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AI-Driven Smart Agriculture: An Intelligent Farming System Using AI, IoT, ESP32, Edge AI, and Smart Solar Irrigation

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Abstract

Agriculture is the mainstay of the Indian economy, However, water insecurity, climate variability and degradation of soils are the challenges faced by farmers. Increasing energy prices and crop diseases. Existing studies show that Artificial Intelligence (AI), the Internet of Things (IoT), Edge AI, It is believed that computer vision and smart irrigation could be applied to enhance agricultural production. They are typically used for decision-making and resource use, although the use of them is not always restricted. independently, rely on internet connection or cloud computing, Still be expensive for small and medium-sized farmers. This paper surveys eight recent studies from 2022 to 2026, derives seven research gaps from them, and proposes a conceptual, affordable platform that combines an ESP32 microcontroller, soil and environmental sensors, Edge AI-based crop and fertilizer recommendation, computer-vision detection of crop diseases, pests and weeds, solar-powered smart irrigation, and a mobile application with a multilingual voice assistant. An evaluation plan is also given. The contribution is a literature-grounded design and research agenda; the platform has not yet been implemented or empirically validated.

Keywords : Artificial intelligence; Internet of Things; ESP32; Edge AI; computer vision; smart solar irrigation; precision agriculture

I. INTRODUCTION

Agriculture is essential to the Indian economy but faces challenges such as water scarcity, climate change, soil degradation, increasing energy costs and crop diseases. AI and IoT technologies can support real-time monitoring, prediction and intelligent decision-making in agriculture [2], [7].

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IoT sensors such as soil moisture, pH, NPK, temperature and humidity sensors can collect field data for soil analysis, crop selection, fertilizer recommendations and irrigation management [2], [3], [6]. Using smart irrigation systems based on IoT and edge. Computing can optimise water usage, minimise wastage and Make more prompt decisions at the local level [4,8,9].

AI based computer vision and Edge AI can identify crop issues, such as pest infestation, from a distance. scouting from the field images, and thus direct (real-time) scouting for diseases and pests. and low-latency monitoring [1]. However, cost, connectivity, The needs for energy and complexity of systems continue to be challenges. for resource-limited farmers [5].

This paper thus looks into the smart agriculture system using AI. concept that integrates ESP32, IoT sensors, Edge AI, computer A mobile app, smart solar irrigation and vision into an. Cost-effective and viable platform.

The concept aims to improve farm-level decision-making while conserving water, energy and other agricultural resources [1]–[9].

The paper makes three contributions. First, it reviews eight studies published between 2022 and 2026 on AI, IoT, Edge AI and smart irrigation, comparing their methods, findings and limitations (Section III). Second, it derives seven research gaps from that comparison (Section IV). Third, it proposes a conceptual framework, an implementation roadmap and an evaluation plan that respond to those gaps (Sections V–X). The paper is a literature-grounded design rather than an implemented or validated system.

II. Problem Statement and Objectives

A. Problem Statement

Many existing smart agriculture systems are costly, depend on the internet and combine AI, IoT and irrigation only partially, which leaves small and medium-scale farmers underserved. This paper therefore proposes an affordable AI-based smart agriculture system using ESP32, IoT, Edge AI and smart solar irrigation for intelligent farming.

B. Objectives

1) Study the role of Artificial Intelligence (AI), IoT, ESP32 and Edge AI in smart agriculture.
2) Explore the use of soil moisture, pH, NPK, temperature and humidity sensors for real-time farm monitoring.
3) Understand the concept of an AI-based smart solar irrigation system for efficient water and energy management.
4) Examine AI-based crop and fertilizer recommendations using soil and environmental data.
5) Study computer-vision techniques for early detection of crop diseases, pests, weeds and nutrient deficiencies.
6) Propose an affordable, modular smart farming system with a mobile application and multilingual voice assistant for small and medium-scale farmers.

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III. Related Work

Eight studies published between 2022 and 2026 were reviewed. The evolution of smart agriculture can be summarised as: Traditional Farming → IoT → AI → Edge AI → Smart Solar Irrigation. Earlier approaches focused on soil moisture monitoring and automated irrigation using sensors and basic control mechanisms [6], [9]. Fig. 1 shows this progression and Table I summarises the reviewed studies.

A. AI and IoT for Soil Analysis and Decision Support

Das et al. [2] combine ESP32-based IoT monitoring with AI-powered decision support, enabling real-time monitoring and intelligent farming decisions; the system depends on the cloud and is more complex. Khaliq et al. [3] review AI, IoT, deep learning and explainable AI (XAI) and report accurate crop, fertilizer, soil-analysis and irrigation recommendations, but such models need more computational resources. Muhammed et al. [7] review the Artificial Intelligence of Things (AIoT) and find that it improves crop monitoring, irrigation, pest detection and resource management, with limited real-world deployment, interoperability and data-privacy challenges.

B. Edge AI and Computer Vision

Chung et al. [1] build a low-cost Edge AI system with ESP32-CAM and Raspberry Pi 5 using YOLOv8n and ResNet-18 over MQTT and HTTP for real-time pest and disease detection in chili pepper fields. They report a 0.86 s response time and approximately 60% lower computational cost. The system is mainly image-based and chili-specific, and it lacks environmental sensor data and multi-crop testing. Edge processing is also used for irrigation: Obaideen et al. [4] present an ET-based smart irrigation system using LoRa and edge computing for farmland.

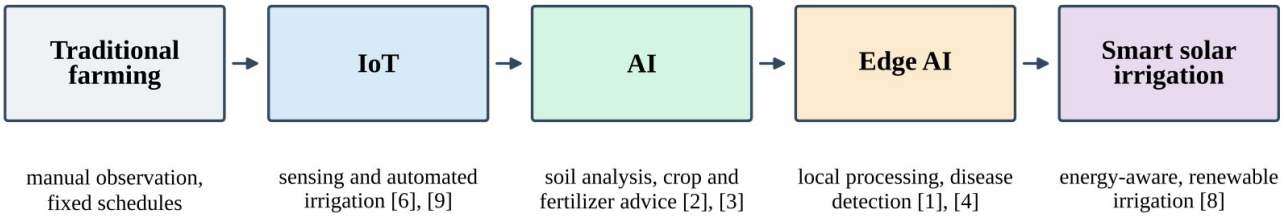


Fig. 1. Evolution of smart agriculture, from traditional farming to energy-aware smart solar irrigation, with the reviewed studies that represent each step.

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TABLE I
COMPARATIVE SUMMARY OF REVIEWED LITERATURE

Ref.	Author / Year	Methodology	Key finding	Limitation
[1]	H. Chung et al. (2026)	ESP32-CAM, Raspberry Pi 5, IoT, Edge AI, YOLOv8n, ResNet-18, MQTT, HTTP	Low-cost Edge AI for real-time pest and disease detection; 0.86 s response time, about 60% lower computational cost	Mainly image-based and chili-specific; no environmental sensor data or multi-crop testing
[2]	A. Das et al. (2025)	ESP32-based IoT monitoring with AI-powered decision support	AI and ESP32 enable real-time monitoring and intelligent farming decisions	Cloud dependency and higher system complexity
[6]	S. Gupta et al. (2025)	IoT-based automated irrigation with predictive algorithms	Reduced water usage; improved water and energy efficiency	Arduino-based system; limited AI capabilities
[3]	A. Khaliq et al. (2025)	AI + IoT + deep learning + Explainable AI (XAI)	Accurate crop, fertilizer, soil-analysis and irrigation recommendations	Requires advanced AI models and higher computational resources
[5]	A. Cisse et al. (2025)	Systematic review of AI, IoT and Agriculture 4.0 technologies	Improve precision farming, crop monitoring and resource management	High cost, cybersecurity issues, limited adoption in resource-limited areas
[7]	D. Muhammed et al. (2024)	AIoT review for smart agriculture	Improves crop monitoring, irrigation, pest detection and resource management	Limited real-world deployment, interoperability and privacy challenges
[8]	Y. Gamal et al. (2023)	Survey of smart irrigation using IoT and energy harvesting	Reduces water waste; supports sustainable agriculture	High sensor cost and limited AI integration
[9]	K. Obaideen et al. (2022)	IoT, WSN and smart irrigation review	Real-time monitoring improves irrigation efficiency	Focuses on irrigation rather than complete smart farming

C. Smart and Solar-Powered Irrigation

Gupta et al. [6] use IoT-based automated irrigation with predictive algorithms and report reduced water use and improved water and energy efficiency, although the Arduino-based system has limited AI capability. Gamal et al. [8] survey smart irrigation with IoT and energy harvesting and find that it reduces water waste and supports sustainability, but note high sensor cost and limited AI integration. Obaideen et al. [9] review IoT, wireless sensor networks and smart irrigation, and conclude that real-time monitoring improves irrigation efficiency; the focus is on irrigation rather than complete smart farming.

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D. Resource-Limited Contexts

Cisse et al. [5] systematically review AI, IoT and Agriculture 4.0 technologies and find that they improve precision farming, crop monitoring and resource management. They also report high implementation cost, cybersecurity issues and limited adoption in resource-limited areas.

IV. Research Gaps

Reading the eight studies together surfaces seven gaps that motivate the framework proposed in Section V.

G1. High implementation cost. Many existing smart agriculture systems are expensive to deploy [5], [8].

G2. Internet dependency. Many systems rely on cloud processing and continuous connectivity [2].

G3. High energy consumption. Some smart agriculture applications consume considerable energy.

G4. Limited integration. AI, IoT, Edge AI and smart solar irrigation are rarely combined in a single affordable system [6], [8], [9].

G5. Sensor and vision data are not combined. Environmental sensor data is seldom integrated with Edge AI-based disease and pest detection [1].

G6. Limited testing. Existing systems are rarely tested across multiple crops and real-world agricultural environments [1], [7].

G7. Small and medium-scale farmers. Affordable solutions for these farmers are lacking [5].

Main gap: no reviewed study combines AI, IoT, Edge AI, computer vision and solar-powered irrigation in a single, affordable, modular system suited to resource-limited farms.

V. Proposed Framework

A. Design Principles

The framework responds directly to the gaps in Section IV: low-cost hardware (G1, G7), local Edge AI processing that keeps working offline (G2), solar power with energy-aware scheduling (G3), a single integrated platform (G4, G5) and multi-crop evaluation (G6). Four principles guide the design.

- **Affordable and modular:** low-cost components such as the ESP32 so that farmers can adopt parts of the system step by step.
- **Edge first:** data is processed locally for faster response, lower latency and offline operation.
- **Site-appropriate:** watering according to the specific needs of each site, and Forecasts for the weather, battery and available solar energy.
- **Farmer-friendly:** a mobile application and a multilingual voice assistant provide advice in the farmer's language.

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B. System Architecture

The layers in the proposed system are presented in Fig. 2. Soil moisture, A camera and sensors that measure the pH, NPK, temperature and humidity feed in. an ESP32 microcontroller. An Edge AI layer yields crop and fertiliser recommendations based on soil and environmental data and, and applies computer vision in the early detection of crop diseases, pests, weeds and nutrient deficiencies. A smart watering system for the garden that uses solar energy. A solar panel and battery power the controller which controls the pump, As the mobile app and voice commands alert, and device. The role of each technology is given in Table II.

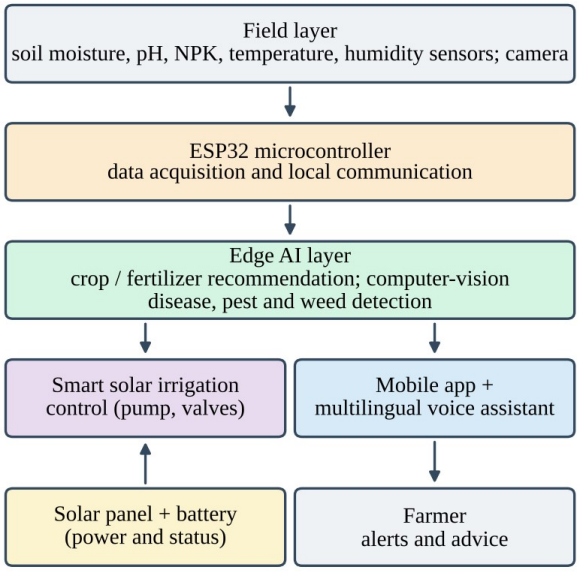


Fig. 2. Proposed layered architecture: sensing, ESP32, Edge AI, solar irrigation control and farmer interface.

TABLE II
TECHNOLOGY ROLES IN THE FRAMEWORK

Technology	**Role in the framework**
Artificial Intelligence	Decisions for irrigation, crop recommendation, fertilizer optimization and disease detection
Internet of Things	Real-time monitoring of soil moisture, pH, NPK, temperature and humidity
Edge AI	Local processing for faster response, lower latency and offline operation
Computer vision	Detects crop diseases, pests, weeds and nutrient deficiencies
Smart solar irrigation	Irrigation based on soil moisture, weather, solar energy and battery status
Precision agriculture	Improves yield while conserving water and energy

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C. Sensing and Data Acquisition Layer

The sensing layer gives the system its picture of the field. The ESP32 is a low-cost microcontroller with built-in wireless connectivity, which makes it a natural hub for reading several sensors and passing the data on [2]. Table III lists the sensors considered in this work and how each reading is used. The same readings can be logged over time, so that the Edge AI layer sees trends rather than single values, for example a slow fall in soil moisture over several days.

TABLE III
SENSORS AND THEIR USE

Sensor	Parameter	Use in the system
Soil moisture	Water content of the soil	Triggers and stops irrigation
pH	Soil acidity or alkalinity	Crop suitability; soil condition
NPK	Nitrogen, phosphorus, potassium	Fertilizer recommendation
Temperature	Air / soil temperature	Irrigation need; disease risk
Humidity	Air moisture	Irrigation need; disease risk
Camera	Crop and leaf images	Disease, pest and weed detection

D. Edge AI Module

The Edge AI module has two branches, shown in Fig. 3. The first branch takes the soil and weather readings and produces crop and fertilizer recommendations [2], [3]. The second branch analyses field images with a compact vision model to find diseases, pests, weeds and nutrient deficiencies. Chung et al. [1] show that a low-cost combination of ESP32-CAM, Raspberry Pi 5, YOLOv8n and ResNet-18 can run such detection at the edge with a 0.86 s response time, which is the kind of lightweight approach this work follows. A decision-fusion step then combines both branches, so that a disease alert can be judged together with humidity and temperature rather than from the image alone (G5).

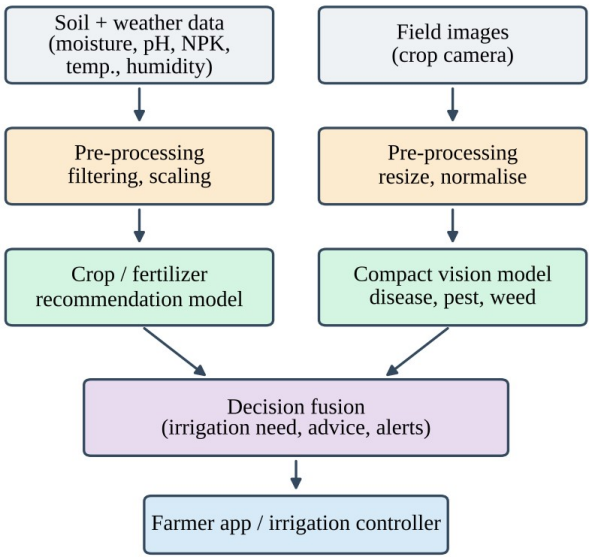


Fig. 3. Edge AI module: a sensor branch for recommendations and an image branch for detection, joined by decision fusion.

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Running both branches locally keeps the system working when the internet is unavailable (G2). The models themselves are not fixed by this paper; the design only requires that they are small enough to run on low-cost edge hardware and that they can be updated when new labelled data becomes available.

E. Smart Solar Irrigation Controller

The irrigation controller opens the pump relay only when two conditions hold: the Edge AI module judges that the crop needs water, and the power subsystem can supply the pump (Fig. 4). The energy monitor reports the energy to the ESP32, so that the controller can delay or reduce the irrigation cycle when the energy level is low, rather than consuming the battery. A few example rules are shown in Table IV. Addressing these requirements, using solar power in this manner tackles with energy consumption and running cost (G1, G3) and follows the energy-harvesting approaches surveyed in [8].

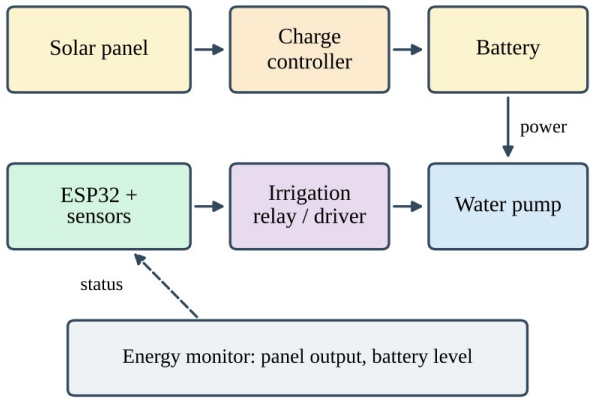


Fig. 4. Solar power and irrigation subsystem with an energy monitor reporting to the ESP32.

TABLE IV

EXAMPLE ENERGY-AWARE IRRIGATION RULES

Soil moisture	Energy available	Action
Adequate	Any	No irrigation
Low	High	Irrigate now
Low	Medium	Shorter cycle; recheck
Low	Low	Defer; alert farmer

F. Mobile Application and Multilingual Voice Assistant

Many small and medium-size farmers would prefer to have received information by means of thick text in their native tongue instead of dashboards (G7). The mobile application shows soil readings, History of irrigation, recommendations and disease alerts. A multilingual voice assistant allows the farmer to ask questions and listen to responses, such as the current soil moisture, Deciding whether or not to irrigate on the day. Because the Edge AI layer produces from the local area, basic advice can be provided during. When

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there are network outages, the application will sync with a The number of times a network is broken. Once the connectivity is restored, the server will be restored.

G. Irrigation Decision Workflow

Fig. 5 shows one irrigation cycle. The ESP32 is used to read soil Vital information such as moisture, weather, solar level and battery status are all available on the Edge AI. model determines locally the need for irrigation. If it is, the controller ensures an adequate supply of solar and battery energy to inoperable until the pump is run; then the cycle is deferred.

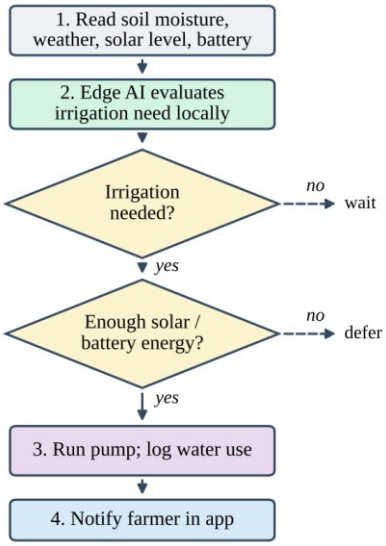


Fig. 5. One irrigation cycle: sensing, local Edge AI decision, energy check, pump control and notification.

VI. Implementation Roadmap

Since the framework is a design, Fig. 6 sets out the stages through which it could be built and tested. Phase 1, the literature survey and gap analysis, is the work reported in this paper. Phase 2 would assemble a prototype with the ESP32, the sensors in Table III and a solar-powered pump. Phase 3 would develop and test the recommendation and vision models on the edge hardware. Phase 4 would integrate the models with the irrigation controller, the mobile application and the voice assistant. Phase 5 would run field trials and evaluate the system with the measures in Table VI.

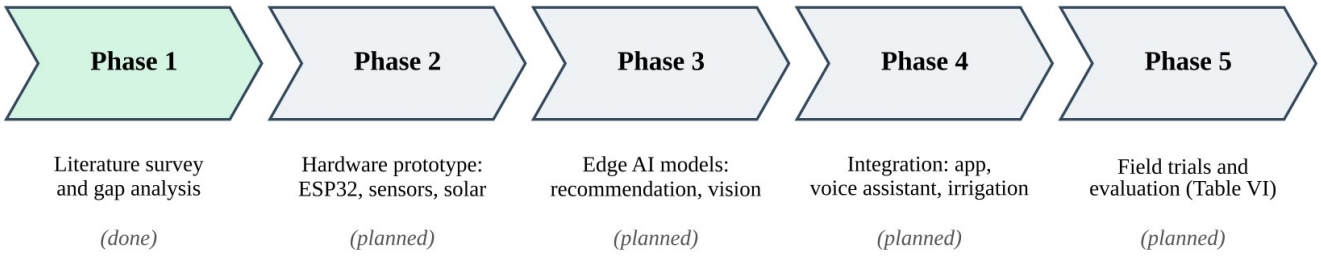


Fig. 6. Proposed implementation roadmap. Phase 1 is complete; later phases are planned.

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VII. Comparative Analysis

Fig. 7 compares the reviewed studies with the proposed framework on seven capabilities taken from Table I: AI analytics, IoT sensing, edge processing, computer vision, irrigation control, solar or energy-aware operation, and a low-cost focus. A tick marks a capability the study covers, and a tilde marks partial coverage. The marking is qualitative and based only on the findings and limitations summarised in Table I.

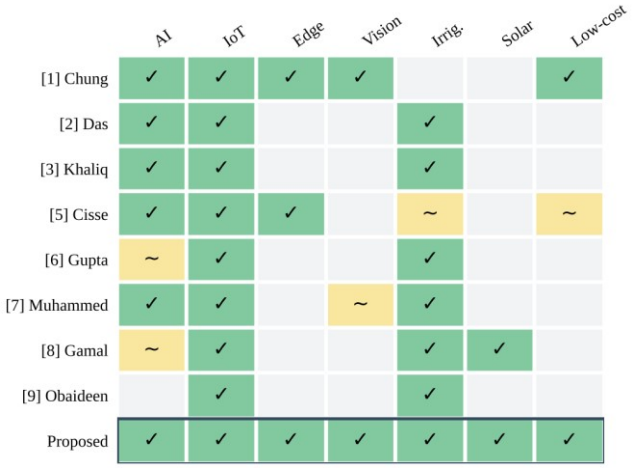


Fig. 7. Qualitative capability coverage of the reviewed studies and the proposed framework (✓ covered, ~ partial, blank not reported).

Most studies cover IoT sensing and irrigation well, and some add AI analytics [2], [3], [7]. Only one reviewed study combines edge processing with computer vision [1], and it does not control irrigation. Only one touches energy harvesting [8], and it has limited AI integration. None covers every column, so the combination proposed here is the distinguishing feature of the framework rather than any single component.

Table V and Fig. 8 relate each research gap to the part of the framework intended to address it.

TABLE V
Research Gaps and Proposed Response

Gap	Proposed response
G1 High cost	Low-cost ESP32-based, modular hardware
G2 Internet dependency	Edge AI with local, offline operation
G3 Energy use	Solar power; energy-aware irrigation scheduling
G4 Limited integration	One platform for AI, IoT, Edge AI and irrigation
G5 Data not combined	Sensor data used alongside vision-based detection
G6 Limited testing	Multi-crop, multi-site evaluation (Section IX)
G7 Small farmers	Mobile app and multilingual voice assistant

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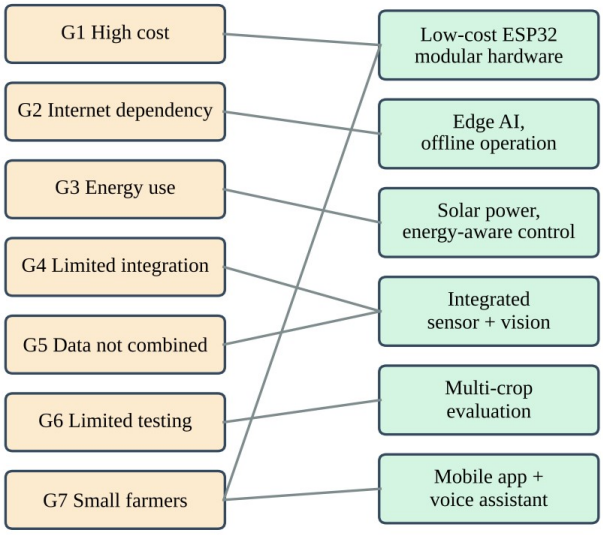


Fig. 8. The proposed is divided into seven components and each of these components is mapped to the seven research gaps. framework.

VIII. Ethical and Practical Considerations

Farm data such as soil conditions, yields and field images perishable goods are produced.Should be kept locally where perishable goods are produced and belongs to the farmer. feasible, if the consent of other is involved. Cybersecurity and privacy concerns are reported in [5],[7] a system that processes privacy concerns. data at the edge exposes less data than one that sends everything to the cloud.

Practical limits include the cost of the sensors, and their calibration [8], Access to variable sunlight and battery, and farmers' digital literacy and language. Soil sensors drift and need to be recalibrated, and if the sensor is damaged it will input incorrect values into the models, so Should be range checked in readings and values that are out of range should be rejected. flagged. Single crop-based models may not generalise [1] so recommendations should be made as a suggestion, and the Farmer (at decision point).

Another key aspect of affordability is maintenance. The modular design allows the farmer to introduce soil sensing and irrigation control first and then later introduce vision and the voice assistant, making this spread out over time. Local repair and spares should be considered at an early stage in the system's design, as systems that are not repairable in the field are likely to be abandoned [5].

IX. Evaluation Plan

Because the system has not been implemented, Table VI sets out the questions and measures a future study would need. Each measure should be compared with a baseline such as timer-based irrigation or expert advice, and results should be reported per crop and per site rather than only as an average.

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TABLE VI
PROPOSED EVALUATION PLAN

Question	Measure
Does it save water?	Water use vs. timer-based irrigation
Are recommendations sound?	Agreement with agronomist advice
Is detection accurate and fast?	Precision, recall, response time [1]
Does it run offline?	Function during connectivity loss
Is it energy-autonomous?	Solar/battery uptime over days
Does it generalise?	Results across crops and sites
Is it affordable and usable?	Cost; farmer usability feedback

The study should include several crops and more than one season, since a result obtained on one crop in one season says little about others (G6). Farmer feedback on the application and voice assistant should be collected in the local language, because usability is part of whether the system is adopted (G7).

X. LIMITATIONS AND THREATS TO VALIDITY

This paper has three main limitations. First, it is a literature-based design: no prototype has been built, so the benefits described are expected rather than measured. Second, the review covers eight studies, which is enough to identify gaps but not to claim that no other work combines these technologies. Third, the capability comparison in Fig. 7 is qualitative and relies on how each study is summarised in Table I, so different readers could mark a few cells differently.

A further threat is that the reviewed systems were built for different crops, regions and hardware, so their results are not directly comparable. The framework therefore treats reported figures, such as the response time in [1], as indications of feasibility rather than as targets.

XI. CONCLUSION AND FUTURE WORK

This paper surveyed eight studies on AI, IoT, Edge AI and smart irrigation. Smart agriculture has evolved from sensing and automated irrigation to AI-based analysis and, more recently, Edge AI, yet existing systems remain costly, connectivity-dependent and only partly integrated. The major gaps are high cost, internet dependency, limited integration of AI and IoT, and the lack of affordable solutions for small and medium-scale farmers. The proposed ESP32-based framework with Edge AI, computer vision and smart solar irrigation responds to these gaps and is offered as a literature-grounded design, not a validated system.

Future work should follow the roadmap in Fig. 6: build a prototype for one or two crops, evaluate it with the measures in Table VI, and then test it across crops and real farm environments with farmers' participation.

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