AI-ENHANCED SMART IRRIGATION

ESP32 | Firebase | Machine Learning

A Technical Report on Autonomous Closed-Loop Precision Agriculture

EXECUTIVE SUMMARY

⚠ PROBLEM & SOLUTION

Traditional timer-based methods are inefficient. This project implements an autonomous, closed-loop system that integrates **Vapor Pressure Deficit (VPD)**, **ML forecasting**, and **Real-time Diagnostics** for precision agriculture.

KEY TECHNOLOGIES

Edge: ESP32

Cloud: Firebase Realtime DB

AI: Python FastAPI & Random Forest

SYSTEM ARCHITECTURE

IoT Layer (Edge)

ESP32 collects telemetry (Soil Moisture, Temp, Humid) and handles immediate safety overrides.

Cloud Layer (Data Bus)

Firebase Realtime Database acts as the central nervous system, decoupling hardware from AI.

Intelligence Layer

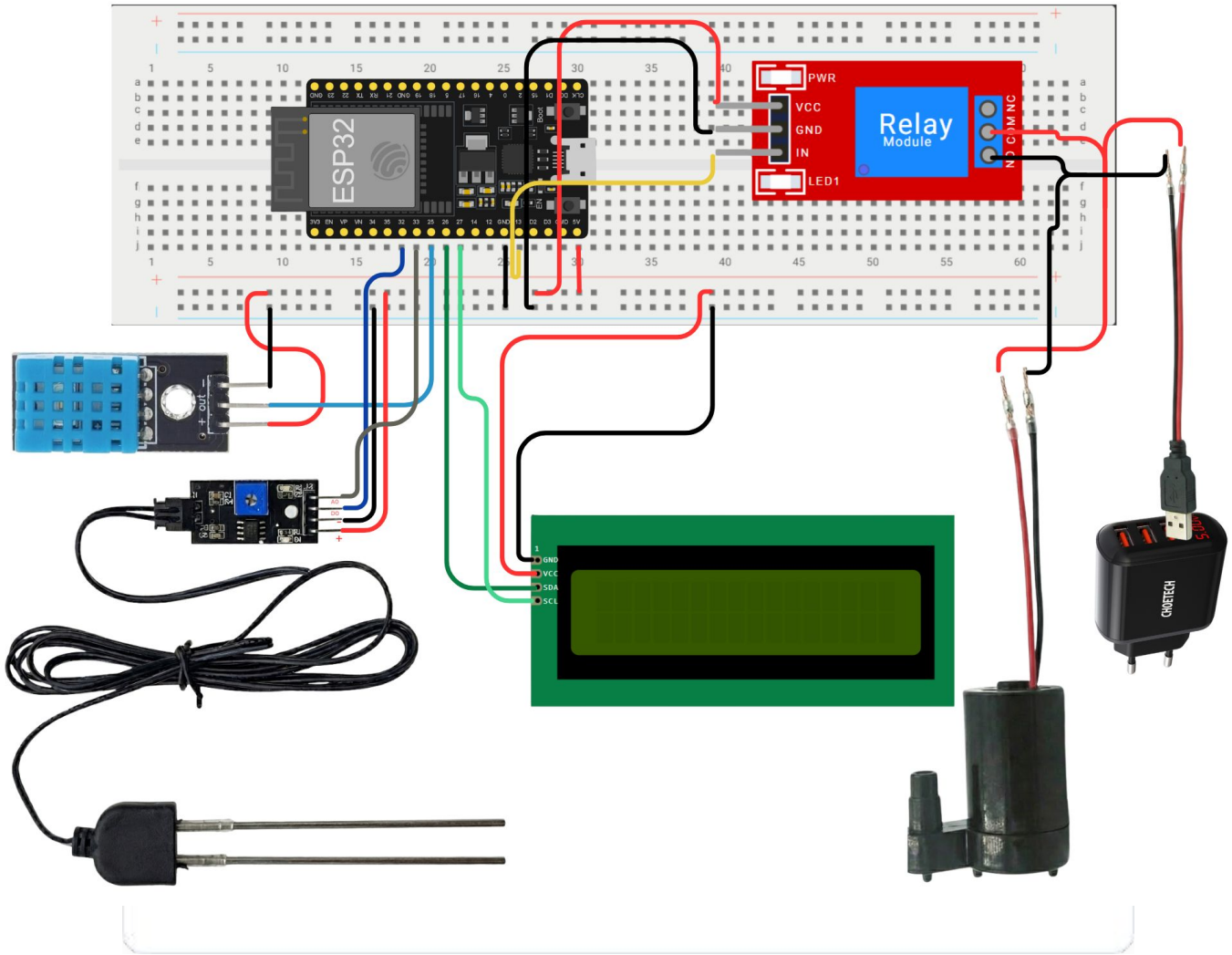
Python FastAPI backend computes VPD, runs ML inference, and pushes "IRRIGATE" decisions.

Visualization Layer

HTML5/Bootstrap dashboard serves as the "Control Center" for growers.

HARDWARE IMPLEMENTATION

- **Microcontroller:** ESP32 (Dual-core, WiFi/BLE).
- **Sensors:**
  - DHT11: Digital Temp & Humidity.
  - Capacitive Soil Moisture v1.2: Corrosion-resistant analog input (GPIO 33).
- **Actuation:**
  - Relay Module (5V): Opto-isolated, active-high.
  - DC Water Pump: Submersible 5V/12V.
- **Interface:** LCD 1602 with I2C Backpack (GPIO 26 SDA, 27 SCL).



FIRMWARE: DEFENSE-IN-DEPTH

A hierarchical control strategy prioritizes crop survival over AI commands.

LAYER 1: CRITICAL SAFETY

Condition: Soil < 40%

Action: Force Pump ON. Hardware priority prevents wilting if WiFi/Server fails.

LAYER 2: AI CONTROL

Condition: Soil > 40%

Action: Listen to Firebase. Executes optimized IRRIGATE/WAIT commands.

LAYER 3: FAILSAFE

Condition: Offline/Network Lost

Action: Hysteresis Loop. ON at <40%, OFF at >80% to maintain basic stability.

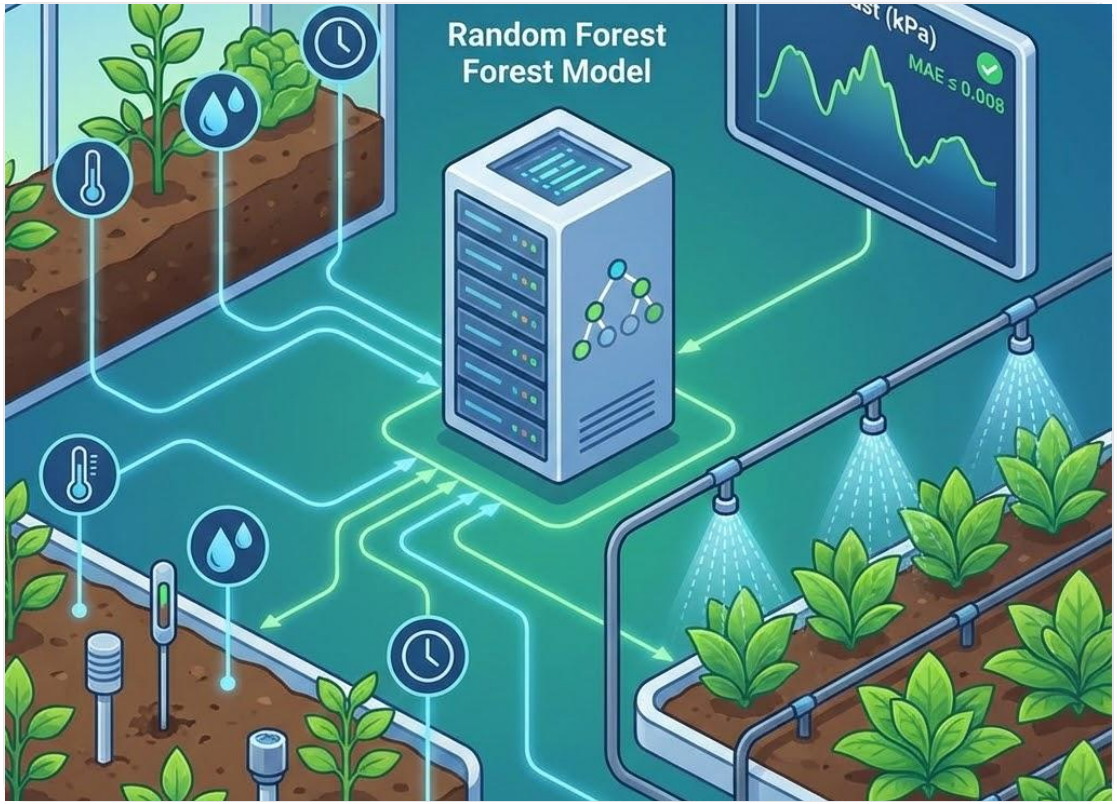
PHYSICS-BASED METRICS: VPD

What is VPD ?

- **Vapor Pressure Deficit (VPD)** is the difference between saturation vapor pressure and actual vapor pressure in the air at the same temperature.
- The system uses **VPD rather than simple humidity** to determine plant transpiration rates.

$$VPD = 0.6108 \times e^{\frac{17.27T}{T+237.3}} \times 1 - \frac{RH}{100}$$

This metric drives the **Dynamic Irrigation Policy**, ensuring water is applied only when the atmospheric demand (transpiration) justifies it.

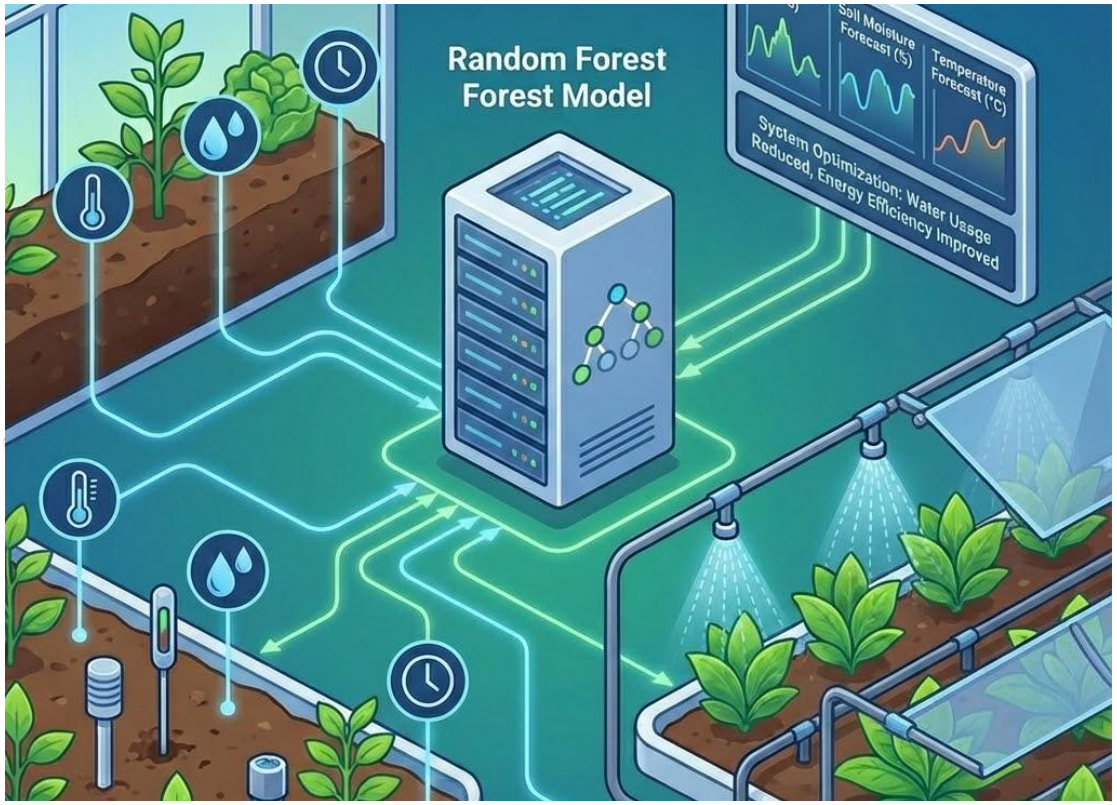


DYNAMIC IRRIGATION POLICY

Instead of fixed thresholds, the target soil moisture adapts based on VPD (Atmospheric Stress).

VPD Range (kPa)	Condition	Target Soil %	Reasoning
< 0.75	Low (Night/Humid)	65%	Low transpiration; save water.
0.75 - 1.1	Optimal	70%	Standard growth phase.
> 1.1	High (Dry/Stress)	72%	High transpiration; pre-water to prevent stress.

PREDICTIVE MODELING



RANDOM FOREST REGRESSOR

Task: Forecasting Soil Moisture in the next 3 hours

Accuracy: 95% (MAE ≈ 0.0079 & RMSE ≈ 0.015)

Key Features:

- **Lagging index:** Soil lag & Soil delta in 1h & 3h
- **Rolling Stats:** Trends (Mean, Std Dev).
- **Time Encoding:** Sin/Cos of Hour (Day/Night cycles).
- **VPD & Irrigation history**

3-LAYER DECISION ARCHITECTURE

Layer 1: Forecast

AI Model predicts soil moisture for T+3 hours.

Output: Pred_Soil = 60%

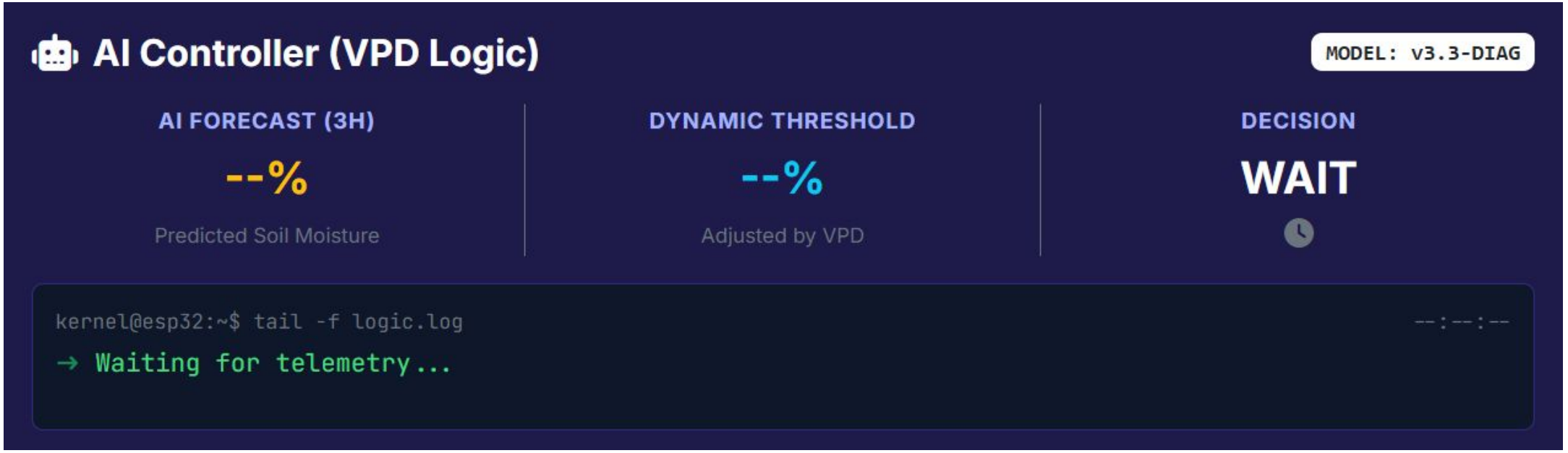
Layer 2: Threshold

Dynamic Threshold based on VPD.

Output: Threshold = 70%

Layer 3: Controller

Checks Forecast vs Threshold.
IF Pred < Threshold - Margin:
DECISION: IRRIGATE



SYSTEM DIAGNOSTICS ("AI DOCTOR")

SELF-DIAGNOSIS LOGIC

The system compares **Real vs. Predicted** soil moisture to identify hardware anomalies.

Pump Failure:
If Pump == ON but Real_Soil <= (Predicted - 10%).
Diagnosis: Pump running but soil not wetting (Blockage).

Sensor Failure / Leak:
If Pump == OFF but (Predicted - Real) > 10%.
Diagnosis: Soil drying faster than physics predicts (Leak).

RESULTS & EVALUATION

Operational Impact:

The system achieves high reliability (high Recall), rarely missing a drying event. By using the Dynamic VPD policy, it conserves water during low-VPD periods (night/rain) compared to static timers.

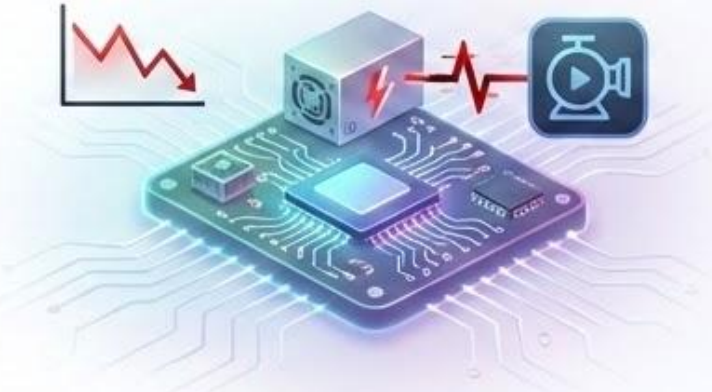
LIMITATION

Challenges and Future Opportunities for Improvement

Limited Dataset & Seasonal Models

Dataset size is limited, so seasonal effects are not fully modeled.

ESP32 Power Constraints



ESP32 experiences occasional brownouts when pump and LCD run together.

Fixed VPD Thresholds

VPD thresholds are currently fixed — future versions should learn optimal values per crop.”

CONCLUSION

- **Viability:** Successfully demonstrated AI-driven IoT in precision agriculture, moving beyond simple "IF/THEN" logic.
- **Autonomy:** Incorporated predictive modeling and atmospheric physics (VPD) for a higher level of decision-making.
- **Reliability:** The "AI Doctor" and Defense-in-Depth firmware bridge the gap between fragile prototypes and production-ready tools.