[1.]Uduakobong Ndiana-Abasi AKPAN, [2.]Ndifon AGBIJI, [3.]Kingsley UMANI

INNOVATIVE IRRIGATION TECHNIQUES FOR EFFICIENT WATER SUPPLY TO ENHANCE FOOD SECURITY: A REVIEW

[1.]Department of Agricultural and Food Engineering, Faculty of Engineering, University of Uyo, Uyo, Akwa Ibom State, NIGERIA
[2.]Cross River Basin Development Authority, Murtala Mohammed Highway, Calabar, Cross River State, NIGERIA
[3.]Department of Agricultural Engineering, Faculty of Engineering, Akwa Ibom State University, Ikot Akpaden, Mkpat-Enin, Uyo, Akwa Ibom State, NIGERIA

Abstract: Water is an essential requirement for crop development, and humans' survival. Insufficient water supply and the increasing demand for food present extensive tasks for water managers and farmers. So, innovative technologies in irrigation have become necessary tools in water resources management. Therefore, this study was carried out to present some innovative irrigation systems for efficient water usage in agriculture to enhance food security from available literatures. In nutshell, innovative technologies such as smart irrigation controllers, soil moisture sensors, wind sensor, micro-irrigation systems, drip irrigation, bubbler micro irrigation system, robotics, artificial intelligence, and precision agriculture in irrigation were addressed. These systems could boost the future of irrigation water management which in turn could increase water-use efficiency, reduce water consumption, and curtail environmental impacts. It is therefore depended on farmers' capability and willingness to embrace these innovative technologies in irrigation.
Keywords: Irrigation techniques, Water supply, Innovative technology, Crops, Food Security

1. INTRODUCTION

Water is indispensable for crop growth and development, and the survival of humans. In the aspect of climate variation, urbanization, and population expansion, water management is very critical for the sustainable development in agriculture (Alghory and Yazar, 2019). Inadequate water resources and the cumulative demand for food present substantial tasks for water managers and farmers. Therefore, innovative technologies in irrigation, for instance as shown in Figure 1, have become indispensable tools in water resources management (Adeboye, 2024).

Figure 1: A typical innovative technology in irrigation Source: Adeboye (2024)

The developments, in this regard, are geared towards increasing water-use efficiency (WUE), decrease water consumption, and minimize environmental effects triggered by irrigation. However, their acceptance and implementation may depend on government exertions to boost financial investment and education for water managers and farmers. The future of water management may depend on farmers' aptitude and readiness to welcome innovative technologies in irrigation in the background of social and cultural barricades, such as the traditional ways of irrigation that have been established methods and cultural customs (Adeboye, 2024). The transformation agendum of the innovative technologies in irrigation which can shape irrigation water management future include smart irrigation controllers, soil moisture sensors, wind sensor, micro-irrigation systems, drip irrigation, bubbler micro irrigation system, robotics, artificial intelligence, and precision agriculture (Freddie et al., 2021; Shi et al., 2022). Let's look at some of these innovative technologies one after the other. However, the main objective of this study was to search the available literatures and present some innovative irrigation techniques for efficient water usage in agriculture towards enhanced food security.

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2. INNOVATIVE IRRIGATION TECHNIQUES

Smart Irrigation Controllers

Smart irrigation controllers include devices that use sensors and predictive analytics to power irrigation schedules depending on soils and crops requirements; and up-to-date weather conditions (Ayars, 2008). Smart irrigation controllers could regulate irrigation schedules by accounting for the occurrence and precipitation duration, temperature, wind speed and humidity through the data collated from weather sensors (Adeboye, 2024). Alternatively, the predictive analytics forestall future weather conditions which could be used to mitigate the risk of over or under-irrigation. Smart irrigation controllers are extremely efficient and could save about 50% of the crop irrigation water compared to orthodox irrigation systems (Arya et al., 2017). These systems not only enhance irrigation efficiency but also decrease labour costs, increase crop harvests, and lower pumping water energy consumption (Adeboye, 2024). Classical examples of such systems are shown in Figure 2. The two key groups of irrigation controllers (Climate-based and soil moisture-based controllers) are discussed in detail below.

(a) **(b)**

Figure 2: Smart irrigation controllers for (a) Climate-based, and (b) soil moisture-based Utilization. Source: Adeboye (2024).

— Climate-Based Controllers

Climate-based controllers also known as evapotranspiration (ET) controllers employ local weather information to regulate irrigation schedules (Figure 3). Evapotranspiration is the amalgamation of evaporation from the soil surface and transpiration by plant materials. These sensors collect local weather data and make irrigation run-time regulations so that the farmland only gets the adequate amount of water (Jamrey & Nigam, 2018). There are three fundamental kinds of ET controllers: (i) Signal-based controllers make use of meteorological data from a public domain and the ET value is computed for a grass surface at the site. The ET data is then directed to the controller by a wireless link. (ii) Historic ET controllers employ a pre-programmed water-utility curve, depending on historic water usage in various regions. The curve can be attuned for temperature and solar radiation. (iii) On-site weather measurement controllers employ weather information gathered on-site to compute continuous ET measurements and water respectively. Evapotranspiration controllers have the capability to minimize outdoor water usage. In Las Vegas, Nev., houses with ET based controllers recorded an average of 20% irrigation reduction compared to houses with homemade-scheduled irrigation (Devitt *et al.,* 2008). Furthermore, a study carried out on St. Augustine turfgrass disclosed mean irrigation savings of 43% in the summer compared to homemade-scheduled irrigation, with no drop in turfgrass quality (Davis *et al.,* 2009). The precision of ET controllers depends on the build-up algorithm.

Figure 3: Evapotranspiration based controllers (made by Hunter Industries). Source: Gotcher *et al.* (2017)

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— Soil Moisture-based Controllers

Soil moisture-based controllers are devices that quantify soil moisture content, allow the farmers to evaluate water availability for crops growth and at the same time make well-versed decisions on irrigation schedules. Soil moisture sensors (Figure 4) offer farmers real-time information on soil volumetric water content, allowing a more accurate water application. Under-watering or over-watering can be dangerous to crop growth. Soil moisture sensors aid farmers to evade such problems by realizing more accurate irrigation, reducing water intake, and improving crop yields in the long run (Cardenas-Laihacar *et al.,* 2010).

(a) Hand-held soil moisture sensor- Hunter Industries (b) Soil moisture controller- Hunter Industries

Figure 4: Soil Moisture Sensors. Source: Adeboye (2024) and Gotcher *et al.* (2017)

Soil volumetric water content denotes the part of the total volume of soil occupied by water. The controllers may be adjusted to un-close the valves and begin irrigation once the soil volumetric water content reaches a user-defined threshold. The suitable threshold amount depends on type of soil and vegetation, and typically ranges from about 10% to 40%. Soil moisture sensors should be installed in a demonstrative area of the turf; far from sprinkler heads, tree roots, walls and sidewalks (Figure 3). Akin to ET controllers, soil moisture controllers have shown to decrease irrigation, while preserving turfgrass quality. Comparing with homeowner irrigation schedules, soil moisture controllers had an average 72% irrigation savings and a 34% water savings during drought conditions (Cardenas-Laihacar et al., 2008). Research have shown that smart controllers can increase water usage at sites that characteristically use less than the theoretical irrigation necessity (Mayer & Deoreo, 2010).

Rain and Freeze Sensors

Rain and freeze sensors, as shown in Figure 5, can interject the irrigation cycle where there is rain or freeze event, and at this time irrigation is not necessary. Watering when there are rain wastes resources such as water and money, and results in unwanted runoff. There are three different types of rain sensors and each works depending certain concepts (Cardenas-Laihacar & Dukes, 2008).

a) The original type of rain sensor has a small cup that collects water, once a set quantity is collected, the mass of the cup interjects the irrigation cycle. Rubbles in the cup may also disrupt irrigation cycle and should be monitored and cleared occasionally.
b) The second type of rain sensor utilizes a dish with two electrodes that are at a certain distance from the cup bottom. The distance may be attuned to permit small rain occurrence. However, the debris in the cup can reduce working efficiency, hence, should be cleaned regularly. The irrigation cycle would be disrupted as soon as water reaches the electrodes.
c) The third type of rain sensors do not use cups rather utilize numerous disks that can expand as they get wetted (Figure 4 [b]). This makes them reliable and easier to maintain. The expanded disks activate the switch and interject the cycle. The system resumes a soon as the disks dry out. The disks should be monitored at least once a year to assess its replaceability. These devices should be placed in an open area where they can receive rainfall.

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Likely water savings are based on the quantity of rainfall per year. During years with mean to above mean rainfall, water savings are more important than during dry years. The performance of rain sensors has been so remarkable; but it should be checked for optimal performance when in used (Cardenas-Laihacar & Dukes, 2008). For instance, if a homeowner's irrigation system waters a one-fourth-acre yard and uses 1-inch of water in each irrigation cycle, then each cycle uses 6,789 gallons of water. If water costs $5.00 per 1,000 gallons, the monetary savings could be $33.95 each time the irrigation cycle is interjected during period of rainfall. Considering each rainfall occurrence, the homeowner would expect considerable water and money savings. Freeze sensors interject an irrigation cycle when air temperatures are below 32°F. Eliminating irrigation during freezing temperatures can possibly extend irrigation system life and avert sidewalks and streets from icing over, causing unsafe situations.

(a)

(b)

Figure 5: Rain sensors (made by Hunter Industries)- (a) Rain sensor attached to a gutter (top) and the inside of an expanding disc rain sensor (bottom), and (b) Rain sensor attached to a gutter (top) and the inside of an expanding disc rain sensor (bottom)
Source: Gotcher et al. (2017)

Wind Sensors

Oklahoma has mean wind speed of 16 miles per hour (mph) with wind drafts from 20 mph to 30 mph. Watering during windy conditions decreases irrigation distribution consistency across the landscape and reduces the quantity of water infiltrating into the soil profile. Wind sensors interrupt the irrigation cycle if wind speed surpasses a definite threshold (Figure 6). Smart irrigation technology may help decrease water waste, while also enhancing a healthy, attractive landscape. Irrigation system owners should offer consistent maintenance and ensure that the irrigation system is only watering the landscape when desired (Malarie et al., 2017).

Figure 6**:** Wind sensor (made by Hunter Industries) for use in the landscape
Source: Gotcher et al. (2017)

Micro-irrigation Systems

Micro-irrigation systems (Figure 7), also called as low-volume irrigation, offer an exact application of water right to the root zone of plants, abating water losses due to evaporation, runoff and wind drift (Ware, 2021).

(a)

(b)

Figure 7: Micro-irrigation systems. Source: Adda-247 (2022) and Ware (2021)

These systems may be modified or customized to fit water needs of several soil types, crops and field conditions where water-use efficiency is improved and reduce water intake. These systems can also improve crop productivity and quality by enhancing nutrient uptake and decreasing plant stress. They can avert soil erosion and improve overall reduction in fertilizer requirements. They are highly efficient in areas suffering water scarcity. They have the following characteristics (Camp, 1998; Ware, 2021):

a) They bring down water pressure and flow easier than traditional sprinkler systems.
b) They deliver water right to the plants root zone.
c) They decrease overwatering and prevent overflow.
d) They are appropriate for high-return value crops.
e) They aid homeowners to save water while maintaining a luxurious landscape.

— Working Principle of Micro-irrigation Systems

Micro-irrigation systems integrate tiny openings called emitters. These enable the release of water in minute quantities. These emitters are tactically arranged on or in the ground to deliver water directly to the crops root systems. They have the following advantages (Howell et al., 1995; Ware, 2021):

a) They encourage water absorption by the soil.
b) They minimize evaporation wastage.
c) They only deliver water to where it is most desirable.

— Technology Behind Today's Micro-Irrigation Systems

Most irrigation systems integrate filtering systems such as sand separators, pre-filters and screen filters, etc. The magnitude of filtration is based on the size of the emitters designed into the system and the water quality used. Some systems are embedded with pressure regulators to balance the pressure, thus producing the needed flow strength (Bordovsky & Lyle, 1998; Ware, 2021). These systems may also integrate automatic delivery software associated with a timer device, which enables water to be channelled to different areas at a programmed time of the day. Some systems are sophisticated with inbuilt sensors that can quantify the soil's moisture and shut down or regulate irrigation for rainfall. Some also are in the weather stations. All these technologies are designed to regulate both soil and weather conditions to ensure that the micro-irrigation systems can control themselves and deliver the optimal quantity of water no matter the prevailing circumstances (Bordovsky & Mustian, 2020; Ware, 2021). There are various types of micro-irrigation systems. These include drip irrigation and bubbler micro-irrigation system.

▦ Drip Irrigation Systems

This a kind of micro-irrigation system (Figure 8) is designed to be water and nutrient-effective by distributing water droplets that leak or seep slowly down into the plants root systems, thus meaningfully decreasing wastage loss through evaporation (Ware, 2021). This system uses a link of pipes and emitters. When compared to other irrigation systems, drip irrigation is extremely efficient if correctly designed, fixed, operated, and managed (Aydinsakir et al., 2021).


Figure 8: Drip irrigation system. Source: Bernard (2021)

Drip irrigation systems have the following components for channeling water from its source: pressurized water source or pump, water filters, backwash regulator, pressure control valve, meters, distribution lines, electronic control block valves or hand-operated, tubes, fittings and accessories, chemical injectors and emitting devices (Marsails et al., 2007).

Majority of huge drip irrigation systems have some kind of filter to avert clogging. The equipment may be clogged or bio-clogged if there is no effective filtration (Shi et al., 2022).

a) Water Source: Irrigation water may come from a cistern, well, municipal council supply, etc.
b) Pressurized Water Source or Pump: The water source should have sufficient pressure to channel water through, and guarantee good water distribution within the irrigation system and. The pressure could be obtained by raising tanks to utilize gravitational force or pumps based on the farm size. Pumps can be submersible, centrifugal, or turbine, based on the water source and the pressure requirement. These pumps could be electricity, generators, or solar powered.
c) Filters: These prevent unwanted materials from clogging the system. The filter should be installed in such a way to give room for easy cleaning. The key kinds of filters are screen filters, disc filters, and gravel filters.
d) Backwash Regulators: These devices that stop water from flowing back to source of water supply. This component must be fixed to avoid contamination of the water source.
e) Pressure Control Valves: These sustain the water pressure and always guarantee precise the drip emitters operating pressure. To ensure that the emitters function properly and last longer; over-watering or under-watering of crops must be avoided.
f) Tubing: This could be plastic pipes which transport water from the source to the plants. The plastic pipes could be HDPE/PVC or polyethylene, which are available in diverse diameters, lengths, and colours. Black tubing is superlative for outdoor use because it resists degradation from UV light.
g) Fittings and Accessories: These components are connecting pieces between tubings and emitters/drippers. They are chosen depending on the size and kind of tube and emitters/drippers used. Fittings include but are not limited to elbows, couplers, tees, end caps, and valves.
h) Emitters or Drippers: These are the major components of a drip irrigation system. The emitters/drippers are fixed on the lateral lines with a pre-determined space by the crop type grown and sizes based on crop water requirement. The emitters/drippers deliver aid in delivery the required amount of water to the crops. They could either be pressure compensating or non-pressure compensating.
i) Chemical Injectors: These are sub-components meant to deliver nutrients into the irrigation system in definite amounts and time intervals. These include electric dosing pump, venturi injector and piston motor injector.
j) Meter: This part is fitted on an irrigation system to quantify the volumetric water supplied to a farmland.
k) Timer: This regulates the rate and watering duration. It is programmed to turn on and off the irrigation system at specific intervals, thus decreasing watering during cooler weather condition and increasing watering rate during hot or dry seasons.

Types of Drip Irrigation Systems

Drip irrigation systems are categorized into four different kinds (Phene et al., 1991).

(a) SURFACE DRIP IRRIGATION: Surface drip irrigation involves arranging pipes or tubing on the soil surface and using drippers or drip emitters to discharge water into the soil. This type is suitable for irrigating crops and orchards that are grown in row. This system is advantageous in that it saves water, reduces soil erosion and has low energy requirements, because it is gravity-fed. It is disadvantageous in that it requires the laying of tubing or pipes on the soil surface, which can be damaged; it can be hindered by wind, which may change water flow direction; and it may favour growth weed between crop rows (Zhu et al., 2004; Polat et al., 2024).

(b) SUBSURFACE DRIP IRRIGATION: Sub-surface drip irrigation (Fig. 9) relies on delivery pipes and emitters that are fitted between 12 and 18 inches below the soil's surface, thus decreasing evaporation loss (Ware, 2021). It has similar advantages observed in surface drip irrigation. Unfortunately, it involves special equipment for installation, which lead to increase in the installation cost (Enciso et al., 2005); plant roots can intrude and damage the system; and requires regular maintenance to guarantee that the system remains unblocked (Freddie et al., 2010).

Figure 9: Sub-surface drip irrigation systems. Source: AR. INSPIRED PENCIL (2023)

(c) INLINE DRIP IRRIGATION: Inline drip irrigation uses drippers or drip emitters combined into tubing or pipes, which discharge water directly onto plants. This is best suitable for landscapes and gardens. It is easy to install and use; reduces water wastage, can be easily attuned to meet the precise needs of specific plants. Unfortunately, it can be blocked by particles in the water, requires periodic maintenance and may be expensive than traditional irrigation systems (Freddie et al., 2016).

Figure 10: Micro-sprinkler irrigation (360° type). Source: Hozelock AU Limited (2025)

(d) MICRO SPRINKLER IRRIGATION: Micro sprinkler irrigation (Fig. 10) uses tiny sprinklers attached to tubing or pipes, which discharge water in form of spray. This system is best recommended for vegetable gardens and small orchards. Fortunately, it can provide good coverage for small areas, aid to cool down plants in hot weather, and be easily attuned to meet the precise needs of individual crops. The major demerits are that it can result in greater water loss due to evaporation, requires consistent cleaning and maintenance to avert clogging, and very costlier than traditional irrigation systems (Doty et al., 1975; Schneider & Howell, 1998).

Bubbler Micro-Irrigation Systems

Bubbler micro-irrigation systems (Figure 11) are usually fixed where the crops' water requirements are high. They channel water in form of fountains and small streams. Classically, they dissipate the water at a rate of about 230 litres/ hr. They are, thus, more suitable where large quantities of water are needed relatively short space of time (Ware, 2021). They are designed to discharge constant water to crops' root systems, like natural raindrops. Unlike common sprinklers, bubblers provide more accurate watering by focusing the area directly at ground level, where the water is required, rather than spraying water in the air. They are usually used with trees, mainly young trees, shrubs and flowers that require direct, steady water at root balls. They could be used in landscapes, farms and gardens where high-volume irrigation is required (Hills et al., 2024).

Figure 11: Bubbler micro- irrigation system. Source: The Irrigation Warehouse (2024)

— Types of Bubblers

They are various types of bubblers, namely: micro bubbler, flood bubblers, stream bubblers and mushroom bubblers.

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(a) Micro Bubblers: Micro bubblers are minute-sized bubblers that have lesser flow rates and discharge a fine mist of water droplets. They are obtainable as adjustable flow dischargers with barbs to permit installation directly onto drip tubing. Micro bubblers permit flows at 4 gallons/hour and at the same time can give efficient water supply and adjustability. They are ideal for seedlings, small areas and delicate plants. They evenly distribute water and as such averts soil erosion and over-saturation (Hills et al., 2024).

(b) Flood Bubblers: Flood bubblers release water in a wider pattern; they flood the soil. They discharge water at a higher rate and efficiently soak the soil. They are suitable for thirsty plants, shrubs, and larger areas that need moderate to higher water levels. They are both adjustable and non-adjustable. Nevertheless, the common ones are the adjustable flood bubblers, which have a minute water valve with a screw or knob for adjusting the water discharge rate (Hills et al., 2024).

(c) Stream Bubblers: Stream bubblers discharge water about two to five feet away from the bubbler. These bubblers are perfect for watering container plants, flower beds, small gardens, shrubs and trees (Drip-Work, 2024).

(d) Mushroom Bubblers: Mushroom bubblers release water in a mushroom-like and full-circle spray pattern (Fig. 9). They can be adjusted from light drip to full flow. They are suitable for watering medium-sized plants, plants grown in garden/bed, shrubs and trees. They guarantee even water distribution, avert under or over-watering (Tarkalson & Payero, 2008).

— Choice of Right Drip Irrigation Bubblers

There are certain factors to be considered before choosing the right irrigation bubbler. These include crop/plant type, crop/plant water requirements and soil conditions (Drip-Work, 2024).

(a) Select micro bubblers to water trees, shrubs, flower beds, and small areas. Micro bubblers are suitable for providing dependable water to young plants and germinating seeds.

(b) Use flood bubblers for larger crop areas and sloppy landscapes. Adjustable flood bubblers are very effective in controlling water flow rate and avert soil erosion on slopes.

(c) Choose stream bubblers for individual trees, shrubs and container plantings.

(d) Select mushroom bubblers for irrigating smaller landscape areas, garden beds and containers. Their exceptional mushroom-like circular pattern guarantees thorough coverage without wasting of water.

— Adjustment, Repair and Replacement of Irrigation Bubblers

Like any other irrigation system, adequate maintenance of drip irrigation bubblers is critical to enhance continual water delivery and boost plant growth. Here are some steps to take while adjusting, and repairing bubblers (Drip-Work, 2024; Hills et al., 2024):

(a) Adjusting Bubblers

(i) Turn on the irrigation system and assess its performance. Be sure that the water flow is uniform and discharged to the required areas.

(ii) Majority of bubblers are adjustable with adjustable flow rate settings which have a control valve with the screw. The valve is used to control water flow rate based on the plant's needs. Others may be adjusted with a spray head twist. These are perfect for gardeners that need a simple and affordable alternative.

(iii) The emitter holes must be gently cleaned to remove any debris, dirt or extraneous materials buildup that may hinder the water flow. Cleaning returns the system to its optimum performance and guarantees right water flow (Hamblin, 1995).

(b) Replacing Bubblers

(i) The system must be turned off and ensure the water supply is stopped before repairs.

(ii) In removing old bubbler, screw must be used disengage the old bubbler from the irrigation tubing.

(iii) To install a new bubbler, the new bubbler must be tightly screwed to the tubing to prevent any leaks (Drip-Work, 2024; Hills et al., 2024).

(c) Repairing Bubblers and Replacement of Parts

(i) If the bubbler is not functioning properly and there is inadequate water distribution. The system must be thoroughly inspected to identify the issue. There may be likely a clog or damaged part.

(ii) The emitter holes must be cleaned to remove the clogs and rinse the bubbler to eliminate any dirt.

(iii) If the bubbler cannot be repaired, replace the spoiled components. Most firms provide replacement parts for their irrigation products (Drip-Work, 2024; Hills et al., 2024).

Robotics Application in Crop Irrigation

Developments in robotics have been promising advancement in irrigation management. Robotic systems could be used to evaluate plant health, spot pests and diseases or stressed plants, and regulate water needs. Leveraging machine learning, robotic systems can run autonomously and offer real-time information about the condition of crops and soil to farmers and water managers which enhance timely interventions (Ware, 2021). Typical examples of robotics application are shown in Figure 12.

(a) High clearance robotic system (b) Oscar autonomous irrigation robot (c) Reducing water waste with robotic irrigation

Figure 12: Robotics in Crop Irrigation

Source: Arora and Andersen (2022); Future Farming (2024); Moore (2021).

Artificial Intelligence for Decision-Making and Irrigation Scheduling

Artificial intelligence apparatuses can provide treasured insights into irrigation management by improving predictive modeling and decision-making (AI Trend India, 2024). Machine learning algorithms can evaluate large and complex data sets created by soil moisture sensors, weather sensors, and other sensors to give recommendations for optimum irrigation schedules. This technology can enhance the precision of irrigation management, enhance water distribution, and lessen water waste. Using artificial intelligence in irrigation could give

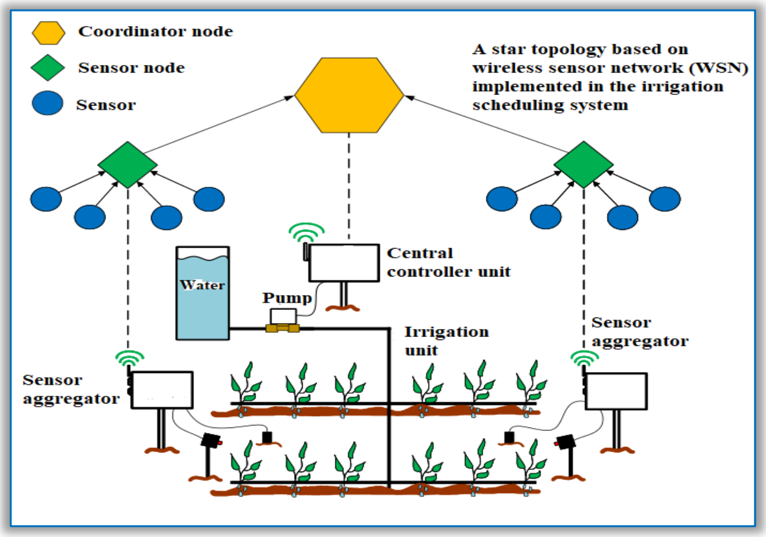

Figure 13: Artificial intelligence for decision-making and irrigation scheduling.
Source: Jamroen et al. (2020)

better data management, exact irrigation schedules, decreased water consumption, and eventually increased crop yields (Ware, 2021; Freepik, 2024). Classical examples of artificial intelligent in irrigation schedules are shown in Figures 13 and 14.

Figure 14: Smart irrigation system using IoT (internet of things) . Source: Ahmed (2019)

In Figure 14, "IoT" is referred to as the interconnection between the separately recognizable embedded computing device in the reachable internet infrastructure. The 'IoT' links numerous devices or equipment and transportations with the aid of internet as well as electronic sensor. The chief components of IoT based smart irrigation system include field data collection device with relay switch (standalone and WSN scenario); web service for collection of field sensor data; web service for collation weather information accessible online (Internet); web service that regulates water motor; soil moisture forecasting algorithm; responsive web-based interface for real-time monitoring and IoT enabled motor pump. These components can be clustered into three different layers, i.e., data collection and transmission layer, data processing & intelligence layer and application layer of IoT (Ware, 2021).

3. CONCLUSION

In a nutshell, innovative irrigation techniques in agriculture have become indispensable tools in managing water resources. These technologies (smart irrigation controllers, soil moisture sensors, wind sensor, micro-irrigation systems, drip irrigation, bubbler micro irrigation system, robotics, artificial intelligence, and precision agriculture, etc.) in irrigation can boost the future of irrigation water management which in turn could increase water-use efficiency, reduce water consumption, and curtail environmental impacts. It is therefore depended on farmers' capability and readiness to embrace these innovative technologies in irrigating crops to enhance food productivity.

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