

Low-Cost Soil Moisture Sensing for Smallholder Irrigation

Design and Field Evaluation

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Scope

PhD Dissertation Defense

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The Problem

Global Scale

Irrigation accounts for **~70%** of freshwater withdrawals worldwide. Smallholder farms (under 2 ha) produce a large share of food in Sub-Saharan Africa and South Asia – yet most farmers irrigate by calendar or by feel.

The Cost Barrier

Commercial soil moisture probes cost **$150-$800 per node**, require lab calibration and data subscriptions – far out of reach for farmers earning a few dollars a day.

> Central question: Can we deliver "good enough" soil moisture data for **under $15 per node** – and does it change irrigation decisions on real farms?



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Research Questions

1

Sensor Accuracy

Can a PCB-based capacitive sensor reach VWC accuracy within **±3%** after simple field calibration?

2

Seasonal Drift

How do drift, soil texture, salinity, and temperature affect accuracy over a full growing season?

3

Irrigation Outcomes

Does sensor-guided irrigation reduce water use without reducing yield on smallholder plots?

4

Farmer Interface

What do farmers need from the advisory interface to actually act on the readings?

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Related Work & Gap

Reference Methods

Gravimetric sampling is gold standard but destructive; TDR is accurate but costs **$1,000+** per installation.

Low-Cost Sensors

Resistive probes corrode within weeks; hobby-grade capacitive boards show **±8–12% VWC** variation and strong temperature sensitivity.

Decision Support

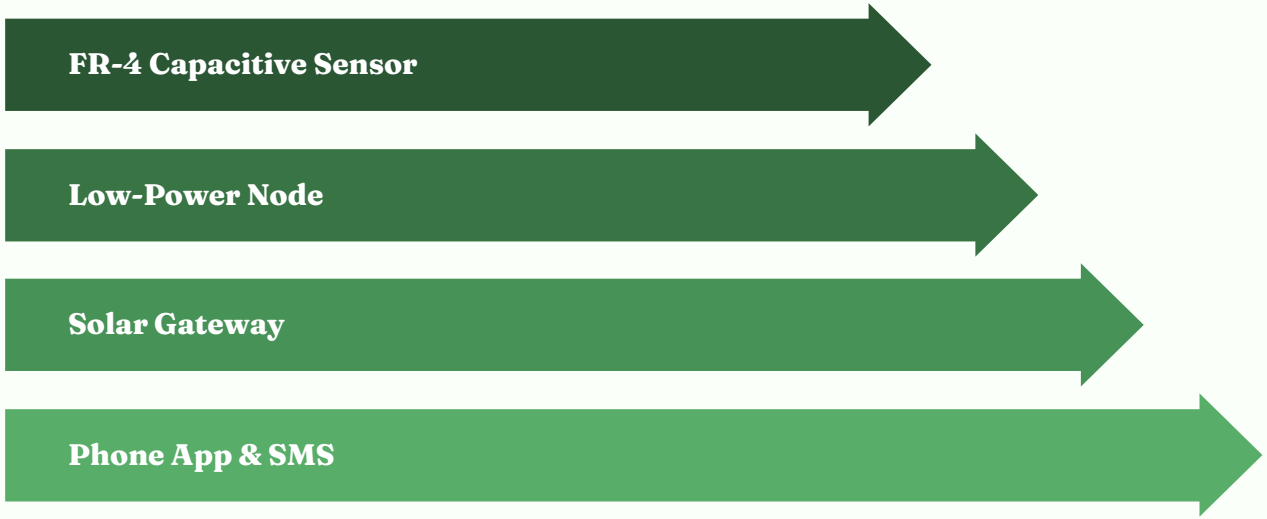
Satellite soil moisture is kilometer-scale – far too coarse for a 0.5 ha plot. SMS services exist but lack local sensing.

The Gap

No low-cost design validated over full seasons, across soil types, with both **yield outcomes and farmer adherence data**.

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Sensor & Node Design



Key Specifications

- 1.6 mm FR-4 board, conformal coating, epoxy-sealed electronics
- 70 MHz oscillator; onboard thermistor for temperature compensation
- 38 µA average sleep current; **14-month** estimated battery life at 30-min sampling
- One solar-powered gateway per village

Bill of materials: **$11.40 per node** at 500 units

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Calibration Method

1

Two-Point Field Cal

One reading in air-dry soil, one at saturation – taken by the farmer or extension worker at installation. No lab equipment needed.

2

Texture Correction

Correction table built from lab measurements on **6 soils**, ranging from sand to clay.

3

Temperature Compensation

Model fitted on **4,800 lab readings** between 5 °C and 45 °C to remove diurnal error.

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Field Study Design



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Study Parameters

- **3 sites**, semi-arid regions; **2 growing seasons** (2023 & 2024)
- **48 plots** (0.2 - 0.8 ha): tomato, onion, maize
- Randomized: 24 sensor-guided vs. 24 farmer-practice control plots
- Ground truth: **2,976** weekly gravimetric samples + 6 TDR reference stations

Advisory System

🟢 Green = no irrigation needed | 🟡 Amber = irrigate within 2 days | 🔴 Red = irrigate today – delivered by SMS and app.

Results — Sensor Accuracy

1.9%

Lab RMSE

After calibration (vs. 7.8% uncalibrated)

2.6%

Field RMSE

Across all soils (2.1% sandy loam; 3.4% clay)

93%

Within ±3%

Nodes staying within target after a full season

91%

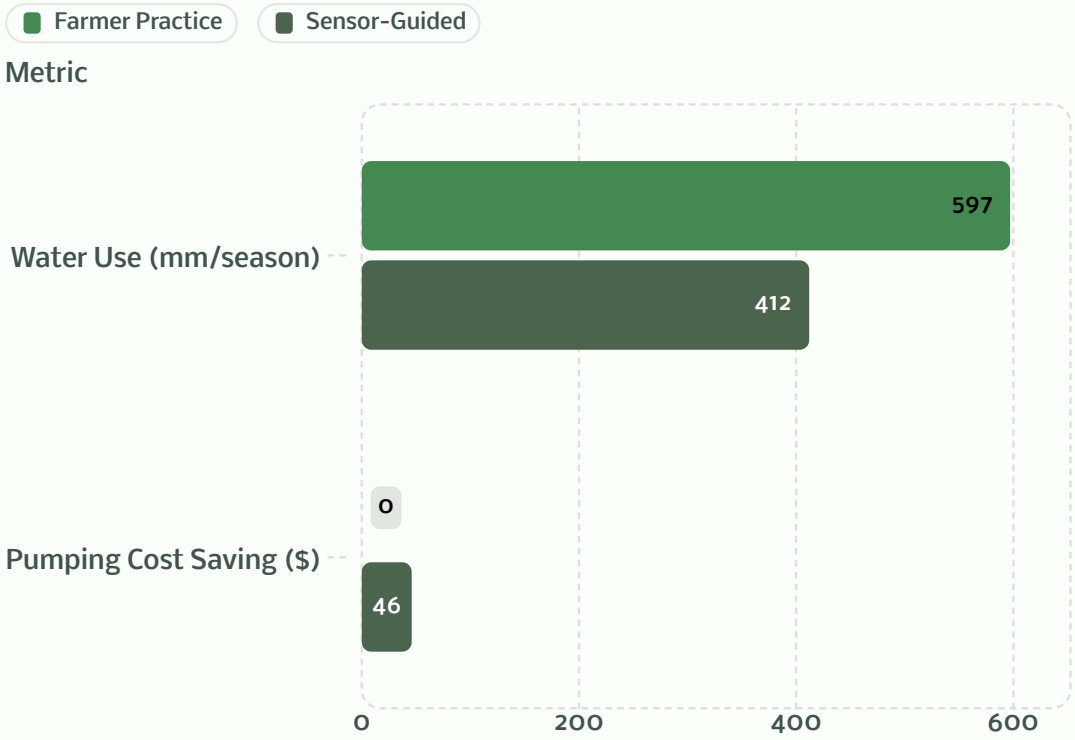
Reliability

Nodes still operating at season end

Temperature compensation reduced diurnal error from **2.2% to 0.6% VWC**. Median drift: **0.4% VWC per month**. Most failures caused by rodent and tool cable damage.

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Results — Irrigation Outcomes



Key Findings

- **31% less** irrigation water (412 mm vs. 597 mm per season)
- Yield: no significant difference (tomato +4%, onion −2%, maize +1%; all $p > 0.3$)
- **+38%** water productivity (kg crop per m^3)
- Pumping cost down **27%**; avg. saving **$46/plot/season**
- Node pays for itself **within one season**

Farmer adherence: **72%** of days. SMS alerts outperformed the app.

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Contributions

1 Open Hardware Design

Sub-$12 capacitive soil moisture node with built-in temperature compensation, released under an open license.

2 Two-Point Field Calibration

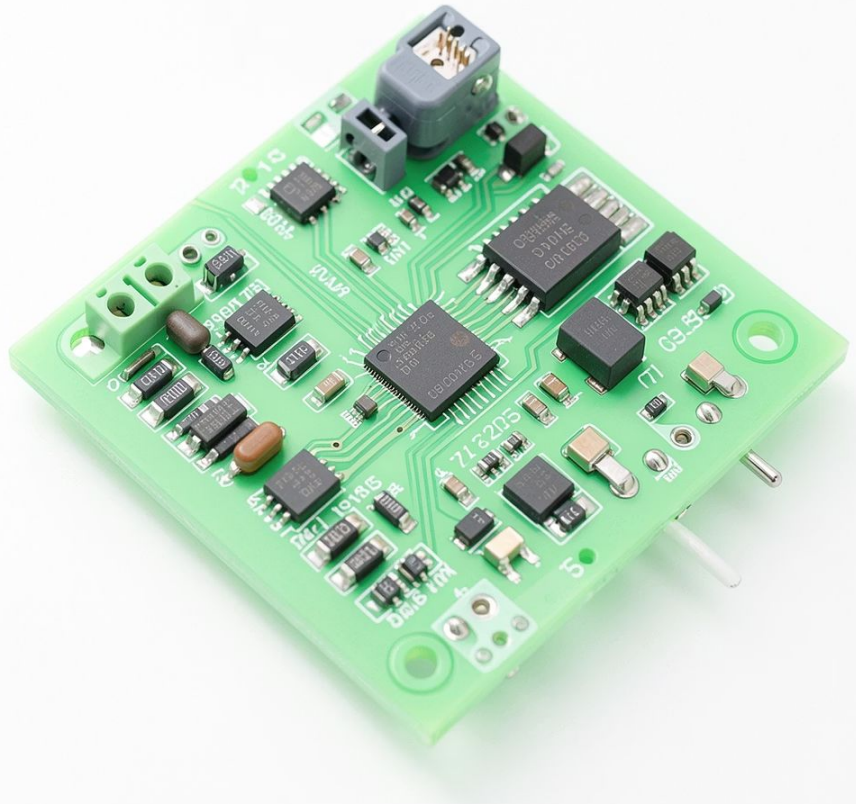
Brings low-cost sensors within **±3% VWC** without any lab equipment.

3 Two-Season Randomized Trial

Links low-cost sensing to water use, yield, and cost on 48 smallholder plots.

4 Advisory Design Guidelines

Color-coded thresholds, SMS-first delivery, one action per message.



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Limitations & Future Work

Current Limitations

Saline & Heavy Clay Soils

EC above 4 dS/m remains outside the ±3% target.

Durability

Two seasons only; performance beyond 18 months is untested.

Generalizability

48 plots at 3 sites; may not extend to other crops or rain-fed systems.

Future Directions

01

Salinity-Aware Calibration

Using a second measurement frequency.

02

Predictive Scheduling

Combining node data with weather forecasts.

03

Shared-Node Models

One sensor serving neighboring plots via spatial interpolation.

04

Cooperative Pilot

500 nodes with a pay-per-season service model.

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Summary & Next Steps

Accuracy Achieved

2.6% field RMSE; 93% of nodes within ±3% after a full season.

Water Savings

31% less water, +38% water productivity, no yield loss.

Economic Impact

$46 avg. saving per plot – node pays for itself in one season.

Open & Scalable

Hardware and code open-licensed; 3 journal articles, 2 conference papers.

Thank you to Prof. L. Chen, the committee, field teams, and the farmers who hosted the trials.

Questions?



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