for both human requirements, and crop production. In many concentrations of intensive agriculture, groundwater offers reliability and flexibility in access to water that irrigation canals can hardly match. Additionally, groundwater is generally less prone to pollution than surface water. Like India, Pakistan, and parts of the U.S., millions of tube wells draw groundwater continuously for surface irrigation, stressing aquifers (Bierkens, 2019). In agriculture sector, used of groundwater through surface irrigation is a major cause of groundwater depletion. In humid regions, groundwater recharge is likely to exceed groundwater withdrawals such that groundwater discharge contributes significantly to river flows (the base flow component). In semi-arid and arid regions, high water withdrawals are required by the agricultural sector as it takes advantage of long growing seasons, high insulation and low pest and disease risk. Generally, the rates of groundwater recharge in these semi-arid and arid regions are low such that, in the absence of alternative sources of water, groundwater withdrawals can exceed aquifer recharge and can result in depletion. Aquifer depletion has been reported for many semi-arid and arid regions world-wide and can be attributed to agricultural withdrawals (Ahmed and Umar, 2009; Foster and Loucks, 2006; Guzman-Soria et al., 2009; Konikow and Kendy, 2005; Rodell et al., 2009; Scanlon et al., 2007; Shah et al., 2007).

Asoka et al. (2017) reported an in situ well observation-based decline of up to 25 cm/yr in northern India for 1996–2013 while GRACE observation indicates an overall decline of 2 cm/yr for 2002–2013. (Janardhanan et al. 2023) reported a median decline in GW levels in the Ganges Basin of 2.6 cm/yr based on in situ well measurements (1996–2017) and a GW storage anomaly trend of 1.7 cm/yr from GRACE data (2003–2016).To sustain crop production, farmers increasingly rely on groundwater pumping, by conventional flood irrigation often extracting water faster than natural recharge can replenish aquifers. This imbalance has caused declining groundwater levels in many areas of the Ganga Basin in india. According to the study (Dangar, et al., 2021) improper flood irrigation practices are a major cause of groundwater depletion in north-western India, particularly in Punjab, Haryana, and Rajasthan by cultivated water-intensive crops such as rice, sugarcane. This method applies more water than crops require, resulting in significant losses through evaporation, runoff, and inefficient field application rather than productive crop use. As groundwater tables continue to decline, farmers must pump water from greater depths, increasing both energy consumption and irrigation costs. This trend threatens agricultural productivity, rural livelihoods, and long-term water security. Using data from the Gravity Recovery and Climate Experiment (GRACE) satellites, the authors found that the region lost approximately 109 km³ of groundwater between 2002 and 2008. The study (Rodell, et al., 2019) concluded that this decline was primarily caused by excessive groundwater extraction for agricultural irrigation rather than changes in climate or natural recharge. To address on more than 324 million people in China's second-largest basin, the Yellow River Basin (YRB), rely primarily on groundwater. In the YRB, where a sizable portion of water consumption depends on groundwater, including 24.8% of drinking water and 61.6% of irrigation water, water shortages constitute a serious danger to sustainable development and ecosystem stability (YRCC, 2022 & Yin, et al., 2017). The YRB's groundwater removal grew from 1.43 km³ in 1965 to 3.69 km³ in 2016, with irrigated fields and highly inhabited areas experiencing the most extraction (Huang et al., 2023). Along with the degradation of shallow-rooted plants, it has also contributed to a 0.5–3.0 m regional drop in groundwater levels.

According to water scarcity effect, the 2018 edition of the United Nations World Water Development Report stated that nearly 6 billion peoples will suffer from clean water scarcity by 2050 (WWAS, 2018). It has provided an update on the present trends of clean water availability and future expectations. Water security, the capacity of a population to safeguard sustainable access to adequate quantities of water of acceptable quality, is already at risk for many, and the situation will become worse in the next few decades (Burek, 2016). Clean water scarcity is a major issue in today's' world of 7.7 billion people. The strain on the water system will grow by 2050 when the world population will reach between 9.4 and 10.2 billion, a 22 to 34% increase. To sustainable the water for future generations most needed to adopt advanced irrigation technologies in population and agriculture demand.

5. Modernizing the Conventional Irrigation Technology into Green Irrigation (Drip Irrigation):

The modernization in irrigation is the process of replacing ageing irrigation infrastructure and methods, often with new or "modern" equipment and technologies that have been developed in the recent past. The aims of irrigation modernization include water saving and improved water delivery, and lower operating and labour expenses, which leads to sustainable agricultural production and enhanced livelihoods of farmers (Plusquellec, 2009). Researchers were interested in irrigation optimization from 1970 to 1985 because of the introduction of intelligent monitoring systems and water limitations for irrigation. Water usage efficiency and information were introduced in the late 1970s when water demand began to rise with population growth and natural resource depletion. Since then, WUE has become a key indicator for evaluating irrigation performance and improving agricultural sustainability (Doorenbos, et al., 1979 & Michael, et al., 2005).The scenario necessitated the improvement of the irrigation technique as important of Water Crises issue in achieving more advance. The modernization of irrigation systems is primarily reshaping irrigation practices by replacing traditional surface irrigation (e.g., flood irrigation) with modern pressurized systems such as drip irrigation.

In general, there are two types of irrigation techniques: (1) Pressure-driven irrigation (modern techniques) and (2) Gravity-driven irrigation (traditional techniques) (Bwambale, et al., 2022). It is well known that farmers using gravity-driven techniques administer the same amount of irrigation water throughout the farm, ignoring crop water requirements and field variations in favor of applying consistent irrigation water throughout the property (Sherpa, et al., 2021). Furthermore, the gravity-driven approach supplies water without the use of pumps or external pressure. It depends only on the water speed or the slope of the field. However, the pressure-driven system uses pumps or external pressure rather than gravity to supply water. Pressure-driven systems boost crop yield and produce higher efficiency to proper utilizing the water than gravity-driven methods. Furthermore, compared to gravity-driven techniques, pressure-driven devices can save more water (Fereres, et al., 2003). They might also increase the likelihood of an uneven distribution of water. This inconsistent water distribution may cause crops to experience unwelcome water stress. Conversely, pressure-driven systems are incredibly water-efficient methods that don't damage soil, plants, or the environment. The significance of pressure-driven systems has been previously shown in numerous researches (Singhal, et al., 2019). These solutions are better than gravity-driven methods for conserving irrigation water.

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The story of modern irrigation begins in a place where water scarcity drove innovation. In 1960s Israel, when Simcha Blass and his son Yeshayahu tested the first plastic drip emitter, they sparked a revolution in agricultural water management (Tal, A. et al., 2006). The transition from traditional irrigation systems, such as flood irrigation, Surface Irrigation**,** and sprinkler irrigation to modern ones, like drip irrigation, is often seen as a panacea to improve irrigation efficiency and address water shortages. The modernization of irrigation systems is primarily reshaping irrigation practices by replacing traditional surface irrigation (e.g., flood irrigation) with modern pressurized systems such as drip irrigation (Jin, et al., 2018 & Vandern et al., 2013). Drip irrigation is sometimes called trickle irrigation and involves dripping water onto the soil at very low rates (2-20 litres/hour) from a system of small diameter plastic pipes fitted with outlets called emitters or drippers (Van D., 1989)**.** Water is applied close to plants so that only part of the soil in which the roots grow is wetted, unlike surface and sprinkler irrigation, which involves wetting the whole soil profile. With drip irrigation water, applications are more frequent (usually every 1-3 days) than with other methods and this provides a very favorable high moisture level in the soil in which plants can flourish (Venot, et al., 2017). The widespread diffusion of drip irrigation can be attributed to its effectiveness in reducing water losses and improving water productivity, which in turn contributes to higher crop yields. A drip irrigation system that is properly planned and operated has an irrigation efficiency of about 85-90%, in contrast to the surface irrigation method with 40% (Narayanamoorthy, 2009). Furthermore, showed that surface flood irrigation, micro-spray irrigation, and furrow irrigation all produced lower vegetable yields in the root zone than did alternate subsurface drip irrigation(Huang, et al., 2010 & Zhang, et al., 2013).In addition to distributing air and water via drip irrigation systems, they also maintain the emitters' functionality and modify the soil ecosystems in the crop root zone via a variety of biochemical and biophysical processes (Zhu, et al., 2020 ; Zhu, et al., 2019 & Bhattarai, et al., 2005). Also by supplying water-soluble fertilizers straight to the root zone and lowering nutrient leaching, volatilization, and surface runoff, drip irrigation dramatically improves Nutrient Use Efficiency (NUE), frequently by more than 30% [Haoure]. Compared to conventional irrigation, this tailored application (fertigation) enables accurate, stage-specific nutrient management, enhancing crop yield, quality, and overall resource-use efficiency. Moreover, modernization processes extend beyond biophysical impacts: they can reshape water governance and use, alter the patterns of energy use required for water application, and affect farmers' income, labor demand as well as other socio–economic factors (Sese-Minguez, et al., 2017).

6. Automation the System into Advance Smart Technology:

The automation of irrigation systems as Precision/smart irrigation is the use of equipment that allows the irrigation process to proceed with minimum human involvement, except for periodic inspections, routine maintenance and water-saving systems (Haoru. Et.al., 2020). After 1989, when the Internet became available to the general public, it sparked the development of control systems based on the internet and web-based data storage. The internet-based monitoring, remote control systems and web-enabled data management ware began to integrated into irrigation systems. These technologies enabled real-time monitoring of soil moisture, weather conditions, and irrigation scheduling, laying the foundation for modern smart irrigation and precision agriculture (Evans, et al., 2009 & Kim, et al., 2008). Ground water Conservation management and irrigation efficiency requires the use of IoT, AI, cloud computing, and edge computing. In order to improve crop quality and identify diseases in insects and plants, technologies like Internet of Things (IoT), Geographic

Information Systems (GIS), Global Positioning System (GPS) devices, and artificial intelligence (AI) –based crop and soil monitoring, data analysis using artificial intelligence to make appropriate decisions, automated irrigation systems, and weather measurement and prediction to deliver the right amount of water to crops at the right time and place are in high demand .This results in increased crop efficiency with a significant reduction in farmers' reliance on human labor. Sensors and Internet of Things devices can be used to monitor the plant field. Edge computing collects sensor data in the field and transmits it to the cloud, where it is processed and examined to identify the optimal course of action.

Advanced Precision/smart Irrigation Technologies (Kumar, A., et al 2019)can enhance irrigation efficiency, especially with the introduction of wireless communication systems, monitoring devices, such as real-time irrigation scheduling, IoT, the importance of an internet connection, smart sensing, and energy harvesting for efficient irrigation scheduling that benefitted water to crops with high accuracy based on real-time data and crop productivity. The technology effectively combines wireless communication capabilities with a number of sensors to offer remote monitoring and automatic irrigation control (Kumar, A., et al., 2017). Significant water conservation potential while preserving crop health and productivity is confirmed by experimental results.

This maximize irrigation efficiency technology is appropriate for small, residential landscapes as well as large, managed landscapes and potentially reduce outdoor water consumption. The core component of a smart irrigation system is the irrigation controller, (**Figure 2**.).This automates irrigation scheduling based on real-time data. Different types of controllers are used depending on the complexity of the irrigation system and crop requirements, like Time-Based Controllers, Soil Moisture Sensor-Based Controllers, Weather-Based Controllers (Evapotranspiration Controllers), IoT-Based Smart Controllers. Artificial Intelligence (AI)-Based Controllers and Variable Rate Irrigation (VRI) Controllers etc(Cardenas et al., 2010 & Mayer et al., 2010). Their integration with digital agriculture technologies supports sustainable water resource management and helps address global challenges related to food security and climate change. These irrigation technologies have become more popular among farmers in recent years as a solution to the growing problems of water shortages, climate change, increased production costs, and diminishing groundwater supplier (Khaled, et al. 2022). Conventional irrigation techniques frequently administer water evenly over fields without taking into account changes in soil moisture, crop water requirements, or weather conditions. This leads to large water losses through deep percolation, runoff, and evaporation. By administering the appropriate amount of water at the appropriate time and location, precision irrigation improves irrigation efficiency and conserves water, overcoming these constraints. Farmers can also monitor and manage irrigation remotely using smart phones or computers, reducing labor requirements and improving operational efficiency.

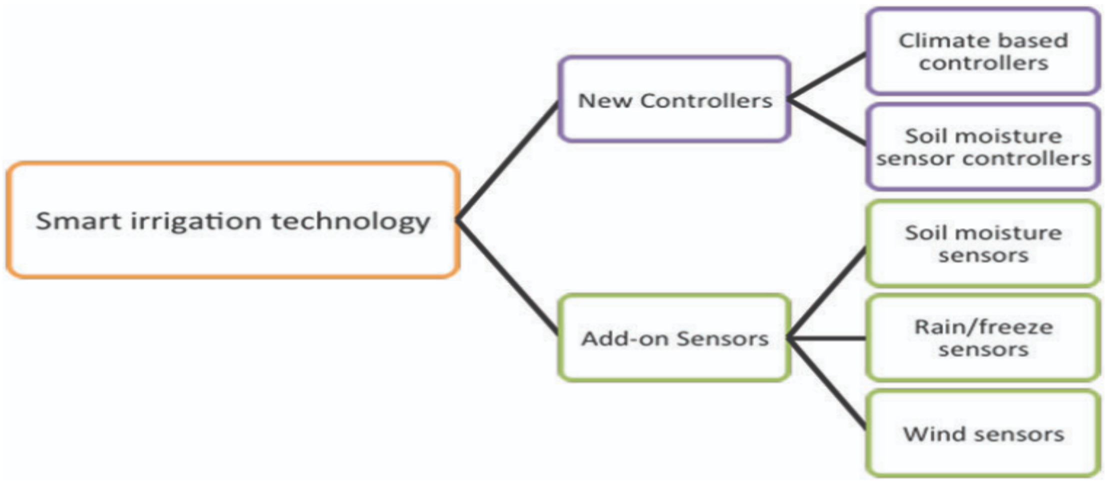

Figure 2. Different types of controllers of Smart irrigation.

7. Water Conservation Strategies Embedded in modern/smart Irrigation system:

Advancing the Irrigation technique to increase Water Use Efficiency (WUE),is widely recognized as a key indicator of water conservation and sustainable groundwater management in agriculture.WUE shows how well irrigation water is transformed into crop output, even though it does not evaluate groundwater depletion directly. A greater WUE reduces groundwater abstraction and contributes to aquifer resource conservation since less water is needed to achieve the same yield.

Water use efficiency (WUE) (Wang et al., 2018) usually is defined as the total dry matter produced by plants per unit of water used,

$WUE=D/W$,

where *D* is the mass of dry matter produced (usually aboveground) and *W* is the mass of water used (usually including direct evaporation from the soil). Sometimes, the *D* is the economically valuable part of the crop (for example the grain, tuber, or fruit) and *WUE* refers to yield and it can also be defined as the rate of photosynthesis over transpiration (Gao et al., 2019). The higher the production per unit of water use, the higher the efficiency. In irrigated agriculture, WUE serves as an indicator of how efficiently available water resources are utilized and how much irrigation water can be conserved without compromising crop productivity (Howell, 2001). The efficiencies of conventional irrigation techniques, such as flood, basin, and furrow irrigation, are typically only 30–50% of water pumping. Surface runoff, evaporation, and deep percolation outside of the crop root zone all result in significant water loss. Ground water depletion is accelerated as a result of farmers pumping more groundwater than crops actually need (FAO, 2017). Improving WUE through Efficient watering technology such as drip irrigation or sprinkler systems to deliver water directly to plant roots substantially reduces irrigation water demand. This minimizes water loss through evaporation and runoff, potentially reducing water consumption by plant to booting WUE. By supplying water directly to the crop root zone, drip irrigation usually achieves application efficiencies of 85–95%. The overall amount of groundwater that has to be retrieved drastically decreases as a greater percentage of the applied water is utilized by plants. In order to increasing water use efficiency in agriculture through development of green irrigation system keeping in mind for improving the lower land and water productivity (by providing more quantity of water) to cropping system. Thus, the lower water use efficiency is the challenge in way for sustainable agriculture and could be improved by adopting modern irrigation technologies. Drip irrigation can save 20–60% of irrigation water while preserving or even raising agricultural yields, according to numerous researches (Postel et al., 2001; Narayanamoorthy, 2004). Water-use efficiency can therefore be considered an indirect indicator of groundwater conservation. Conventional irrigation method lowering the WUE indicates **(Table 1.)** inefficient water use, greater irrigation demand, and a higher likelihood of groundwater depletion. Higher Water-Use Efficiency → Lower Irrigation Water Requirement → Reduced Groundwater Pumping → Improved Aquifer Sustainability.

According to S.R. Evett, et al.,(2007) drip irrigation significantly improves water use efficiency (WUE) and crop productivity compared with conventional furrow irrigation in Uzbekistan. Under the optimum irrigation scheduling regime of 70–70–60% of field capacity (FC), irrigation WUE increased by 71%, while seed cotton yield improved by 14% compared with furrow irrigation. On average, 32% less irrigation water was required under drip irrigation over three growing seasons, demonstrating its superior water-saving potential. These findings indicate that drip irrigation can achieve higher yields while conserving scarce water resources, making it a sustainable irrigation practice. The agronomic benefits are substantial, further economic analysis is recommended to evaluate the long-term financial feasibility of large-scale conversion from furrow to drip irrigation. Another study demonstrated that water-use efficiency (WUE) was significantly affected by both the cropping system and irrigation method. Intercropping elephant foot yam with green gram achieved higher WUE than sole elephant foot yam cultivation due to better utilization of available water and enhanced overall productivity. Among the irrigation methods, drip irrigation outperformed conventional surface irrigation by providing precise water application, which increased corm yield while reducing water losses (Nedunchezhiyan,M et al., 2018 , 2017). This research demonstration that, WUE further improved as the rate of water application decreased under drip irrigation, indicating the benefits of optimized irrigation scheduling. The interaction between cropping system and irrigation level was significant, with the elephant foot yam–green gram intercropping system under drip irrigation at 60% cumulative pan evaporation (CPE) recording the highest water-use efficiency, highlighting its potential as a sustainable water-saving agricultural practice. In an investigation by Fan et al.& Arafa et al. (Fan J. et al., 2022 & Arafa, Y.E.,et al., 2009) conducted a field experiment on two irrigation methods were sprinkler irrigation method: solid set sprinkler irrigation system and drip irrigation method: surface and subsurface drip irrigation systems, founded that, the water productivity of pepper cultivation grown with drip irrigation achieved its maximum and outperformed those grown with micro-sprinkler irrigation by a substantial margin. The observation revealed that water use efficiency and water saving had been enhancement with about 43.13 and 76%, respectively, when using drip irrigation systems.

Table 1. Advantage of modernization irrigation technology:

Irrigation System	**Water-Use Efficiency / Water Productivity**	**Major Advantages**	**Research References**
Surface (Flood/Basin)	Low	Simple and inexpensive but high runoff, evaporation, and deep percolation losses.	Howell (2001); FAO (2017); Nair et al. (2013)
Furrow Irrigation	Moderate	Better than flood irrigation but still experiences significant seepage and runoff losses	Bjorneberg et al.; Camp (1998);
Surface Drip Irrigation	High	Delivers water directly to the root zone, reducing evaporation and runoff	Martínez & Reca (2014); Camp (1998
Subsurface Drip Irrigation (SDI	Very High	Minimizes soil evaporation, improves root-zone moisture, and increases crop water productivity	Ayars et al. (1999); Global Meta-analysis (2022
Smart Irrigation (IoT/Sensor/AI-based Drip)	Excellent	Real-time irrigation scheduling based on soil moisture and weather data further improves WUE	Mourad, B.,et al., (2022).

In the country of China's water supply from underground has drastically decreased, thus since 1996, the central government has given approximately 5 billion in loans year in an effort to increase water use efficiency (Xue et al., 2018). Irrigation is the main cause of groundwater depletion in this country Yellow River Basin (YRB) regions; water-use efficiency is usually below 0.6, suggesting a significant potential for water savings of more than 40% (Han et al., 2021, YRCC, 2022). These monies are designated to help agricultural infra structure development, with a special focus on projects such as water-saving irrigation systems and well drilling particularly installing effective drip irrigation and micro- system in agriculture. These innovations can guarantee more efficient groundwater resource conservation, achieved sustainable water management and optimize water use.

A research paper in Science highlighted , increased local beneficial water consumption due to a higher irrigation efficiency must be completely countered by a decrease in nonbeneficial water consumption, recoverable return flows (to surface or groundwater), and nonrecoverable flows to sinks in order to maintain conservation of mass. Because of decreased soil evaporation (5% for drip and 20% for surface), a greater IE (generally 90% for drip versus 50% for surface) is linked to lower rates of nonbeneficial water consumption **(Figure 3.).** These modifications from a higher IE also lead to a decrease in return flows, which go from 30% of the water used for surface irrigation to 5% for drip irrigation (Grafton et al., 2018).The authors' assessment of potential values the paradox of water inflows and outflows and irrigation efficiency (surface, sprinkler, and drip) for crop transpiration, evaporation, runoff, and recharge ranges. Also (Xiong, R. et al. 2021) demonstrated that the paradox of irrigation efficiency: drip irrigation provides higher field-scale irrigation efficiency by delivering water directly to the crop root zone, thereby minimizing evaporation, runoff, and deep percolation losses. Their integrated basin-scale modeling showed that drip irrigation increases the proportion of applied water that is beneficially used by crops, leading to improved crop water productivity and reduced non-beneficial water losses. However, the study also emphasized that higher field-scale efficiency does not necessarily translate into basin-scale water savings because reduced return flows and expansion of irrigated land may offset the water conserved at the field level. Therefore, the authors concluded that while drip irrigation is highly efficient for individual farms, its regional water-saving benefits depend on integrated basin-scale water management and policy.

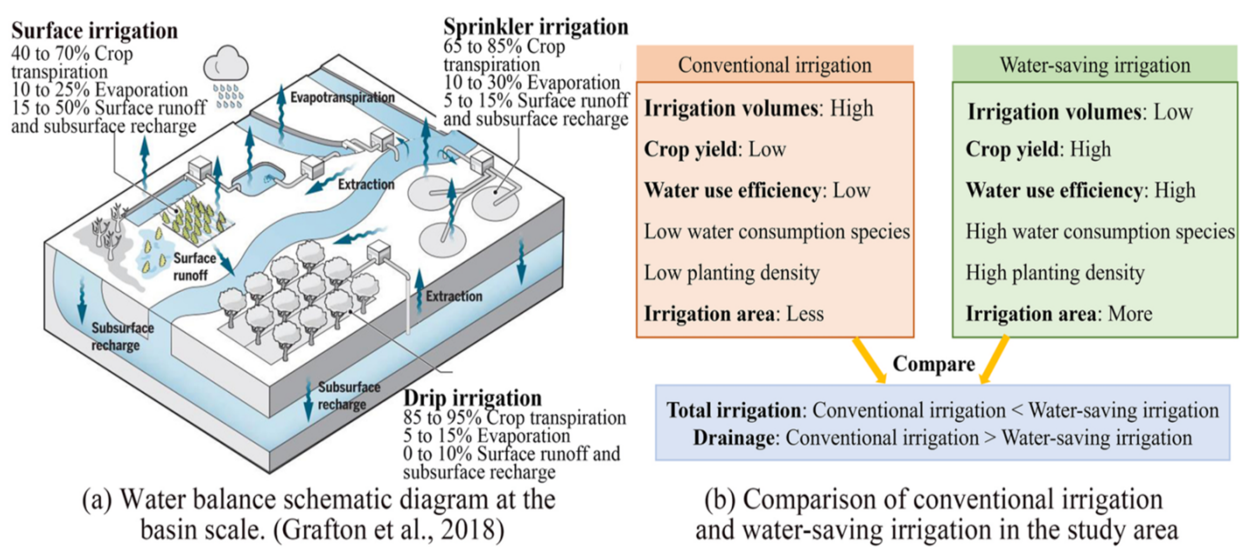

Figure 3. Irrigation Efficiency (a) Water Distribution under the surface , Sprinker and Drip Irrigation (Grafton et al., 2018) (b) Paradox of Irrigation Efficiency

Water use efficiency(WUE), crop production, and environmental sustainability are all being revolutionized by recent advanced level developments Smart irrigation technology in agricultural, such as precision irrigation (Singh, et al 2019 & Misra et al., 2020) sensor-based automation (Vij, A., et al., 2020) and data-driven decision-making (Abioye, E. A. et al., 2020). These systems automatically adjust irrigation timing and volume according to soil moisture status and climatic conditions. In order to optimize irrigation techniques, this management uses a variety of sensors to track plant and soil conditions also as evapotranspiration(Abioye, E. A. et al., 2020 & Vera J, et al., 2021). The thing that all of these systems have in common is that they show that smart irrigation is better than conventional irrigation in terms of efficiency and timeliness(Wu, C.L., et al., 2020 & Zhu, X.Y., et al., 2018). This strategy is essential to attaining sustainable and effective water use and is a component of the larger area of precision agriculture with reducing groundwater depletion. By dynamically adjusting water distribution (especially for ground water conservation), these intelligent irrigation systems ensure ideal plant growth while preserving resources. Developing effective water-saving irrigation requires further advancements in agricultural irrigation technology and management. Research was founded that, in comparism to the control irrigation system CIS, under Sprinkler irrigation, with the modified contron system as such smart irrigation system (SIS) for wheat crop production in Saudi Arabia under arid region, observed that, SIS managed to significantly reduced water consumption and saved irrigation water by creating a good moisture distribution in the root zone depth which is more efficient scheduling control (Hussein, et al., 2014). Therefore, the SIS irrigation method would be recommended due to its easy application and more water saving. Also, the results indicated that the value of WUE was higher with SIS than those with CIS. This result indicated that the water was used most effectively with the SIS treatment.

8. Future Prospects in Green Irrigation Technologies

Green irrigation technologies emphasize sustainable water management through efficient irrigation methods, renewable energy integration, digital monitoring, and precision agriculture. The future of these technologies offers significant opportunities to reduce water consumption, improve crop productivity, and enhance environmental sustainability. Alternative water sources including captured rainfall, recycled agricultural drainage water, and treated wastewater will be used more frequently in irrigation schemes in the future. While lessening the strain on freshwater supplies, properly treated wastewater offers a reliable source of irrigation water. Seasonal rainfall may be collected and effectively used during dry spells with rainwater collecting systems combined with storage reservoirs and drip irrigation. Overall water saving is greatly enhanced by such circular water management techniques. Climate forecasting models that anticipate rainfall, drought risk, and agricultural water demand will be integrated into future irrigation devices. Farmers will be able to apply water only when needed thanks to adaptive irrigation scheduling based on real-time climatic data, which will minimize water losses and preserve crop output in the face of shifting environmental circumstances. Green irrigation systems' future success will rely not just on technology advancement but also on financial incentives, farmer education, and supporting government policies. Small and marginal farmers can adopt water-efficient agricultural techniques, digital agriculture platforms, micro-irrigation systems, and renewable energy infrastructure more quickly if they get subsidies. Public-private collaborations, agricultural extension agencies, and research institutes will continue to provide affordable technology appropriate for a variety of agro climatic situations. Continuous research and innovation will further strengthen the effectiveness of green irrigation technologies. Future developments in artificial intelligence, machine learning, nanotechnology, advanced sensor networks, satellite-based monitoring, and precision agriculture are expected to improve irrigation accuracy while reducing operational costs.

9. Conclusion: Green irrigation technologies provide workable answers to the escalating problems of freshwater shortage, climate change, and rising food demand. They are a revolutionary approach to sustainable water management in agriculture. Conventional irrigation techniques, especially flood irrigation, can cause significant water losses due to deep percolation, runoff, and evaporation. Green irrigation solutions, on the other hand, prioritize water efficiency through digital monitoring, precise application, integration of renewable energy sources, and ecologically conscious resource management. In order to achieve sustainable agricultural growth and protect water resources for future generations, their adoption is becoming more and more crucial. Drip irrigation and precision irrigation are two of the many green irrigation techniques that have shown notable increases in water-use efficiency. By delivering water straight to the crop root zone, these systems minimize needless losses and guarantee that crops receive water in accordance with their actual needs. By providing real-time monitoring and automated irrigation scheduling, the integration of soil moisture sensors, weather forecasting systems, Internet of Things (IoT) devices, artificial intelligence (AI), and remote sensing technologies has significantly improved irrigation efficiency. These solutions greatly lower water losses and increase the resilience of agricultural systems by combining effective irrigation techniques, renewable energy, digital monitoring, and climate-smart management techniques. The widespread use of green irrigation technologies will be crucial for maintaining food security, safeguarding freshwater resources, promoting sustainable rural development, and accomplishing the more general objectives of environmental sustainability and climate resilience as the world's water scarcity worsens.

Reference:

1. Bhattacharya. A., (2021). Effect of Soil Water Deficit on Growth and Development of Plants: A Review, *Soil Water Deficit and Physiological Issues in Plants (pp.393-488)* DOI:10.1007/978-981-33-6276-5_5.
2. Paul, J., Kramer. (1944).Soil moisture in relation to plant growth. *The Botanical Review*. (10). 525-559.
3. Viets, F.G., (1966). Increasing water use efficiency by soil management, *In Plant Environment and Efficient Water Use*, Pierre WH et al. (eds). American Society of Agronomy: Madison, Wisc.
4. Israelsen, O.W., (1950). Irrigation Principles and Practices. Wiley: New York; 471.
5. Bouwer. H., (2000). Integrated water management: emerging issues and challenges. *Agricultural Water Management*, **45**, 217–228.
6. Gusev, Y., and Novak, V., (2007). Soil water-main water resources for terrestrial ecosystems of the biosphere. *Journal of Hydrology and Hydromechanics*, 55(1), 3–15.
7. Roux, G., (1992). Ancient Iraq, third edition, penguin books, London,. p.4.
8. Kuiper, K., (2010). Mesopotamia: the world's earliest civilization. Britannica Educational Publishing, p18
9. Manish, D., (2011). Problems of Agricultural Growth in India, (Cyber Tech Publications) P.3
10. Larry, W. M. (2010). Ancient Water Technologies. Springer Dordrecht Heidelberg, New York , DOI 10.1007/978-90-481-8632-7
11. Joel, M., (1998).The Second Industrial Revolution, (1870-1914).

12. Mohajan, H., (2019), The First Industrial Revolution: Creation of a New Global Human Era. *Journal of Social Sciences and Humanities*, 5(4), pp. 377-387
13. Vibeke, B. & Henning, B. (2010). *Sustainable irrigation: A historical perspective.* WIT Transactions on State of the Art in Science and Engineering, WIT Press Vol 37,
14. IFAD, (2014). Water Conservation and Management: Evaluation Synthesis. Independent Office of Evaluation. Available at: http://www.ifad.org/evaluation/public_html/eksyst/doc/syn/2014/water/WATER%20ES%20- %20Full%20Report%20for%20web.pdf
15. Peasants, K.S. et al. (2021). Agriculture Water Management Theory and Practices Academic Press is an importance .
16. Iván, F., García, T., Víctor. H., Durán, Z., (2018) Water *Scarcity and Sustainable Agriculture in Semiarid Environment: Tools, Strategies and Challenges for Woody Crops* Academic Press.
17. Jury, W.A., and Vaux, Jr., H.J. (2007). The Emerging Global Water Crisis: Managing Scarcity and Conflict between Water Users. *Advances in Agronomy*, 95, 1-76.
18. Debaere, P., & Kurzendoerfer, A. (2017). Decomposing US water withdrawal since 1950. *Journal of the Association of Environmental and Resource Economists,* 4(1), 155–196.
19. WEF.,(2019). Global Risks. World Economic Forum. https:// www.weforum.org/reports/the-global-risks-re port-2019 (accessed June 10, 2020).
20. Burek, P. et al. (2016).Water Futures and Solution: Fast Track Initiative (Final Report). IIASA Working Paper (International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
21. G.O.I., (2013). Department of Agriculture and Cooperation, Ministry of Agriculture. State of Indian Agriculture. p. 221.
22. Ananda, J., & Aheeyar, M. (2020). An evaluation of groundwater institutions in India: A property rights perspective. *Environment, Development and Sustainability*, 22(6), 5731–5749. https://doi.org/10.1007/s10668-019-00448-8
23. Mukherjee, D., (2016). A Review on Artificial Groundwater Recharge in India. *International Journal of Civil Engineering*, 3(1), 60–65. https://doi.org/10.14445/23488352/IJCE-V3I1P108
24. Chindarkar, N., & Grafton, R. Q. (2019). India's depleting groundwater: When science meets policy. *Asia & the Pacific Policy Studies,* 6(1), 108–124. https://doi.org/10.1002/app5.269
25. Zhou, Q.; Zhang, Y.; Wu, F. (2021), Evaluation of the most proper management scale on water use efficiency and water productivity: Acase study of the Heihe River Basin, China. *Agric. Water Manag.* 246, 106671. [CrossRef]
26. Van Halsema, G.E.; Vincent, L. (2012)., Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. *Agric. Water Manag.* 108, 9–15. [CrossRef]
27. Kambou, D., Xanthoulis, D., Ouattara, K., Degré, A., (2014). Concepts d'efficience et de productivité de l'eau (synthèse bibliographique). *Biotechnol. Agron. Soc. Environ.* 18, 108–120.
28. Pigou, A., (1932). The economics of welfare, 4th ed. Palgrave Macmillan. http://www.palgrave.com/la/ book/9780230249318 (accessed June 10, 2020).
29. Knapp, K. C. (1992). Irrigation management and investment under saline, limited drainage condi tions: 1. Model formulation. *Water Resources Research* 28 (12): 3085–90.
30. Molden, D., (1997). Accounting for water use and productivity. SWIM Paper 1. IIMI: Colombo.
31. El-Ghonemy, A., (2012). Future sustainable water desalination technologies for the Saudi Arabia: a review, *Renew. Sustain. Energy Rev.* 16 (9) 6566, https:// doi.org/10.1016/j.rser.20

32. Wada, Y., Van Beek, L.P., Van Kempen, C.M. Reckman, J.W. Vasak, S. Bierkens, M.F. (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.* 37 (20) https://doi.org/10.1029/2010GL044571.
33. Shaji, E. Santosh, M. Sarath, K. Prakash, P. Deepchand, V. Divya, B., (2021). Arsenic contamination of groundwater: a global synopsis with focus on the Indian Peninsula, *Geosci. Front.* 12 (3) 101079, https://doi.org/10.1016/j.gsf.2020.08.015.
34. Siebert, S., Burke, J., Faures JM, Frenken K, Hoogeveen J, Doell P & Portman FT (2010). Groundwater use for irrigation–a global inventory. *Hydrology & Earth System Science* 14: 1863-1880.
35. Siebert, S., and P. Döll. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology* 384: 198–217. https://doi. org/10.1016/j.jhydrol.2009.07.031
36. Misstear, B. Clark, B. D, L. (2017).Water Wells and Boreholes, John Wiley & Sons Ltd, UK,
37. Wada, Y. et al. (2010).Global depletion of groundwater resources. *Geophys. Res. Lett.* 37
38. Minderhoud, P. S. J. et al. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environ. Res. Lett. 12*,
39. Singh. AK., (2018). Water Security – A Reality Check . *Journal of the Indian Society of Soil Science*, Vol. 66 (Supplement) pp S179-S192 .
40. Bahinipati, C. S., & Viswanathan, P. K. (2019). Can Micro-Irrigation Technologies Resolve India's Groundwater Crisis? Reflections from Dark-Regions in Gujarat. *International Journal of the Commons*, 13(2), pp. 848–858. DOI: https://doi.org/10.5334/ijc.888
41. Soumendra, N. B., Abhijit. M.,, Matthew, R., Yoshihide W., Siddhartha, C., Isabella, V., Kishore P., & James, S. F., (2017). Groundwater rejuvenation in parts of India influenced by water-policy change implementation. *Scientific Reports*, volume 7, Article number: 7453.
42. Goldin, T. (2016).Groundwater: India's drought below ground. *Nature Geoscience.* 9, 98–98
43. Alberto, B., and Lorenzo, R., (2019).Reassessing the projections of the World Water Development Report. *npj Clean Water*. 2:15 ; https://doi.org/10.1038/s41545-019-0039-9
44. UNWWD,(2018). Nature-Based Solutions for Water Paris,
45. UNESCO, (1999). Summary of the Monograph 'World Water Resources at the Beginning of the 21, Century.
46. FAO,(2016). Fao Water Use Index,. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en.
47. Sara S. F., et. al., (2022). Landscape-based regeneration of the Nile Delta's waterways in support of water conservation and environmental protection. *Ecological Indicators* ,Volume 145,109660
48. Levidow, L., (2014) Improving water-efficient irrigation: Prospects and difficulties of innovative practices, ***Agricultural Water Management***, Volume 146, Pages 84-94
49. Raveendra, K. R., (2017), **Planning and Evaluation of Irrigation Projects**, Methods and Implementation Pages 353-363
50. Larry W. M.,(2010). Ancient Water Technologies, Springer Dordrecht Heidelberg London, New York DOI 10.1007/978-90-481-8632-7
51. FAO., (2011). Aquastat Main database. Rome, Italy: United Nations.
52. USDA.,(2019). Irrigation and water management survey. Vol. 3. Special studies, Part 1. AC-17- SS-1. Washington, DC.
53. Oweis, T., (2018). Water management for sustainable agriculture, Burleigh Dodds Science Publishing, Cambridge, UK, , (ISBN: 978 1 78676 176 7; www.bdspublishing.com)

54. Cui, Z.J., Gao, Y.H., Yan, B. Wu, B. Niu, J.Y. Zhao, B.Q. Zhao, Y.W. (2019). Effect of water and nitrogen coupling on spatial and temporal distribution of soil water and water consumption characteristic and grain yield of oil flax *J. Nucl. Agric. Sci.*, 33 , pp. 398-411, 10.11869/j.issn.100-8551.2019.02.0398
55. Jagermeyr , J., Linkages J. Gerten, D., Heinke, J., Schaphoff, S., Kummu M., Lucht, W., (2015).Water savings potentials of irrigation systems: global simulation of processes. *Hydrol. Earth Syst. Sci.,* 19, 3073–3091,
56. Wang. C., Bai. D., Li. Y., Yao, B., Feng, Y., (2021).The comparison of different irrigation methods on yield and water use efficiency of the jujube. Agric Water Manag,:252:106875.
57. Fuentes I, van Ogtrop F, Vervoort RW. Long-term surface water trends and relationship with open water evaporation losses in the Namoi catchment, Australia. J Hydrol,2020:584:124714.
58. Yin, et al., (2020). Water utilization in intercropping: a review *Agric. Water Manag.*, 241 Article 106335, 10.1016/j.agwat.2020.106335 View PDFView articleView in ScopusGoogle Scholar
59. Wang, Z.H., Li. SX., (2019).Nitrate N loss by leaching and surface runoff in agricultural land: A global issue (a review). *Adv Agron*.156:159-217.
60. Salmerón,Y.F., Urrego. R. I., Cavero, J. (2012).Effect of non-uniform sprinkler irrigation and plant density on simulated maize yield. *Agricultural Water Management* Volume 113, October, Pages 1-9 https://doi.org/10.1016/j.agwat.2012.06.007
61. Fadul,E., Masih, I., De Fraiture C., Suryadi, FX.,(2020). Irrigation performance under alternative field designs in a spate irrigation system with large field dimensions. *Agric Water Manag,* 231:105989.
62. Oster, J.D., (2006).Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management.,* Volume 86, Issues 1–2, 16 Pages 114-127
63. Ma et al., (2020).Recovery growth and water use of intercropped maize following wheat harvest in wheat/maize relay strip intercropping. *Field Crop. Res.*, 256 . Article 107924, 10.1016/j.fcr.2020.107924 Scanlon, B. R., et al. (2012). *Proceedings of the National Academy of Sciences*, **109**(24), 9320–9325.
64. Bierkens, M. F. P., & Wada, Y. (2019). *Environmental Research Letters*, **14**, 063002.
65. Ahmed, I. and Umar, R.,(2009). Groundwater flow modelling of YamunaKrishni interstream, a part of central Ganga Plain Uttar Pradesh, *J. Earth Syst. Sci*., 118(5), 507–523, 2009.
66. Foster, S. and Loucks, D.P.,(2006). Non-Renewable Groundwater Resources, Series on Groundwater No. 10, UNESCO, Paris,
67. Guzman-Soria, E., Hernandez-Martinez, J., Garcia-Salazar, J. A., Rebollar-Rebollar, S., de la Garza-Carranza, M. T., and Hernandez-Soto, D. (2009). Groundwater consumption in Guanajuato, Mexico, *Agrociencia*, 43(7), 749–761, 2009.
68. Konikow, L. F. and Kendy, E. (2005). Groundwater depletion: A global problem, Hydrogeol. J., 13, 317–320, doi:10.1007/s10040-004- 0411-8, 2005.
69. Rodell, M., Velicogna, I., and Famiglietti, J. S.,(2009).Satellite-based estimates of groundwater depletion in India, Nature, 460, 999–1002, doi:10.1038/nature08238.
70. Scanlon, B. R., Jolly, I., Sophocleous, M., and Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality, Water Resour. Res., 43, W03437, doi:10.1029/2006WR005486.

71. Shah, T., Burke, J., and Villholth, K.(2007). Groundwater: a global assessment of scale and significance, in: Water for Food, Water for Life, edited by: Molden, D., Earthscan, London, UK and IWMI, Colombo, Sri Lanka, 395–423.
72. Asoka, A., Gleeson, T., Wada, Y., Mishra, V., 2017. Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nat. Geosci. 10, 109–117. https://doi.org/10.1038/ngeo2869.
73. Janardhanan, S., Nair, A.S., Indu, J., Pagendam, D., Kaushika, G.S., (2023). Estimation of groundwater storage loss for the Indian Ganga Basin using multiple lines of evidence. *Sci. Rep*. 13, 1797. https://doi.org/10.1038/s41598-023-28615-y.
74. Dangar, S., Asoka, A., Mishra, V., (2021). Causes and implications of groundwater depletion in India: a review. *J. Hydrol.* 596, 126103. https://doi.org/10.1016/j. jhydrol.2021.12610
75. Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). *Satellite-based estimates of groundwater depletion in India.* ***Nature,*** **460,** 999–1002. https://doi.org/10.1038/nature08238
76. YRCC, (2022). Yellow River water resources bulletin. Yellow River Conservancy Commission of the Ministry of Water Resources
77. Yin, Y., Tang, Q., Liu, X., Zhang, X., (2017). Water scarcity under various socio-economic pathways and its potential effects on food production in the Yellow River basin. *Hydrol. Earth Syst. Sci*. 21 (2), 791–804. https://doi.org/10.5194/hess-21-791-2017.
78. Huang, Z., Yuan, X., Sun, S., Leng, G., Tang, Q., (2023). Groundwater depletion rate over China during 1965–2016: The long-term trend and inter-annual variation. *J. Geophys. Res.: Atmosph*. 128 (11), e2022JD038109. https://doi.org/10.1029/2022JD038109.
79. World Water Assessment Programme (Nations Unies), The United Nations World Water Development Report (2018) (United Nations Educational, Scientific and Cul tural Organization, New York, United States) www.unwater.org/publications/ world-water-development-report-2018/. (2018).
80. Burek, P. et al.(2016). Water Futures and Solution: Fast Track Initiative (Final Report). IIASA Working Paper (International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,)
81. Plusquellec, H. (2009). Modernization of large-scale irrigation systems: Is it an achievable objective or a lost cause. *Irrig. Drain.* 58, 104–120
82. Doorenbos, J. and Kassam, A.H. (1979). Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. *Food and Agriculture Organization* (FAO), Rome.
83. Michael, A. Bos, David, J. M., and Ramesh, S., (2005). Water Productivity in Managing Water for Agriculture. *Agricultural Water Management*, 80(1–3), 15–28.
84. Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation for climate change adaptation and improved food security. *In Irrigation Advances. and Drainage—Recent InTech* Open. https://www.intechopen.com/chapters/8318
85. Sherpa, T.S.; Patle, G.T.; Rao, K.V.R. (2021). Gravity Fed Micro Irrigation System for Small Landholders and Its Impact on Livelihood—A Review. *Int. J. Environ. Clim. Change*, 12, 310–323
86. Fereres, E., Goldhamer, D. A., & Parsons, L. R. (2003). Irrigation water management of horticultural crops. *Hort Science,* 38(5), 1036–1042.
87. Singhal, S., Rasane, P., Kaur, S., Garba, U., Singh, J., Raj, N., & Gupta, N. (2019). Mushroom cultivation, processing and value-added products: A patent based review. *Recent Patents on Food, Nutrition & Agriculture*, 10(1), 3–19.

88. Tal, A. (2006). "Rethinking the Sustainability of Israel's Irrigation Practices." Water Policy, 8(1), 1–25
89. Jin, X.; Chen, M.; Fan, Y.; Yan, L.; Wang, F. (2018). Effects of Mulched Drip Irrigation on Soil Moisture and Groundwater Recharge in the Xiliao River Plain, China. *Water*, 10, 1755.
90. Vandern, S., Zwarteveen, M., Boesveld, H., Kuper, M., (2013).The efficiency of drip irrigation unpacked. Agric. Water Manag., 123, 103–110.
91. Van D., (1989). Irrigation Water Management: Irrigation Methods, Food and Agriculture Organisation of the United nations (Chapter 5)Wageningen, The Netherlands.
92. Venot, J.-P., Kuper, M., Zwarteveen, M., (Eds.)., (2017). Drip Irrigation for Agriculture: Untold Stories of Efficiency, Innovation and Development. Routledge, London. https://doi.org/10.4324/9781315537146.
93. Venot, J.P.; Kuper, M.; Zwarteveen, M. Drip Irrigation for Agriculture; Routledge: London, UK; New York, NY, USA, 2017.
94. Narayanamoorthy A. (2009). Drip and sprinkler irrigation in India: Benefits, potential and future directions in: India's water future: scenarios and issues; Strategic analyses of national river linking project of India. New Delhi, India: Strategic Analyses of National River Linking Project of India; 2:253-266.
95. Huang, H., Li, W., Xie, L., Xiang, L., Meng, X., Xie, A., Wei, L., Chen, Q., Nong, T., (2010). Effects of drip irrigation on agronomic characters and yield of sugarcane. *Modern Agric. Sci. Technol.*;19:107–108.
96. Zhang, Z., Liang, B., Li, J., He, H., Jin, S., (2013). Effects of different fertigation methods on yield and nutrient uptake of potato. Chin. *Agric. Sci. Bull.*;29:268–272.
97. Zhu, Y., Cai, H., Song, L., Wang, X., Shang, Z., Sun, Y., (2020). Aerated irrigation of different irrigation levels and subsurface dripper depths affects fruit yield, quality and water use efficiency of greenhouse tomato. *Sustainability* 12, 2703. https://doi. org/10.3390/su12072703.
98. Zhu, Y., Dyck, M., Cai, H., Song, L., Chen, H., (2019). The effects of aerated irrigation on soil respiration, oxygen, and porosity. *J. Integr. Agric*. 18, 2854–2868. https://doi. org/10.1016/S2095-3119(19)62618-3.
99. Bhattarai, S.P., Su, N., Midmore, D.J.,(2005). Oxygation unlocks yield potentials of crops in oxygen-limited soil environments. *Adv. Agron*. 88, 313–377. https://doi.org/ 10.1016/S0065-2113(05)88008-3
100. Sese-Minguez, S.; Boesveld, H.; Asins-Velis, S.; Van der Kooij, S.; Maroulis, J.(2017). Transformations accompanying a shift from surface to drip irrigation in the Cànyoles Watershed, Valencia, Spain. *Water Altern.* , 10, 81–99.
101. Haoru. Li et.al. (2020). Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agricultural Water Management* 244 (6223):1065342021 DOI:10.1016/j.agwat.2020.106534
102. Evans, R.G. and Bergman, J.W. (2009). Relationships Between Crop Production and Internet-Based Irrigation Scheduling. *Agricultural Water Management*, **96**(10), 1491–1498.
103. Kim, Y., Evans, R.G., and Iversen, W.M. (2008). Remote Sensing and Control of an Irrigation System Using a Distributed Wireless Sensor Network. IEEE *Transactions on Instrumentation and Measurement*, **57**(7), 1379–1387.
104. Kumar, A., & Singh, P. (2019). Smart irrigation systems: A comprehensive review. Agricultural Water Management, 215, 78 95. https://doi.org/10.1016/j.agwat.2019.01.01

105. Kumar, A., Kumar, A., & Sharma, P. K. (2017). Smart irrigation system using IoT: SIS. International Journal of Engineering & Technology (IJERT), 6, 103–107.
106. Ali, A. I., Partal, S. Z., Kepke, S., & Partal, H. P. (2019, June). ZigBee and LoRa based wireless sensors for smart environment and IoT applications. In 2019 1st Global Power, Energy and Communication Conference (GPECOM) (pp. 19–23). IEEE
107. Cardenas,L.B., Dukes, M. D., and Miller. G. L. (2010). Sensor-based automation of irrigation on bermudagrass, during dry weather conditions. *Journal of Irrigation and Drainage Engineering*. 136(3): 184-193.
108. Mayer, P.W. and Deoreo, W.B. (2010). Improving urban irrigation efficiency by using weather-based "smart" controllers. *American Water Works Association.* 102(2):86
109. Khaled, O., et al., (2022).An overview of smart irrigation systems using IoT. *Energy Nexus,* 7, 100124.
110. Wang, X., Fan, J., Xing, Y., Xu, G., Wang, H., Deng, J., Wang, Y., Zhang, F., Li, P., Li, Z., (2018). The effects of mulch and nitrogen fertilizer on the soil environment of crop plants. *Advances in Agronomy* 153, 122–173.
111. Gao, H., Yan, C., Liu, Q., Ding, W., Chen, B., Li, Z., 2019. Effects of plastic mulching and plastic residue on agricultural production: a meta-analysis. *Science of the Total Environment,* 651, 484–492.
112. Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, **93**(2), 281–289.
113. FAO. (2017). *Water for Sustainable Food and Agriculture*. Food and Agriculture Organization of the United Nations, Rome.
114. Narayanamoorthy, A. (2004). Drip irrigation in India: Can it solve water scarcity? *Economic and Political Weekly*, **39**(36), 3973–3977.
115. Perry, C., Steduto, P., Allen, R. G., & Burt, C. M. (2009). Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*, **96**(11), 1517–1524.
116. Postel, S. L., Polak, P., Gonzales, F., & Keller, J. (2001). Drip irrigation for small farmers: A new initiative to alleviate hunger and poverty. *Water International*, **26**(1), 3–13.
117. Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, 93, 281–289.
118. FAO. (2017). *Water for Sustainable Food and Agriculture*. Rome
119. Nair, S., et al. (2013). Efficiency of Irrigation Water Use: A Review from the Perspectives of Multiple Disciplines. *Agronomy Journal,* 105, 351–363.
120. Camp, C. R. (1998). Subsurface Drip Irrigation: A Review. *Transactions of the ASAE*, 41(5), 1353–1367.
121. Martínez, J., & Reca, J. (2014). Water Use Efficiency of Surface Drip Irrigation versus an Alternative Subsurface Drip Irrigation Method. *Journal of Irrigation and Drainage Engineering*, 140(10).
122. Ayars, J. E., et al. (1999). Subsurface drip irrigation of row crops: A review of 15 years of research. *Agricultural Water Management*, 42, 1–27.
123. Global Meta-analysis (2022). Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation. *Agricultural Water Management*, 269, 107645.
124. Mourad, B.,et al., (2022).Towards Smart Irrigation: A Literature Review on the Use of Geospatial Technologies and Machine Learning in the Management of Water Resources in Arboriculture., *Agronomy* .2022, *12*(2),297; https://doi.org/10.3390/agronomy12020297

125. Jata, S.K., Nedunchezhiyan, M., Maitay, S.K. and M. Mallikarjun M.,(2018). Intercrop and drip irrigation effects on growth, yield, water-use efficiency and economics of elephant foot yam (Amorphophallus paeoniifolius), *Indian Journal of Agronomy* 63 (4): 506-512 .
126. Nedunchezhiyan, M. (2017). Drip irrigation and fertigation effects on corm yield, water and fertilizer use efficiency and econom ics in elephant foot yam (Amorphophallus paeoniifolius). Indian Journal of Agronomy 62(4): 24–29.
127. Fan J. et al., (2022) Effects of different irrigation methods on pepper growth. Hydro Sci. Cold Zone Eng. 2022;5:41–45. (In Chinese)
128. Arafa, Y.E., Essam, A.W., Hazem, E.M. (2009).Maximizing water use efficiency in wheat yields based on drip irrigation systems. Australian Journal of Basic and Applied Sciences. 2009;3(2):790–6.
129. Xue, C., Huang, Y., Han, W., (2018). Influence of government subsidies and adoption effect on continuous adoption behavior of water-saving irrigation technology by farmers. Resour. Sci. 40 (7), 1418–1428. https://doi.org/10.18402/resci.2018.07.10.
130. Han, S., et al., (2021). Groundwater resource and eco-environmental problem of the Yellow River Basin. Geol. China 48 (4), 1001–1019. https://doi.org/10.12029/ gc20210402.
131. YRCC, 2022. Yellow River water resources bulletin. Yellow River Conservancy Commission of the Ministry of Water Resources
132. Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., (2018). The paradox of irrigation efficiency. Science 361, 748–750. https://doi.org/10.1126/science.aat9314.
133. Xiong, R., Zheng, Y., Han, F., Tian, Y.,(2021). Improving the scientific understanding of the paradox of irrigation efficiency: an integrated modeling approach to assessing basin-scale irrigation efficiency. e2020WR029397 Water Resour. Res. 57 (11). https://doi.org/10.1029/2020WR029397.
134. Singh, U., Praharaj, C.S., Gurjar, D.S., Kumar, R., (2019). Precision Irrigation Management: Concepts and Applications for Higher Use Efficiency in Field Crops; *Indian Institute of Pulses Research*: Kanpur, India,; pp. 181–190.
135. Misra, N.N., Dixit, Y., Al-Mallahi, A., Bhullar, M.S., Upadhyay, R., Martynenko, A., (2020). IoT, Big Data and Artificial Intelligence in Agriculture and Food Industry. *IEEE Internet Things J.* 9, 6305–6324
136. Vij, A., Vijendra, S., Jain, A., Bajaj, S., Bassi, A., Sharma, A.(2020). IoT and Machine Learning Approaches for Automation of Farm Irrigation System. *Procedia Comput. Sci.* 167, 1250–1257
137. Abioye, E. A. Abidin, M. S. Z. Mahmud, M. S. A. Buyamin, S. Ishak, M. H. I. Abd Rahman, M. K. I. Otuoze, A. O. Onotu, P. and Ramli, M. S. A. (2020). A review on monitoring and advanced control strategies for precision irrigation, *Computers and Electronics in Agriculture, vol.* 173, p. 105441.
138. Vera, J., Conejero, W., Mira-García, A. B., Conesa, M. R., and Ruiz, M. C., (2021).“Towards irrigation automation based on dielectric soil sensors,” *The Journal of Horticultural Science and Biotechnology,* vol. 96, no. 6, pp. 696–707,
139. Lee, S., & Kim, T. (2020). Challenges and opportunities in the adoption of smart irrigation systems. Journal of Cleaner Production, 258, 120–135. https://doi.org/10.1016/j.jclepro.2020.1201
140. Wu, C.L., Xu, D., Bai, M.J., Li, Y.N.,(2020). Real-time feedback control technology for precise furrow irrigation. *J. Drain. Irrig. Mach. Eng.* 38, 536–540.
141. Zhu, X.Y., Chikangaise, P., Shi, W.D., Chen, W.H., Yuan, S.Q. (2018). Review of intelligent sprinkler irrigation technologies for remote autonomous system. Int. J. Agric. Biol. Eng. 2018, 11, 23–30. [CrossRef]

142. Hussein, M.A.G., Mohamed, S. A. E. M.,(2014). Effect of smart sprinkler irrigation utilization on water use efficiency for wheat crops in arid regions . *Int J Agric & Biol Eng*, Vol. 7 No.1, 26 Open Access at http://www.ijabe.org