

Wireless Sensor Network Technologies for Intelligent Smart Irrigation

Mithilesh M. Wasu¹, Dr. Kishor M. Dhole², and Sagar A. Durge³

¹*Research Scholar, Dept. of Electronics and Computer Science, PGTD, R. T. M. Nagpur University, Nagpur, Maharashtra, India*

²*Associate Professor, Dept. of Computer Science, Seth Kesarimal Porwal College, Kamptee, Dist. Nagpur, Maharashtra, India.*

³*Research Scholar, Dept. of Electronics and Computer Science, PGTD, R. T. M. Nagpur University, Nagpur, Maharashtra, India.*

Abstract—Agriculture is experiencing a rapid digital transformation driven by increasing global food demand, climate variability, water scarcity, and the need for sustainable resource management. Conventional irrigation methods rely on fixed schedules and manual decision-making, resulting in significant water wastage, energy inefficiency, and reduced crop productivity. Precision agriculture introduced site-specific management through sensor technologies, while digital agriculture further integrated the Internet of Things (IoT), Cloud Computing, wireless communication, and Artificial Intelligence (AI) to enable data-driven farm management. Among these technologies, Wireless Sensor Networks (WSNs) have emerged as the primary infrastructure for real-time environmental monitoring by continuously collecting soil moisture, temperature, humidity, and other agronomic parameters. Cloud – IoT platforms facilitate large-scale data storage, analytics, and remote monitoring, whereas Reinforcement Learning (RL) enables autonomous irrigation scheduling through sequential decision-making based on dynamic environmental conditions.

This paper systematically examines the evolution from traditional agriculture to precision and digital agriculture before providing an in-depth analysis of WSN architectures, sensing technologies, and communication protocols for intelligent irrigation. The paper critically reviews recent literature, compares existing WSN and AI-based irrigation systems, identifies current technological limitations, and analyzes challenges related to it.

Index Terms—Smart Irrigation, Wireless Sensor Networks, Internet of Things, Cloud Computing, Precision Agriculture, Digital Agriculture,

Reinforcement Learning, Artificial Intelligence, Sustainable Agriculture, Water Resource Management.

I. INTRODUCTION

Global population is projected to reach about 9.7 billion by 2050, up from ~8 billion today, implying roughly a 50% increase in food demand[1]. Meanwhile, climate change is already harming agriculture: droughts affected ~75% of global cropland in recent decades, cutting staple-crop yields by ~10–12% (maize, soy, wheat)[2]. Water is scarce – agriculture withdraws roughly 70% of global freshwater – yet traditional irrigation is highly wasteful, with field efficiency often <50% (water losses to runoff/percolation commonly exceed 50%)[3] [4]. These trends, combined with growing demands, have spurred automation in farming (IoT, robotics, AI) to make irrigation more efficient. Smart irrigation (sensor-driven, automated watering) is now seen as essential to save water and boost yields in a changing climate[5].

II. BACKGROUND

A. Global Food Demand

The world's population is rising rapidly. UN projections estimate ~9.7 billion people by 2050 and ~10.4 billion by 2100. Feeding this population will require roughly a 50% increase in food production relative to 2013 levels. Much of this increase must come from intensified agriculture [3].

B. Climate Change Impacts on Agriculture

Climate change is already affecting food systems. Heatwaves, droughts and floods have become more frequent, disrupting crops. One analysis found drought-related yield losses on about 75% of harvested area, and combined heat-and-drought events have cut global average maize, soybean, and wheat yields by roughly 10–12%. Rising temperatures also increase crop water demand (evapotranspiration) and the risk of extreme events. These stresses undermine food security, especially for vulnerable regions (e.g. sub-Saharan Africa, South Asia). Adaptation limits (water shortages, socio-economic barriers) are being reached in many agricultural systems as warming continues[2] [3].

C. Water Scarcity and Irrigation

Freshwater is a critical and limited resource. Globally, agriculture uses by far the largest share – roughly 70–72% of freshwater withdrawals – dwarfing industry (~18–20%) and domestic uses (~10–12%) [6]. In many developing regions (e.g. South Asia, North Africa), agriculture can exceed 80–90% of use. However, traditional irrigation is inefficient: FAO reports field application efficiency often below 50% and in the worst cases ~30%, meaning 50–70% of water is lost via runoff or deep percolation. For example, typical furrow/flood systems have <60% efficiency, while sprinkler systems average ~75% and drip systems ~90% [7]. Overall, an estimated 30–60% of irrigation water may be wasted in conventional systems [8] depicted in the chart below.

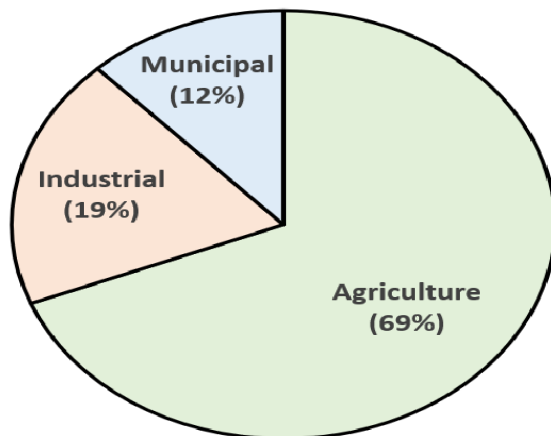


Figure 1: Global freshwater withdrawals by sector (agriculture ~69%, industry ~19%, municipal/domestic ~12%) [4].

D. Agricultural Automation Trends

The convergence of IoT, sensors, robotics, and AI is driving a “precision agriculture” revolution. Agricultural IoT systems (sensors on soil/crops, drones, automated equipment) are increasingly deployed to boost productivity and sustainability. However, agriculture has lagged behind other industries in digital adoption. Emerging trends include smart irrigation controllers, variable-rate fertilizer/drip systems, and data platforms. Market studies forecast strong growth (multi-billion-dollar market by 2030) in precision-farming technologies. In smart irrigation specifically, pilot projects and start-ups are integrating soil-weather sensing with automated valves/pumps to use water more efficiently [3], [5].

III. SMART IRRIGATION SYSTEMS

A. Definition

A smart irrigation system is one that automatically adjusts water delivery to crops based on real-time data and algorithms. It integrates field sensors (soil moisture, weather, etc.), wireless communication, and control algorithms (often in the cloud or embedded) to “close the loop” on irrigation. Unlike fixed schedules, smart systems irrigate on-demand – for example, only when soil moisture falls below a threshold – and can incorporate weather forecasts and evapotranspiration models. In practice, smart irrigation uses the Internet of Things (IoT) to turn traditional irrigation into an intelligent, data-driven process [3], [5].

B. Working Principle

Smart irrigation works in a continuous sensor-control loop. Field sensors (soil moisture probes, soil/air temperature and humidity sensors, rain gauges, solar radiation sensors, etc.) feed real-time data into a controller or IoT gateway. This controller may locally execute logic or relay data via wireless links to a cloud platform. There, decision algorithms (from simple rules to advanced ML models) analyze current conditions (and perhaps forecasts) to determine irrigation needs. The system then actuates pumps or valves (drip emitters, sprinkler zones, etc.) to apply the precise amount of water required to maintain optimal soil moisture. This feedback loop operates

automatically and continuously, greatly reducing manual intervention [3], [5], [9].

C. Sensor-Based Irrigation

Key to smart systems are sensors that monitor field and environmental variables. Common sensors include:

- Soil moisture sensors: (e.g. capacitance or time-domain reflectometry probes) to measure volumetric water content. These are often placed at root depth to directly gauge crop water availability.
- Soil temperature / air temperature and humidity sensors: to capture evaporative demand and heat stress.
- Rain gauges / weather stations: measure precipitation; an imminent rain event can suspend irrigation.
- Solar radiation or ET sensors: sometimes included to estimate crop evapotranspiration.
- Others: advanced systems may use leaf wetness, sap flow, or spectral sensors, but most focus on soil and weather data.

These sensors transmit readings (analog or digital) to the controller/gateway. For example, by monitoring soil moisture and rainfall in real time, a system can determine crop water requirements and adjust irrigation plans accordingly. Collecting multiple parameters allows more accurate scheduling (e.g. only irrigating if moisture < threshold and no rain is forecast) [5].

D. Automated Control (Algorithms)

The “brain” of a smart irrigation system is its control logic. At a basic level, this may be a threshold/hysteresis controller (e.g. irrigate when soil moisture drops below 30% field capacity). More sophisticated controllers use closed-loop regulation (e.g. PID control) to modulate valve opening rate and duration to maintain a setpoint.

Recent research increasingly uses Machine Learning (ML) and Artificial Intelligence (AI). For instance, ML models (neural nets, random forests, etc.) can predict soil moisture or crop evapotranspiration from historical and real-time data to schedule irrigation more precisely. Some experimental systems apply Deep Reinforcement Learning (DRL) - they learn an optimal irrigation policy by trial (simulated or field),

adapting water allocation to maximize yield or profit under varying conditions. The result can outperform fixed schedules: a DRL agent in Australia improved irrigation returns and increased profit by up to 17% versus conventional rules [9], [10].

E. Communications and Architectures

Smart irrigation nodes must communicate sensor data and control commands. Common wireless protocols include:

- LoRaWAN: A long-range, low-power wide-area network (LPWAN) protocol. It can cover several kilometers in open fields and supports battery-powered nodes at low data rates. Suitable for large farms or remote fields.
 - ZigBee (IEEE 802.15.4): Shorter-range (~100 m) mesh network; low power; used in orchards or glasshouses. Typical data rates ~250 kbps.
 - NB-IoT / LTE-M: Cellular IoT standards that use existing mobile networks. Offer long range and good penetration, but require SIM connectivity and network availability. Data rates ~10–250 kbps. Useful when farm is within coverage.
 - Wi-Fi / Bluetooth: Higher data rate, higher power; often used for local short-range links (e.g. to a nearby farm building). Generally power-hungry, so less common for field nodes without mains power.
 - Other: In some places, 4G/5G modules or satellite links may connect controllers to the cloud.
- Tang et al. survey these and note that 5G, Wi-Fi, ZigBee, LoRa, and NB-IoT are all applied in irrigation IoT. Choice depends on range, data needs, and power. For example, LoRa is excellent for very long-distance sensing, while NB-IoT works anywhere there's cellular service [5].

Modern architectures use a hierarchical layout: Field Wireless Sensor Network (WSN) of nodes connected to one or more gateways (e.g. LoRaWAN concentrators or cellular routers) which in turn are connected to a cloud platform/server where data are aggregated, stored, and processed. The cloud runs data analytics and dashboards, and can send back commands. This Cloud-IoT architecture enables remote real-time monitoring: farmers can view soil moisture, pump status, etc., on mobile apps while the system automatically enforces irrigation schedules.

F. Actuation Methods

Water is applied via actuators controlled by the system. Typical methods:

- Valved drip irrigation: Most efficient (~85–90%). Water is delivered via drip tape or soaker lines, valve-controlled zone by zone. Ideal for row crops, orchards, vineyards.
- Sprinkler systems: Moderate efficiency (~70–80%). Pop-up or solid-set sprinklers driven by pumps. Can be automated per zone with solenoid valves.
- Pivot/Center-pivot or linear-move: Mechanized sprinklers; less common in “smart” schemes due to complexity, but can be integrated.
- Flood/furrow irrigation: Least efficient (often <60%). Some smart systems simply time opening canal/furrow gates, but gains here are harder without converting to pressurized irrigation.

Actuators are typically electrically or pneumatically driven valves on each irrigation zone. The smart controller opens/closes valves or switches pumps on/off according to the schedule or sensor triggers. (For instance, a soil moisture sensor drop below setpoint might drive a valve open for a calculated duration.) Modern controllers and valves can be very responsive and precise, improving distribution uniformity.

G. Benefits of Smart Irrigation

Smart irrigation systems deliver multiple benefits across water, energy, crop, labor, and resilience dimensions:

- Water savings: By only irrigating when needed (and often using root-level delivery), studies show water use can be reduced substantially. Many pilots report 20–50% water savings versus fixed schedules. Precise scheduling avoids over-watering and cut down runoff/evaporation losses. For example, IoT-based systems that stop irrigation ahead of rain or gradually meet ET demand have greatly “minimized water wastage”.
- Energy savings: Less pumping and shorter run times mean lower diesel or electricity use. By automating pump control, smart systems also avoid running during peak tariffs or when energy is scarce. Reports suggest energy use can fall in line with water savings.

- Yield and quality: Ensuring crops receive optimal water at critical growth stages can improve yields and quality. Some studies find better uniformity and higher marketable yield under sensor-based irrigation (especially in water-stress years). Smart irrigation also reduces crop stress: UNDP notes that providing adequate water even under scarcity enhances drought tolerance and stabilizes production.
- Labor and cost savings: Automating irrigation scheduling saves labor (no manual gate watering or pump switching). One review highlighted reduced labor needs and higher operational efficiency with IoT irrigation. Overhead, managers get reports and alerts (e.g. low battery or leaks) reducing routine checks. While systems have upfront cost, they often pay back in saved water, energy and increased yield.
- Climate resilience and sustainability: Smart irrigation makes agriculture more resilient to climate variability. By adapting irrigation in real time to heatwaves or drought onset, crops are less likely to experience severe stress. Conserving water also preserves aquifers and ecosystems. All these align with SDG goals: efficient water use supports SDG 6 (Clean Water) and more reliable food production aids SDG 2 (Zero Hunger) [2], [3], [5] [6], [11].

Table 1. Typical irrigation method efficiencies (field application) [7], [8]. Higher application efficiency (Ea) means less waste. Actual efficiency depends on management.

Table 1. Typical irrigation method efficiencies

Irrigation Method	Field Efficiency (Ea)	Water Losses (runoff+ percolation)
Flood/furrow (surface)	~30–60% (often ~50%)	High (>40–70%)
Sprinkler irrigation	~75%	Moderate (~25%)
Drip/micro-irrigation	~90%+	Low (~10%)

H. Limitations and Barriers

Despite their promise, smart irrigation systems face challenges:

- High upfront cost: Sensors, controllers, communication hardware and automated valves are

expensive compared to traditional systems. As noted by the U.S. DOE, each added sensor or wireless module can significantly increase system price [12]. Small-scale or resource-poor farmers may lack capital to invest.

- **Connectivity and power:** Reliable wireless or cellular coverage may be lacking in remote rural areas. Battery-powered sensors also face maintenance (batteries/drainage). Low-power protocols (LoRa, NB-IoT) help, but network infrastructure or intermittent connectivity can still be an issue.
- **Technical complexity and maintenance:** Many farmers and irrigation managers are not trained in IoT/IT. Sensor fouling/calibration, network troubleshooting, and software updates add complexity. Systems can fail if not properly maintained (e.g. a failed sensor leading to wrong watering). Data management and interoperability (different devices, standards) are additional hurdles.
- **Data security and privacy:** Automated irrigation platforms collect data (even images from drones). Ensuring data is secure and farmers' privacy respected is important. Early systems may have cybersecurity vulnerabilities.
- **Socio-economic factors:** Fragmented land holdings (small plots) can limit economies of scale for such technology. Some farmers distrust automated decision-making and prefer traditional cues (rain, visual dryness). Adoption requires demonstrating clear returns on investment.

I. Policy and Implementation Recommendations

To accelerate adoption, policies should reduce barriers:

- **Subsidies and incentives for efficient irrigation equipment** (akin to those for drip irrigation) can lower upfront costs. Public-private programs might offer low-interest loans or grants for smart irrigation pilots.
- **Training and extension services:** Governments and NGOs can train farmers and technicians on system use and maintenance. Building awareness of water prices and scarcity can also drive demand for efficiency.
- **Standards and interoperability:** Developing open standards for IoT farming devices can prevent vendor lock-in.

- **Rural connectivity:** Investment in rural broadband/LPWAN (LoRa, NB-IoT) infrastructure ensures that even remote farms can use IoT sensors.
- **Data platforms and decision support:** Public research can provide localized crop and weather models (ET data), so farmers don't have to build them from scratch.

By combining technology with enabling policies, smart irrigation can help meet future food demand while preserving water resources.

IV. WIRELESS SENSOR NETWORKS (WSN) IN SMART IRRIGATION

Wireless Sensor Networks (WSN) enable smart irrigation by distributed sensing of field conditions (soil moisture, temperature, humidity) and remote monitoring via gateways and cloud servers. Low-power, wide-area protocols and duty-cycling achieve energy-efficient communication, allowing batteries to last years. WSNs can scale to hundreds or thousands of nodes (using mesh or star architectures) to cover large farms. Key sensor types include soil moisture probes (resistive, capacitive, TDR), temperature sensors (e.g. DS18B20 thermometers) and humidity sensors (e.g. DHT22, Sensirion SHT31). Each sensor has trade-offs in accuracy, cost, and maintenance. Control rules typically "close the loop" by irrigating when soil moisture falls below a setpoint (adjusted by temperature/humidity). Common architectures use star-of-stars (LoRaWAN), mesh (ZigBee/IEEE 802.15.4), or cellular (NB-IoT) networks, chosen for range vs. power vs. data needs. Energy-saving techniques (duty cycling, data aggregation, local processing) further extend node life. Proper sensor placement (at crop root depths, avoiding anomalies) and regular calibration/maintenance are crucial for data quality [13], [14], [15].

A. Distributed Sensing

Distributed sensing means deploying many small sensor nodes throughout the field so that each measures local soil and environmental conditions. A WSN node typically includes a microcontroller, RF radio, and one or more sensors (soil moisture, temperature, humidity, etc.). By placing nodes at multiple locations and depths, a WSN captures spatial variability (micro-climates, soil texture

differences). For example, Sui et al. deployed soil moisture probes at 3 depths in multiple fields and aggregated the data for irrigation scheduling.

Distributed sensing benefits smart irrigation by providing fine-grained data – e.g. detecting dry spots under hot sun or wet zones near shade – which static single-point sensors would miss. It enables data-driven control rules (e.g. irrigate only the driest zones).

However, distributed networks add complexity and cost. More sensors mean more batteries to replace and more radio traffic. Synchronization and clock drift among nodes can be issues without careful design. Limited bandwidth means each node usually sends only small packets (e.g. moisture reading every hour) to conserve energy. In practice, nodes often operate asynchronously and forward data through multi-hop links or via a local gateway. Mesh topologies (as in ZigBee/802.15.4) allow nodes to relay messages and extend coverage, enhancing scalability.

Example: In an ASABE study, a 900 MHz WSN (Decagon EM50) with soil and weather sensors sent soil moisture and weather data (precipitation, solar radiation, humidity, etc.) every minute, automatically uploading it via cellular to a web portal. The authors note the advantage of WSN: “continuous, real-time, in-situ measurements” of soil and weather [16].

B. Remote Monitoring and Control

Remote monitoring means that WSN data are made available off-site (e.g. via the Internet or cellular networks) so users can view field conditions and control irrigation from afar. Typically, a WSN gateway or base station collects data wirelessly from field nodes and then relays it via Wi-Fi, cellular (NB-IoT or GSM), or satellite to a cloud server. The cloud dashboard or mobile app then displays sensor readings in real time. This eliminates the need for manual field checks.

Remote monitoring allows operators to visualize trends and alerts (e.g. soil moisture dropping below threshold) and to remotely actuate valves or pumps. For instance, Meric et al. (2025) built a drip-irrigation WSN with cloud connectivity; the system

“provides real-time data and remote-control capabilities” to optimize water use [17]. Their system logged pump runtime, flow, pressure and soil moisture, automatically transmitting data over NB-IoT and LoRa links for on-line decision-making.

Benefits: Remote monitoring enables timely action (e.g. stop irrigation if unexpected rain occurs) and long-term logging (for analysis of irrigation efficiency). It also supports precision scheduling: the controller can compare current soil moisture to crop water needs, using weather forecasts and ET models. During anomalies (e.g. a leak or pump failure), the system can send alarms.

Limitations: Remote communications may depend on cellular or Internet availability. In areas without coverage, some systems must rely on long-range radio (e.g. LoRaWAN) to reach remote gateways. Security and data privacy must be managed. Also, purely remote systems may require initial on-site setup and troubleshooting.

Practical Example: A vineyard WSN used LoRaWAN to link soil and humidity sensors to a gateway, sending data to cloud software where farmers view real-time charts and trigger irrigation from their phone [17].

C. Energy-Efficient Communication

WSN nodes are usually battery or solar powered, so minimizing energy use is crucial. Strategies include:

- Low-power radios/protocols: Use LPWAN standards (e.g. LoRaWAN, NB-IoT, IEEE 802.15.4/Zigbee) that trade off data rate for range and low transmit power. For example, LoRa modulation can span many kilometers at just 10–25 dBm and data rates ~0.3–27 kbps [13], [18]. These protocols often support duty cycling or listen/sleep schedules.
- Duty cycling: Radio and sensors are active only briefly to take measurements and send a packet, then sleep for most of the time. Duty cycles of <1% are common. For example, a LoRa node might wake hourly to send soil-moisture readings, sleeping in between for months. Theoretical battery life for LoRaWAN nodes can be 5–10 years on small batteries, and NB-IoT devices also reach multi-year life by using PSM/eDRX modes [14], [15].

- **Data aggregation:** Nodes or intermediate gateways aggregate multiple readings before transmission. For instance, instead of each node sending every moisture reading, a cluster head might average them or only report changes. By reducing packet counts, this saves energy but at the cost of some resolution [15].
- **Edge processing:** Performing simple processing on-node (e.g. threshold checking, anomaly detection) can avoid sending raw data. For example, an IR sensor might only send “irrigate/don’t irrigate” flags after local decision logic, rather than raw moisture values. Local computation consumes less energy than RF transmission in many cases.
- **Mesh routing:** In a mesh (e.g. Zigbee), nodes forward data via multi-hop paths. This can shorten individual radio links, allowing lower transmit power per hop. However, mesh routers must also consume energy to relay others’ data, so routing protocols often limit hops or use sleep-aware designs.

Meric et al. noted that using efficient LPWAN links (NB-IoT/LoRa) allowed their network to run for long periods on battery, avoiding the need for regular maintenance [17]. Likewise, AWS’s NB-IoT whitepaper highlights that NB-IoT devices in Power Saving Mode can “last several years” on a battery [14]. In practice, careful duty-cycle settings (e.g. hourly wake-ups), and batching of sensor readings, are essential to achieve these lifetimes.

D. Scalability

Scalability refers to the ability of a WSN to support many nodes over large areas. Different architectures scale differently:

- **Zigbee/IEEE 802.15.4 mesh:** Zigbee networks can in theory address tens of thousands of devices (16-bit addresses). In practice, reliability and latency limit them to a few hundred devices per network. However, mesh relaying means coverage can cover large fields by hopping through nodes. Mesh networks are self-healing and support new nodes joining dynamically. Throughput is modest (max 250 kbps per link), but enough for periodic sensor reporting. Since Zigbee is low-power, many battery nodes can be used, but large mesh networks add routing overhead [19].
- **LoRaWAN (star-of-stars):** LoRaWAN supports very long range (several km), so a single

gateway can cover an entire farm. A gateway can handle thousands of end nodes. The LoRaWAN standard allows thousands of devices per gateway (uplink capacity depends on spreading factors).

Trade-offs: low data rate (0.3–50 kbps) and strict duty-cycle limits (regulatory). But it scales well in device count and geography. LoRaWAN is ideal for wide-area irrigation (orchards, large fields) where low data volume per node suffices. Private LoRaWAN networks are easy to deploy without SIM cards [13], [15].

- **NB-IoT (cellular LPWAN):** NB-IoT uses licensed cellular spectrum. It supports massive IoT (3GPP notes “massive number of devices”) and can handle tens of thousands of devices per cell. Range to the base station is typically ~1 km in city, up to ~10 km rural. Throughput is moderate (~20–60 kbps). Since NB-IoT is operated by carriers, deploying it covers large areas with existing networks. It scales well (sharing infrastructure) but incurs SIM/subscription costs. NB-IoT signals penetrate buildings and soil well, reaching devices even in basements or heavy foliage [14].
- **IEEE 802.15.4 (6LoWPAN/Thread) star/tree:** Without mesh routing (star only), range is short (~10–50 m indoor, ~100 m outdoor). Throughput is up to 250 kbps. IEEE 802.15.4 networks (without Zigbee) are mostly point-to-point or star; they can scale by adding multiple coordinators or gateways. Thread (an IPv6 mesh over 802.15.4) can also support large address spaces. However, for vast farms, the limited RF range often makes IEEE 802.15.4 unsuitable unless many repeaters are used [19], [20].

V. SOIL MOISTURE SENSING

Sensor Types: Common soil moisture sensors measure water content. Major types include:

- **Resistive probes:** Two exposed electrodes measure soil conductivity. Very cheap (~\$5–10), but accuracy is poor. Soil chemistry (salt) and corrosion degrade them. They respond more to salinity than true moisture. Studies note that “resistance-based techniques will not yield good results” for moisture.
- **Capacitive sensors:** Two electrodes form a capacitor; the dielectric constant (dominated by

water) changes with moisture. These include FDR (frequency-domain reflectometry) and simple capacitance sensors. Moderate cost (~\$10–50 for hobbyist probes; professional sensors \$100+) and low power. Accuracy can be $\pm 2\text{--}3\%$ volumetric water content (VWC). Vulnerable to poor installation (air gaps) and high salinity (which biases readings). Many low-cost brands exist, but quality varies.

- **TDR (Time-Domain Reflectometry):** Measures the travel time of an electromagnetic pulse along buried probes; this time depends on dielectric constant. TDR is the most accurate ($\pm 1\text{--}3\%$ VWC with calibration) and stable over time. Drawbacks: very expensive (hundreds to thousands of dollars), high power (often mains-powered), and complex installation. TDR probes must be installed in trenches and require soil calibration.

- **Tensiometers/Granular-matrix:** Measure matric suction (soil water tension) instead of VWC. They fill with water and measure vacuum pressure. A Tensiometer gives a direct measure of how tightly plants hold water, which directly relates to when to irrigate. They are moderately priced (hundreds of dollars) but require maintenance (refill with water) and only work in wetter ranges (-0 to -85 kPa) [21]. Granular-matrix sensors (e.g. gypsum blocks) measure resistance in a wetted block; lower cost (~\$40), but slow response and limited range [22].

Measurement Principles: The resistive sensors rely on conductivity, capacitive/TDR on dielectric permittivity, and tensiometers on hydraulic pressure. Each must be interpreted by calibration curves or lookup tables to convert raw signal into soil water content (VWC) or matric potential (kPa).

Accuracy and Limitations: As noted, resistive sensors are inexpensive but low accuracy. Capacitance and TDR (dielectric sensors) achieve high accuracy ($\approx \pm 2\text{--}3\%$ VWC) if properly calibrated. In practice, METER Group finds “TDR and capacitance to be equally accurate with calibration”, while resistive sensors are unreliable. Key error sources: poor contact (air gaps), soil salinity or clay activity, temperature effects. A bad installation gap can cause large errors for dielectric sensors [22].

Calibration and Maintenance: Professional sensors come factory-calibrated for standard soils, but best

practice is soil-specific calibration (e.g. gravimetric samples). Cheap sensors (e.g. Arduino-type capacitive probes) often need in-field calibration (two-point) if precision is needed. Resistive probes require virtually no calibration but should be replaced often (they corrode within months). Tensiometers must be checked for water level and have their porous cup cleaned. Periodically verify sensors against a reference or between depths to detect drift.

Placement Strategies: Sensor location critically affects readings. As per [21], place soil sensors in the active root zone (usually one-third, two-thirds, and full root depth). For row crops, install sensors between plants along a representative row; for orchards/vineyards, under the tree canopy but away from trunks. Avoid anomalous spots (wheel tracks, end-gun overlaps). A single sensor cannot represent a whole field, so use multiple sensors in different zones if possible. An example MSU bulletin recommends, for corn with 3 ft roots, sensors at 12", 24", 36" depths. Infiltration patterns (e.g. drip emitters) should guide placement; a sensor too far from emitters might never get wet or always saturated.

Data Fusion: Soil moisture sensors can be combined with other data (e.g. recent rainfall, evapotranspiration estimates) to refine irrigation decisions. For instance, a sensor showing mild dryness might be ignored if significant rain is forecast. Advanced systems compute an ET balance using temperature/humidity/wind data and compare it to measured soil moisture. Fusing data helps avoid unnecessary watering (e.g. skip irrigation if humidity is high and dew forms).

Irrigation Control: Soil sensors often drive on/off rules. A common rule: if moisture drops below a setpoint (e.g. 40% of plant-available water), open valves; stop when it exceeds a higher threshold. For example, Michigan State recommends irrigating when available water is $\sim 30\text{--}60\%$ depleted [21]. In practice, farmers may use hysteresis (two setpoints) to avoid frequent toggling. In modern WSN systems, the microcontroller in the gateway can implement such logic based on incoming soil moisture and possibly override by weather inputs.

VI. TEMPERATURE MONITORING

Sensor Types: Common air/soil temperature sensors include digital thermometers and thermistors. For e.g. the Maxim DS18B20 (digital 1-Wire, $\pm 0.5^\circ\text{C}$ accuracy), analog thermistors (NTC/RTD), or integrated chips (LM35, BME280 pressure sensor, etc.). Some humidity sensors (like SHT31) also measure temperature. In cost terms, DS18B20 modules run $\sim \$2-5$, thermistors even less.

Measurement Principle: Thermistors/RTDs change resistance with temperature; digital sensors have built-in analog-to-digital converters calibrated to output $^\circ\text{C}$. Many inexpensive sensors are accurate to $\pm 0.5-2^\circ\text{C}$ across -10 to $+50^\circ\text{C}$ range. For example, the DS18B20 datasheet specifies $\pm 0.5^\circ\text{C}$ (-10 to $+85^\circ\text{C}$).

Accuracy and Limitations: Most commodity sensors (DS18B20, DHT series, etc.) have accuracies on the order of a degree. Factory-calibrated chips (e.g. Sensirion SHT3x series) can achieve $\pm 0.2^\circ\text{C}$ [23]. Thermistor beads (inexpensive) might only guarantee $\pm 1-2^\circ\text{C}$. Limitations include self-heating, sensor drift over years, and measurement error if not shaded (direct sun on a sensor will read too high) [24].

Calibration and Maintenance: Most digital temperature sensors are calibrated at manufacture. Field calibration is seldom done, except to correct any offset (e.g. using a reference thermometer in shade). Maintenance mainly involves protecting the sensor: mount in a radiation shield or ventilated screen to avoid solar heating, keep out of rain/splash. Check connections and clean if dust accumulates on exposed probes.

Placement: Place air temperature sensors in shaded, well-ventilated locations at canopy height for plant-level microclimate. Avoid direct sunlight or nearby heat sources. Soil temperature sensors (if used) should be buried at root zone depth (a few inches). Consistent placement is crucial: a sensor reading 5°C higher due to sun exposure will mislead irrigation control.

Data Fusion and Control: Temperature is often used with moisture to estimate evaporative demand. High

air temperature increases evapotranspiration, meaning plants will deplete soil faster. Some systems use temperature to scale irrigation volume or scheduling (warmer $\rightarrow$ more water). If temperature is low (e.g. night or cool season), irrigation might be reduced even if soil is dry, since plant demand is low. For e.g.: a decision rule might be “only irrigate if soil dry AND temperature $> 10^\circ\text{C}$ ” to avoid watering in cold, damp periods. However, precise algorithms vary by crop and climate.

VII. HUMIDITY MONITORING

Sensor Types: Humidity is typically measured with capacitive polymer sensors. Common modules include DHT11 (cheapest), DHT22/AM2302, Sensirion SHT series (SHT21/31/40), Honeywell HIH-4000, Bosch BME280, etc. DHT11 costs a few dollars, DHT22 $\sim \$10$, SHT31 around $\$10-20$. Professional meters (Vaisala, Rotronic) are far more expensive but not practical for WSN.

Measurement Principle: A hygrometer's sensing element is a polymer whose dielectric constant changes with water vapor absorption. The chip measures capacitance and converts to relative humidity (RH). Readings are usually linearized and temperature-compensated. The sensors measure %RH (0–100%).

Accuracy and Limitations:

- DHT11: Low-cost; RH accuracy $\sim \pm 5\%$ (at 25°C) and temperature $\pm 2^\circ\text{C}$ [25]. Range 20–80% RH (poor outside that). Not very accurate or precise, and slow (1 Hz max sampling). Suitable only for very rough control.
- DHT22/AM2302: Better; RH $\pm 2-5\%$ (per Adafruit), temp $\pm 0.5^\circ\text{C}$. Covers 0–100% RH, $-40-80^\circ\text{C}$. Moderate speed (0.5 Hz). These are very common in hobby projects but still not lab-grade.
- Sensirion SHT3x series: High-quality digital sensors. For SHT31/35: RH accuracy $\pm 2\%$ (0–100% range) and temp $\pm 0.2^\circ\text{C}$. Fast response (few seconds) and factory-calibrated. Quite good for precision applications [23].
- Honeywell HIH-4000: $\pm 3.5\%$ RH typical, $\pm 0.4^\circ\text{C}$. Common in OEM products.

Low-cost capacitive sensors drift over years or with contamination. They should be kept clean of dust and

water. At high humidity, condensate on the sensor can cause errors.

Calibration & Maintenance: Most digital RH sensors (DHT22, SHTxx) come factory-calibrated and include calibration data in memory. End-users generally do not need to calibrate, but one should ensure the sensor's readings match a reference if precision is critical. To check, place the sensor in a controlled environment (like a salt bath at known RH or a humidity chamber). Over time, sensors can drift or their polymer degrade; industry practice is to replace or recalibrate every 1–2 years for high-accuracy needs. Dust filters or screen covers (with breathable material) can protect the element, but must be regularly cleaned or replaced.

Placement: Humidity sensors should be sheltered from rain/drips (they measure air moisture, not direct water). A weather station radiation shield or fine mesh cover is ideal – it keeps raindrops off and allows air circulation. Install them at crop height or above the canopy to measure ambient RH (soil-level RH is less common). Avoid placing next to sprinklers or foggers, as local humidity spikes may not represent field-average conditions.

Data Fusion and Control: Air humidity affects plant transpiration: lower RH (dry air) leads to higher water loss. Humidity is often used along with temperature to compute absolute humidity or vapor-pressure deficit (VPD). A common irrigation rule: “If low soil moisture and low relative humidity (dry air), then irrigate” because plant stress is likely. Conversely, if RH is very high (e.g. dewpoint conditions), plants may not need water even if soil is moderately dry. Some controllers use an “evaporative stress index” combining temp and RH to adjust watering [16].

A. Sensor Comparison Table

Below is a comparative summary of representative sensor options.

Table 2. Sensor Comparison

Sensor Type (Example)	Approx. Cost (USD)	Power Use	Accuracy	Field Suitability
Soil – Resistive	\$5 – 10	Very low (μ W)	Very low (qualitative)	Poor (corrodes, uses often)

				only as cheap indicator)
Soil – Capacitive (FDR)	\$10 – 100 (consumer)	Low (mW)	Moderate ($\pm 3\text{--}5\%$ VWC after cal)	Good (widely used); several require calibration; salinity-sensitive [22]
Soil – TDR Probe	\$200 – 2000+	Moderate–High (mA)	High ($\pm 1\text{--}3\%$ VWC with calibration) [22]	Research-grade; durable; expensive; often mains- or solar-powered
Temp – DS18B20 (1W)	\$3 – 5	Very low (μ W)	$\pm 0.5\text{ }^{\circ}\text{C}$ (-10 to $+85\text{ }^{\circ}\text{C}$)	Excellent: digital, waterproof options; multi-drop wiring
Temp – Thermistor	\$1 – 3	Very low (μ W)	$\pm 0.1\text{--}1.0\text{ }^{\circ}\text{C}$ (depending on type)	Good for cheap deployments; nonlinear output requires linearization
Humidity – DHT22/A M2302	\$5 – 15	Low (mW)	$\pm 2\text{--}5\%$ RH; $\pm 0.5\text{ }^{\circ}\text{C}$	Popular hobbyist sensor; moderate speed; limited long-

				term stability
Humidity – SHT31/SH T35	\$10 – 20	Low (μ W)	$\pm 2\%$ RH; $\pm 0.2\text{ }^{\circ}\text{C}$ [23]	High quality; factory- calibrate d; used in high- precisio n systems

VIII. NETWORK ARCHITECTURES AND PROTOCOLS

A. Zigbee/IEEE 802.15.4 (Mesh/Star)

- Architecture: Mesh or cluster-tree. Each node can route for others. Coordinator/gateway at root collects data.
- Range: Short (~10–100 m). Indoor ~10–30 m, outdoor up to ~100 m line-of-sight.
- Throughput: Up to 250 kbps (at 2.4 GHz). Sub-GHz versions (868 MHz) lower data (~20 kbps).
- Power: Low. Nodes can sleep, achieving multi-year battery life (IEEE802.15.4 at low duty cycle, Zigbee adds extra sleep features).
- Scalability: Moderate. Theoretically thousands of addresses, but practical nets are a few hundred nodes due to mesh overhead. Network join is automatic.
- Pros: Low power, reliable mesh (self-healing), good data rate for sensor bursts. Can be deployed privately.
- Cons: Short range (many routers needed for large areas), limited throughput for heavy data (e.g. images). Interference at 2.4 GHz (Wi-Fi) possible [19], [20].

B. LoRaWAN (Star-of-Stars)

- Architecture: Star-of-stars. End nodes (sensors) send to one or more gateways; gateways forward to network server (often cloud).
- Range: Very long. Up to ~10–15 km in rural areas, ~2–5 km urban. Multi-km links at SF7–SF12 spreading factors.
- Throughput: Very low. ~0.3–50 kbps, depending on spreading factor. Uplink-limited (few packets/min).

- Power: Ultra-low. Typical nodes last 5–10+ years on AA batteries. Sleep current often $<10\text{ }\mu\text{A}$.
- Scalability: High. A single gateway can handle thousands of nodes (limit ~10k uplinks/day per channel before congestion). Many public networks exist, or private networks are easy.
- Pros: Excellent coverage, low node cost, long battery life, license-free band. Good for wide-area agricultural deployment.
- Cons: Low data rate and strict duty-cycle ($\approx 1\%$ in many regions). Downlink (server to node) is limited and infrequent. Requires gateway(s) and network server (The Things Network, ChirpStack, etc.) [13], [15], [18].

C. NB-IoT (Cellular LPWAN)

- Architecture: Star. Nodes connect directly to cellular towers (NB-IoT base stations). No local gateway needed.
- Range: ~1 km urban, ~5–10 km rural. Built to penetrate buildings/soil; can reach underground or inside silos with enhanced coverage modes.
- Throughput: Moderate. Peak ~20–60 kbps (uplink), ~20–50 kbps (downlink). Higher than LoRa, but still low by broadband standards.
- Power: Low. Sleep modes (PSM/eDRX) allow multi-year battery life. However, NB-IoT nodes require periodic network synchronization which consumes more energy than LoRa.
- Scalability: Very high. 3GPP designs NB-IoT for massive IoT (e.g. 50,000+ devices per cell). Runs on existing cellular infrastructure (carrier SIM required). The coverage depends on carrier deployment (NB-IoT is now widespread globally).
- Pros: Wide coverage with roaming, good for devices in motion or hard-to-wire areas. Strong QoS and security (SIM-based). Suitable for moderate data and bidirectional commands.
- Cons: Module cost and data plan fees. Higher power use than LoRa, so nodes often need larger batteries or solar. Less privacy (data goes through carrier) [14].

D. IEEE 802.15.4 (Non-Zigbee)

- Architecture: Typically star or tree (e.g. 6LoWPAN, Thread). Coordinator collects from leaves.

- Range: Similar to Zigbee (~10–100 m depending on band). Sub-GHz modes slightly longer range at lower data (20–50 kbps).
- Throughput: Up to 250 kbps.
- Power: Low. Many implementations support deep sleep.
- Scalability: Limited by range; large area requires many coordinators. IPv6/6LoWPAN variants can theoretically address many devices, but each network is local.

E. Energy-Saving Techniques

Practical methods to conserve sensor-node energy include:

- Duty Cycling: Configure each node to wake only when needed (e.g. once every 5–60 minutes). The radio, MCU, and sensors sleep otherwise. For example, sampling moisture hourly and sleeping 59 min yields ~98% duty cycle reduction. The Arduino DS18B20 dev board (1-Wire) can sample in <1 s then sleep, yielding very low average current. Many LPWAN modules support deep sleep (<10 μ A).
- Adaptive Sampling: Dynamically adjust sampling rate based on conditions. For e.g. if soil moisture is far from threshold, measure less frequently; if rapidly changing (or rain forecast), increase rate. This smart scheduling conserves energy when changes are slow.
- Clustering/Aggregation: In dense deployments, elect a cluster-head node that collects readings from neighbors via short-range links, then sends one aggregated packet long-range. This is common in research WSN (e.g. LEACH protocol) to reduce long-range transmissions. Sensors like temperature/humidity could first wirelessly forward data to a soil-moisture node, which then reports all together.
- Edge Processing (On-node Decision): Implement simple control logic on each node. For instance, a moisture node could have thresholds and directly switch a solenoid if connected, without contacting the server. Alternatively, nodes could detect anomalies (e.g. sensor fault, extreme values) and only send alerts instead of raw data. This reduces communication load.
- Transmission Power Control: Use just enough transmit power for reliable communication. For example, LoRa's adaptive data rate (ADR) lets nodes reduce spreading factor or RF power when the

link is good, shortening time-on-air. This saves energy and allows more nodes to share the network.

- Energy Harvesting: Where feasible, use solar panels or energy-harvesting to recharge batteries. Many outdoor sensor nodes include small solar panels to run indefinitely. Even kinetic or microbial fuel cells (for soil) have been demonstrated. These approaches, while beyond pure “duty cycling,” effectively extend network life without maintenance [14], [15].

F. Deployment and Maintenance Best Practices

- Sensor Installation: Follow manufacturer guidelines. For soil probes, insert without air gaps (e.g. by boring a trench and backfilling around the sensor). Use specialized insertion tools if available (e.g. METER's borehole tool [22]). For moisture sensors, ensure good contact by moistening soil or using saline solution. For weather sensors, mount them on poles/shields: temperature/humidity in radiation screens, rain gauges level, anemometers above obstructions.
- Wiring and Power: Use waterproof cables and enclosures (IP65+) for sensors and nodes. Protect electronics from dust, rodents, and moisture. If using solar panels, ensure panels face unobstructed sun and batteries are sized for worst-case weather. Label all nodes with IDs and notes on battery install date.
- Network Planning: Perform a range test for wireless nodes before finalizing placements. Check that each node can reach its gateway (with antenna as needed). In tall crops, place antenna above canopy for line-of-sight (as Sui et al. did) [16]. If range is marginal, add a repeater or use a mesh router.
- Time Synchronization: For time-stamped data, synchronize clocks (via the gateway or GPS time) to correlate sensors. Some protocols (like 802.15.4) support time-sync frames. Periodic re-sync can correct drift.
- Calibration Checks: Establish a calibration schedule. For soil moisture, verify at planting and mid-season using a calibrated probe or manual soil samples. For temperature/humidity, compare a reference thermometer/hygrometer semi-annually. Record and apply any offset.
- Batteries: Use high-quality cells (lithium primary often) to avoid mid-season failure. Replace batteries at least annually or carry spares. For solar systems, clean panels monthly and ensure battery

float-charging is working. Monitor battery voltage via WSN if possible (many node designs include a supply monitor) and send low-battery alerts.

- **Data Monitoring:** Regularly check the data stream. Early missing or flat-line readings may indicate a failed sensor or power loss. Some IoT platforms allow “heartbeat” checks or watchdog alarms. Investigate anomalies promptly to avoid season-long data gaps.
- **Field Logistics:** Protect nodes from farm operations: avoid placing them in vehicle paths. Mark their locations on field maps. If tractors or harvesters may hit a node, consider a protective housing or placing them deeper and closer to crops.
- **Seasonal Maintenance:** Before each planting season, clean and inspect all sensors (wipe off soil, remove vegetation). Re-run any calibration from scratch if possible. Update firmware to fix bugs or improve power management.

IX. CONCLUSION

The evolution of agriculture from conventional farming practices to intelligent digital ecosystems has fundamentally transformed irrigation management through the integration of Wireless Sensor Networks, Cloud computing, the Internet of Things, and Artificial Intelligence. This paper demonstrates that, although substantial progress has been achieved, existing research remains fragmented, with limited integration of sensing, communication, cloud services, and autonomous learning into unified irrigation systems. Challenges related to interoperability, energy consumption, communication reliability, and deployment scalability continue to hinder large-scale adoption.

The synthesis of current literature indicates that future smart irrigation systems will increasingly rely on integrated Cloud-IoT-WSN architectures enhanced by advanced Reinforcement Learning, and next-generation wireless communication technologies. These advances are expected to enable autonomous, resilient, and resource-efficient irrigation systems capable of optimizing water use, improving crop productivity, reducing operational costs, and strengthening climate resilience. Overall, an integrated intelligent irrigation ecosystem that combines real-time sensing, scalable computing, and adaptive decision-making represents a promising

direction for achieving sustainable agriculture and long-term water security.

ACKNOWLEDGMENT

The author would like to extend sincere thanks to the co-author as well as the research supervisor for their constant help, guidance, and support throughout the work.

REFERENCES

- [1] A. Hamad and A. Tayel, “Food 2050 concept: the trends that shape the future of our food,” *J. Future Foods*, vol. 6, no. 6, pp. 1053–1066, Nov. 2026, doi: 10.1016/j.jfutfo.2025.03.003.
- [2] “8 key messages about climate risks to agrifood systems from the IPCC’s Sixth Assessment Report | UNDP Climate Change Adaptation.” Accessed: Aug. 04, 2026. [Online]. Available: <https://www.adaptation-undp.org/8-key-messages-about-climate-risks-agrifood-systems-ipccs-sixth-assessment-report>
- [3] V. Sharma, G. Kaur, S. S., V. Chhabra, and R. Kashyap, “Smart irrigation systems in agriculture: An overview,” *Comput. Electron. Agric.*, vol. 239, p. 111008, Dec. 2025, doi: 10.1016/j.compag.2025.111008.
- [4] “13.2: Water Usage - Biology LibreTexts.” Accessed: Aug. 04, 2026. [Online]. Available: [https://bio.libretexts.org/Bookshelves/Ecology/Environmental_Science_\(Ha_and_Schleiger\)/04%3A_Humans_and_the_Environment/4.02%3A_Water_Resources/4.2.02%3A_Water_Usage](https://bio.libretexts.org/Bookshelves/Ecology/Environmental_Science_(Ha_and_Schleiger)/04%3A_Humans_and_the_Environment/4.02%3A_Water_Resources/4.2.02%3A_Water_Usage)
- [5] P. Tang, Q. Liang, H. Li, and Y. Pang, “Application of Internet-of-Things Wireless Communication Technology in Agricultural Irrigation Management: A Review,” *Sustainability*, vol. 16, no. 9, p. 3575, Jan. 2024, doi: 10.3390/su16093575.
- [6] “The United Nations World Water Development Report 2023: partnerships and cooperation for water - UNESCO Digital Library.” Accessed: May 14, 2026. [Online]. Available: <https://unesdoc.unesco.org/ark:/48223/pf0000384655>
- [7] “Annex I: Irrigation efficiencies.” Accessed: Aug. 04, 2026. [Online]. Available: <https://www.fao.org/4/t7202e/t7202e08.htm>

- [8] "Small-scale irrigation for arid zones Improving water-use efficiency." Accessed: Aug. 05, 2026. [Online]. Available: <https://www.fao.org/4/w3094e/w3094e04.htm>
- [9] L. Umutoni and V. Samadi, "Application of machine learning approaches in supporting irrigation decision making: A review," *Agric. Water Manag.*, vol. 294, p. 108710, Apr. 2024, doi: 10.1016/j.agwat.2024.108710.
- [10] Y. Saikai, A. Peake, and K. Chenu, "Deep reinforcement learning for irrigation scheduling using high-dimensional sensor feedback," *PLOS Water*, vol. 2, no. 9, p. e0000169, Sep. 2023, doi: 10.1371/journal.pwat.0000169.
- [11] "Strains on freshwater resources: The impact of food production on water consumption," *World Bank Blogs*. Accessed: May 18, 2026. [Online]. Available: <https://blogs.worldbank.org/en/opendata/strains-freshwater-resources-impact-food-production-water-consumption>
- [12] "Water-Efficient Technology Opportunity: Advanced Irrigation Controls," *Energy.gov*. Accessed: Aug. 05, 2026. [Online]. Available: <https://www.energy.gov/cmei/femp/water-efficient-technology-opportunity-advanced-irrigation-controls>
- [13] "About LoRa and LoRaWAN," *Arduino Help Center*. Accessed: Aug. 05, 2026. [Online]. Available: <https://support.arduino.cc/hc/en-us/articles/4402394268562-About-LoRa-and-LoRaWAN>
- [14] "NB-IoT - Implementing Low-Power Wide-Area Network (LPWAN) Solutions with AWS IoT." Accessed: Aug. 05, 2026. [Online]. Available: <https://docs.aws.amazon.com/whitepapers/latest/implementing-lpwan-solutions-with-aws/nb-iot.html>
- [15] "TEKTELIC | Comparison of LoRaWAN, NB-IoT, Sigfox, and LTE." Accessed: Aug. 05, 2026. [Online]. Available: <https://tektelic.com/expertise/lorawan-vs-nb-iot-sigfox-and-lte-comparison/>
- [16] "Wireless Sensor Network for Monitoring Soil Moisture and Weather Conditions," *Appl. Eng. Agric.*, pp. 193–200, Mar. 2015, doi: 10.13031/aea.31.10694.
- [17] M. Meric, "Implementation of a wireless sensor network for irrigation management in drip irrigation systems," *Sci. Rep.*, vol. 15, Apr. 2025, doi: 10.1038/s41598-025-97303-w.
- [18] "LoRa," *Wikipedia*. Aug. 03, 2026. Accessed: Aug. 05, 2026. [Online]. Available: <https://en.wikipedia.org/w/index.php?title=LoRa&oldid=1367540315>
- [19] "Zigbee Standard - an overview | ScienceDirect Topics." Accessed: Aug. 05, 2026. [Online]. Available: <https://www.sciencedirect.com/topics/computer-science/zigbee-standard>
- [20] "Zigbee," *Wikipedia*. Jul. 11, 2026. Accessed: Aug. 05, 2026. [Online]. Available: <https://en.wikipedia.org/w/index.php?title=Zigbee&oldid=1363649030>
- [21] "Utilizing Soil Moisture Sensors for Efficient Irrigation Management - Irrigation." Accessed: Aug. 05, 2026. [Online]. Available: <https://www.canr.msu.edu/resources/utilizing-soil-moisture-sensors-for-efficient-irrigation-management>
- [22] "Soil moisture sensors—How they work. Why some are not research grade - METER Group." Accessed: Aug. 05, 2026. [Online]. Available: <https://metergroup.com/measurement-insights/soil-moisture-sensors-how-they-work-why-some-are-not-research-grade/?srsltid=AfmBOoq-bo9IqQXF9whB4NpAKhn52tCgRfKMH0LIY15nJi5S1D8n4KR3>
- [23] S. AG, "SHT31-DIS-B - $\pm 2\%$ (0-100%RH) Digital humidity and temperature sensor." Accessed: Aug. 05, 2026. [Online]. Available: <https://sensirion.com/products/catalog/SHT31-DIS-B>
- [24] "Discover Versatile DS18B20 Sensor for Arduino - IP68 Protection?," *Waterproof DS18B20 Sensor for Arduino - IP68 & Versatile Applications | DFRobot Wiki*. Accessed: Aug. 05, 2026. [Online]. Available: <https://wiki.dfrobot.com/dfrobot198/>
- [25] alldatasheet.com, "DHT11 Datasheet(PDF)." Accessed: Aug. 05, 2026. [Online]. Available: <http://www.alldatasheet.com/datasheet-pdf/pdf/2193416/OSEPP/DHT11.html>