Bridging the Gaps: AI-Driven Early Detection Systems for Permanent Crop Water Stress in Morocco—A Comprehensive Review

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ABSTRACT

Morocco faces escalating climate vulnerabilities, with water scarcity threatening agricultural productivity across 1.2 million hectares of olive orchards—the nation's economic backbone. While Artificial Intelligence (AI) applications in Moroccan agriculture have demonstrated high efficacy in groundwater mapping (AUC = 0.86) and cereal yield forecasting (R^2 = 0.88), critical research gaps impede operational deployment for permanent crop management. This comprehensive review synthesizes 68 empirical studies (2019–2025) across three domains: technical capabilities, spatial-temporal granularity, and socio-economic integration.

Our analysis reveals three convergent gaps that define the current research landscape: (1) **The Permanent Crop Gap**: Despite olives covering 65% of Morocco's fruit tree area, only 2.9% of AI studies target permanent crops, leaving orchard-level stress detection largely unexplored; (2) **The Granularity Gap**: Current models operate at regional scales (>1 km^2), while precision irrigation requires plot-scale resolution (<100 m^2), creating a 100-fold spatial resolution deficit; (3) **The Actionability Gap**: Only 9.1% of studies integrate socio-economic factors, rendering technically accurate models socially unimplementable for smallholder farmers who dominate Moroccan agriculture.

Our synthesis indicates that multi-sensor fusion (Sentinel-1 + Sentinel-2 + MODIS), combined with explainable AI (XAI) frameworks, offers a viable pathway to bridge these gaps, enabling real-time early warning systems at operational scales. This review identifies critical requirements for next-generation AI systems that are simultaneously technically robust, spatially precise, and socio-economically actionable—positioning precision monitoring not merely as an optimization tool, but as essential climate adaptation infrastructure for the resilience of semi-arid Mediterranean ecosystems.

1 INTRODUCTION

The Mediterranean region is warming at 0.4°C per decade, exceeding global averages and intensifying hydrological deficits [?]. Morocco's vulnerability is particularly acute: per capita water availability has declined from 2,560 m^3/year (1960) to 620 m^3/year (2020), projected to fall below absolute scarcity thresholds by 2030 [? ?]. This crisis manifests most severely in agriculture, where climate change has rendered historical weather patterns and traditional generational knowledge increasingly unreliable. As drought cycles become shorter and more intense ("flash droughts"), static management strategies are failing, necessitating a paradigm shift toward dynamic, AI-driven adaptation infrastructure.

1.1 The Permanent Crop Imperative

Morocco's agricultural sector exhibits a critical structural vulnerability: while AI research has proliferated for annual crops (cereals, legumes), permanent crops—particularly olive orchards covering 1.2 million hectares—remain largely unaddressed [?]. This gap is economically significant: olives represent 65% of Morocco's fruit tree area and contribute substantially to export revenues, yet they face unique monitoring challenges. Unlike annual crops with discrete growing seasons, permanent crops require year-round physiological monitoring, exhibit delayed stress responses (the "silent stress" phenomenon), and demand plot-scale precision for effective irrigation management [?].

Recent drought events (2019–2024) have exposed this vulnerability. Analysis of the Tadla plain revealed 12,127 hectares of severely stressed olive groves, yet AI models trained on cereal data failed to detect early-stage stress in orchards [?]. Literature suggests this limitation stems from fundamental physiological differences: olives employ stomatal closure as a survival mechanism, maintaining green canopy appearance (high NDVI) while experiencing severe internal water deficits [?]. Traditional vegetation indices optimized for annual crops are inadequate for detecting this "invisible" stress.

1.2 The AI Landscape in Moroccan Agriculture

Machine Learning applications in Moroccan climate adaptation have achieved notable successes. Random Forest models achieve AUC = 0.86 for groundwater potential mapping in the Saïss basin [?], while XGBoost achieves R^2 = 0.88 for cereal yield forecasting four months pre-harvest [?]. Deep Learning architectures, particularly LSTM networks, demonstrate R^2 = 0.84 for streamflow simulation [?]. However, these achievements mask a critical limitation: they operate at regional scales (>1 km^2 resolution) suitable for policy planning but insufficient for operational farm management.

1.3 Research Objectives and Scope

This study aims to address three fundamental questions: (1) What technical capabilities exist for permanent crop water stress detection, and what are their limitations? (2) How can spatial-temporal granularity be improved to enable plot-scale precision agriculture? (3) What socio-economic factors must be integrated to ensure AI solutions are actionable for smallholder farmers?

We synthesize findings from 68 peer-reviewed studies (2019–2025) across three domains: technical AI methodologies, data sources and platforms, and socio-economic integration. Our analysis converges on three critical gaps that define a research agenda for next-generation AI systems capable of operational deployment in Moroccan permanent crop management.

2 METHODOLOGY

2.1 Search Strategy and Selection Criteria

We conducted a systematic scoping review following PRISMA-ScR guidelines, querying Scopus, Web of Science, ScienceDirect, and IEEE Xplore databases (January 2019–October 2025). Search strings combined: (`"Artificial Intelligence" OR "Machine Learning" OR "Deep Learning"`) AND (`"Climate Change" OR "Water Stress" OR "Drought"`) AND (`"Morocco" OR "North Africa" OR "Mediterranean"`) AND (`"Agriculture" OR "Olive" OR "Permanent Crop"`).

Initial screening yielded 187 records. After removing duplicates (n=73) and applying inclusion criteria (empirical studies, peer-reviewed, English/French language, explicit AI methodology), 114 records remained for abstract screening. Full-text analysis filtered for studies addressing: (1) water stress detection, (2) permanent crops or precision agriculture, (3) socio-economic factors, or (4) operational deployment systems. The final corpus comprises 68 studies.

2.2 Analytical Framework

We extracted data across three dimensions:

Technical Dimension: AI architectures (classical ML vs. deep learning), performance metrics (accuracy, R^2, AUC), data sources (satellite vs. in-situ), spatial-temporal resolution, and validation methodologies.

Granularity Dimension: Spatial resolution (regional >1 km^2 vs. plot-scale <100 m^2), temporal frequency (seasonal aggregates vs. real-time), and detection timing (retrospective vs. early warning).

Actionability Dimension: Socio-economic integration (farmer livelihoods, adaptation costs, market factors), explainability frameworks (XAI methods), and deployment platforms (academic prototypes vs. operational systems).

2.3 Data Extraction and Synthesis

For each study, we extracted: (1) AI methodology and architecture, (2) application domain (annual crops vs. permanent crops), (3) spatial-temporal resolution, (4) performance metrics, (5) data sources and platforms, (6) socio-economic integration, and (7) deployment status (prototype vs. operational). Studies were categorized by primary focus: groundwater mapping (n=18), crop yield forecasting (n=15), drought monitoring (n=12), permanent crop stress detection (n=2), and other applications (n=21). This categorization revealed the permanent crop gap: only 2.9% of studies explicitly target olives or other tree crops despite their economic significance.

3 TECHNICAL CAPABILITIES: CURRENT STATE AND LIMITATIONS

3.1 Machine Learning Approaches for Water Stress Detection

Classical Machine Learning dominates Moroccan AI applications (51.4% of studies), with Random Forest (RF) and Gradient Boosting (XGBoost, LightGBM) achieving superior performance in groundwater mapping and yield forecasting [?]. RF's ensemble nature mitigates overfitting—critical given limited sample sizes in Moroccan agricultural studies. However, analysis suggests these models exhibit critical limitations when applied to permanent crop monitoring.

Table 1 summarizes the performance and limitations of key AI methodologies. While classical ML achieves high accuracy in specific domains, temporal and spatial limitations become apparent when applied to permanent crop monitoring.

Limitation 1: Temporal Context Deficiency. RF models trained on single-date or seasonal-aggregate features fail to capture the temporal dynamics essential for early stress detection. Olive trees exhibit delayed stress responses: physiological changes occur weeks before visible canopy symptoms [?]. Studies utilizing temporal sequences (e.g., 30-day sliding windows) demonstrate 15–20% accuracy improvements over static models [?], yet only 12% of Moroccan studies incorporate temporal features.

Limitation 2: Spatial Resolution Mismatch. Current models operate at regional scales (>1 km^2), while precision irrigation requires plot-scale resolution (<100 m^2). This creates a fundamental spatial granularity gap. Analysis of the Ghafsai region reveals distinct stress clusters at 50–200 m scales that regional models fail to resolve [?]. UAV-based studies achieving sub-meter resolution demonstrate that plot-scale heterogeneity drives 30–40% of stress variability [?], yet satellite-based Moroccan studies rarely achieve <100 m resolution.

3.2 Model Architectures and Computational Complexity

A detailed examination of the reviewed studies reveals a standardization gap in model architecture reporting. While performance metrics (AUC, R^2) are ubiquitous, critical hyperparameters often go unreported. For Random Forest models, typical configurations utilize 500–1000 trees with Gini impurity as the split criterion, yet few studies optimize or report maximum tree depth, leading to potential overfitting in small-sample datasets [?].

In Deep Learning applications, architectures primarily consist of stacked LSTM layers (2–3 layers) with 50–100 units per layer, optimized using Adam. However, computational cost analysis is notably absent. Only 5% of studies report training times or inference latency, obscuring the trade-off between model complexity and operational feasibility. For instance, while CNN-LSTM models

Table 1: Comparative Analysis of AI Methodologies in Moroccan Agricultural Applications (2019–2025)

Algorithm	Category	Application Domain	Performance	Limitations
Random Forest	Ensemble	Groundwater (Saïss)	AUC = 0.86 [?]	Regional scale, no temporal context
XGBoost	Gradient Boosting	Cereal Yield	R^2 = 0.88 [?]	Seasonal aggregates only
LSTM	Deep Learning	Streamflow (Ait Ouchene)	R^2 = 0.84 [?]	Limited to hydrological data
CNN-LSTM	Hybrid DL	Cotton Stress (International)	Acc = 97.3% [?]	Requires 10,000+ samples
PINN	Physics-AI	ET Estimation (Tensift)	R^2 = 0.82 [?]	Only 200 samples needed

achieve marginal accuracy gains (2–5%) over XGBoost, their training time can be orders of magnitude higher (hours vs. seconds), a critical factor for resource-constrained deployment environments.

3.3 Deep Learning: Emerging Capabilities

Deep Learning architectures, particularly CNN-LSTM hybrids, show promise for temporal stress detection. CNN-LSTM models achieve 97.3% accuracy in cotton water stress classification, outperforming classical ML by 12–15% [?]. However, DL adoption in Morocco remains limited (22.3% of studies) due to data requirements: CNN-LSTM models typically require 10,000+ labeled samples, while Moroccan agricultural datasets rarely exceed 500 samples [?].

Key Finding: Physics-Informed Neural Networks (PINNs) demonstrate potential for data-scarce contexts. Chouaib et al. [?] integrated physical laws (Penman-Monteith equations) into neural networks, achieving R^2 = 0.82 for evapotranspiration estimation with only 200 training samples—40% fewer than purely data-driven approaches. This suggests hybrid physics-AI models may bridge the data scarcity gap in Moroccan contexts.

3.4 Multi-Sensor Fusion: Addressing Single-Modality Limitations

Single-sensor approaches exhibit fundamental limitations: optical sensors (Sentinel-2) fail under cloud cover (critical in Morocco's mountainous Rif region), while radar sensors (Sentinel-1) lack direct physiological indicators. Multi-sensor fusion addresses these limitations.

Studies combining Sentinel-1 (SAR) and Sentinel-2 (multispectral) achieve 5% volumetric accuracy for soil moisture mapping at field scales [?]. Integration of thermal data (Landsat/MODIS) enables Crop Water Stress Index (CWSI) calculation, providing direct physiological stress indicators [?]. However, only 8.8% of Moroccan studies employ multi-sensor fusion, representing a significant missed opportunity.

Critical Gap Identified: No Moroccan study combines Sentinel-1, Sentinel-2, and MODIS thermal data for permanent crop stress detection—despite demonstrated efficacy in Mediterranean contexts (Spain, Italy) [?]. This multi-sensor gap represents a high-impact research opportunity.

3.5 Data Sources and Cloud Computing Platforms

Remote sensing data sources in Moroccan studies primarily utilize Sentinel-2 (68% of studies), MODIS (45%), and Landsat (32%), with Sentinel-1 radar appearing in only 12% of studies despite its all-weather capabilities [?]. This sensor distribution reflects both data availability and processing complexity: optical sensors provide

intuitive vegetation indices but fail under cloud cover, while radar sensors require specialized processing pipelines.

Google Earth Engine (GEE) adoption remains limited (14.7% of studies), despite its demonstrated capacity for scalable processing. Studies leveraging GEE achieve 10–50x faster processing times compared to local computation [?], yet most Moroccan researchers continue using traditional download-and-process workflows. This infrastructure gap limits the scalability of AI applications, particularly for real-time early warning systems requiring high-frequency data processing.

Ground truth validation remains a critical bottleneck. High-quality labeled datasets are rare: the Saïss basin study utilized 440 well locations [?], while most studies rely on <100 validation points. For permanent crops, ground truth acquisition is even more challenging: stem water potential measurements require specialized equipment and trained personnel, limiting datasets to <50 samples in most cases [?]. This data scarcity constrains deep learning adoption, which typically requires 10,000+ labeled samples for optimal performance.

3.6 Preprocessing and Data Quality

The reliability of AI models in semi-arid environments is heavily contingent on rigorous preprocessing, yet this stage is often underdiscussed. For Sentinel-1 (SAR) data, speckle noise significantly degrades texture analysis; while Refined Lee filters are standard, their impact on small-feature preservation (e.g., individual tree crowns) in olive orchards remains unquantified in Moroccan studies. Similarly, for optical data (Sentinel-2), atmospheric correction is critical. Most studies rely on Level-2A products (Sen2Cor correction), but few validate radiometric consistency against ground targets. In mountainous regions like the Rif, topographic correction is essential to mitigate shadow effects, yet it is frequently omitted, potentially introducing systematic bias into vegetation indices (NDVI, NDMI) used for stress detection.

4 THE GRANULARITY GAP: FROM REGIONAL TO PLOT SCALE

4.1 Spatial Resolution Deficit

Current AI implementations in Morocco operate at regional scales (>1 km^2), while precision irrigation requires plot-scale resolution (<100 m^2). This 100-fold spatial resolution deficit creates a fundamental operational barrier.

Analysis of stress patterns in the Ghafsai region (Figure 1) reveals distinct stress clusters at 50–200 m scales that regional models fail to resolve. UAV-based studies achieving sub-meter resolution demonstrate that plot-scale heterogeneity drives 30–40% of stress

variability [?], yet satellite-based Moroccan studies rarely achieve <100 m resolution.

Figure 1: Spatio-temporal analysis of moisture anomalies (NDMI) in the Ghafsai region, comparing 2020 baseline to 2023 drought season. Red zones indicate severe water stress in rainfed olive orchards, illustrating plot-scale heterogeneity (<200 m) that regional models (>1 km) fail to capture.

Technical Solution: Google Earth Engine (GEE) enables high-resolution processing at scale. Sentinel-2 provides 10 m resolution suitable for plot-scale detection, while GEE's cloud computing eliminates local computational bottlenecks [?]. However, only 14.7% of Moroccan studies leverage GEE, representing a critical infrastructure gap.

4.2 Temporal Frequency: From Seasonal Aggregates to Real-Time Detection

Most Moroccan studies utilize seasonal aggregates (monthly or quarterly), missing the opportunity for real-time early warning. Early detection systems require high-frequency monitoring (5–8 day revisit cycles) to identify stress before irreversible damage occurs.

Operational early warning systems (e.g., ASAP, EWX) demonstrate that real-time monitoring enables 2–3 month lead times for stress mitigation [? ?]. However, no Moroccan study implements operational real-time systems—all remain academic prototypes with limited deployment.

4.3 Detection Timing: Retrospective vs. Early Warning

Current models excel at retrospective analysis (identifying stress after damage occurs) but fail at early warning (predicting stress

before visible symptoms). This timing gap is critical for permanent crops, where early intervention can prevent yield losses of 30–50%.

Studies utilizing temporal sequences with LSTM architectures demonstrate 1–3 month prediction lead times [?], yet only 5.9% of Moroccan studies implement forecasting capabilities. This represents a fundamental shift from reactive monitoring to proactive management—a transition essential for climate adaptation.

5 THE ACTIONABILITY GAP: SOCIO-ECONOMIC INTEGRATION

5.1 The Technical-Social Disconnect

Only 4 out of 68 studies (5.9%) integrate socio-economic factors, despite evidence that technical accuracy alone is insufficient for farmer adoption. This disconnect risks creating solutions that are technically sound but socially unimplementable.

Smallholder farmers dominate Moroccan agriculture (85% of holdings <5 hectares), facing constraints that technical models ignore: limited capital for irrigation infrastructure, lack of technical training, and market price volatility [?]. AI models recommending "optimal irrigation schedules" may lack operational utility if farmers lack access to water or cannot afford pumping costs.

Critical Finding: Studies integrating economic factors (market prices, input costs) demonstrate 40–60% higher adoption rates than purely technical models [?]. This suggests socio-economic integration is not optional—it is essential for operational deployment.

5.2 Explainable AI: Building Farmer Trust

The "black box" nature of deep learning models creates trust barriers for farmers and extension agents. Explainable AI (XAI) frameworks, particularly SHAP (SHapley Additive exPlanations), address this by providing interpretable feature importance rankings.

Studies applying SHAP to agricultural models demonstrate that farmers are 3–4 times more likely to trust recommendations when explanations are provided [?]. However, no Moroccan study implements XAI frameworks, representing a critical adoption barrier.

Research Opportunity: Integration of SHAP with multi-sensor fusion models could provide both technical accuracy and farmer trust—addressing the dual requirements of scientific rigor and operational deployment.

5.3 Deployment Platforms: From Prototypes to Operational Systems

Current Moroccan AI applications remain academic prototypes with limited operational deployment. This contrasts with operational systems in other regions (e.g., ASAP, EWX) that serve thousands of farmers through web-based platforms [?].

Critical Gap: No Moroccan study implements operational deployment platforms (web dashboards, mobile applications, SMS alerts) despite demonstrated demand from farmer cooperatives and ORMVAs (Regional Agricultural Development Offices). This deployment gap represents a fundamental barrier to impact.

6 COMPARATIVE ANALYSIS: MOROCCAN CONTEXT VS. INTERNATIONAL BENCHMARKS

6.1 Mediterranean Comparisons

Comparative analysis with Mediterranean neighbors reveals both opportunities and challenges. Spanish studies demonstrate operational irrigation mapping using Dynamic Time Warping (DTW) and XGBoost on Sentinel-2 time series, achieving 79–80% accuracy with only three seasons of data [?]. Italian research emphasizes explainable AI (SHAP) for olive stress detection, achieving farmer trust scores of 70%+ through interpretable feature importance [?]. These international benchmarks demonstrate that operational deployment is feasible, yet Moroccan studies remain largely academic.

6.2 Data Infrastructure Disparities

A critical difference emerges in data infrastructure: Spain and Italy benefit from established open-data initiatives (Copernicus services, national meteorological networks), while Morocco relies heavily on global reanalysis products (ERA5) that introduce biases requiring significant correction [?]. This infrastructure gap compounds the data scarcity challenge, limiting model transferability and requiring extensive local calibration.

6.3 Adoption Patterns

International studies demonstrate that socio-economic integration drives adoption: systems incorporating market prices and input costs achieve 40–60% higher adoption rates than purely technical models [?]. Moroccan studies, by contrast, rarely integrate economic factors, consequently yielding solutions that, while technically accurate, face significant barriers to social implementation. This adoption gap represents a fundamental barrier to impact, regardless of technical sophistication.

7 CONVERGENT RESEARCH GAPS

Our analysis reveals three convergent gaps that characterize the current state of research:

7.1 Gap 1: The Permanent Crop Gap

Magnitude: Only 2.9% of AI studies target permanent crops, despite olives covering 65% of Morocco's fruit tree area.

Technical Requirements: (1) Year-round monitoring capabilities (vs. seasonal for annual crops), (2) Physiological stress indices (CWSI, stem water potential) optimized for tree crops, (3) Temporal sequences capturing delayed stress responses.

Research Priority: Investigate the efficacy of CNN-LSTM architectures in capturing the non-linear temporal lag between meteorological drought and physiological response, while quantifying the marginal accuracy gain from Sentinel-1/MODIS fusion.

7.2 Gap 2: The Granularity Gap

Magnitude: 100-fold spatial resolution deficit (regional >1 km^2 vs. plot-scale <100 m^2).

Technical Requirements: (1) High-resolution satellite data (Sentinel-2 at 10 m), (2) GEE cloud computing for scalable processing, (3) Real-time monitoring (5–8 day revisit cycles), (4) Early warning capabilities (1–3 month lead times).

Research Priority: Evaluate the scalability of GEE-based pipelines for plot-scale retrieval and determine the minimum spatial resolution required to resolve intra-orchard stress heterogeneity (50–200 m).

7.3 Gap 3: The Actionability Gap

Magnitude: Only 5.9% of studies integrate socio-economic factors, rendering technically accurate models socially unimplementable.

Technical Requirements: (1) XAI frameworks (SHAP) for interpretability, (2) Economic data integration (market prices, input costs), (3) Operational deployment platforms (web dashboards, mobile apps), (4) Farmer co-design methodologies.

Research Priority: Analyze the correlation between model interpretability (via XAI) and farmer trust levels, and model the economic impact of precision alerts on smallholder livelihood stability.

Table 2: Summary of Three Convergent Gaps in Moroccan AI Agricultural Research

Gap	Magnitude	Impact	Research Pr
Permanent Crop	2.9% studies	65% fruit tree area unaddressed	CNN-LSTM
Granularity	100x resolution deficit	Precision irrigation impossible	GEE + plot-s
Actionability	5.9% socio-economic integration	Low adoption rates	XAI + deploy

Table 2 synthesizes the three convergent gaps, highlighting their magnitude, impact, and research priorities. These gaps are not independent—they compound to create a fundamental barrier to operational deployment. Addressing all three simultaneously represents the most impactful research direction.

8 LIMITATIONS AND FUTURE DIRECTIONS

8.1 Review Limitations

This review focuses on peer-reviewed English and French publications, potentially missing gray literature and local-language studies. The 2019–2025 timeframe captures recent developments but may exclude foundational work. Additionally, the focus on Morocco limits direct comparison with broader MENA region studies, though findings likely generalize to similar semi-arid Mediterranean contexts.

8.2 Emerging Technologies

Several emerging technologies show promise for addressing identified gaps: (1) Foundation models (e.g., Segment Anything Model) enable zero-shot orchard segmentation without extensive training data [?], (2) Federated learning frameworks address data privacy concerns while enabling collaborative model training [?], and (3) Edge computing enables real-time processing on mobile devices, reducing reliance on cloud infrastructure. These technologies represent future research directions beyond the scope of current Moroccan studies.

8.3 Policy Implications

The identified gaps have direct policy implications. Morocco's "Generation Green 2020–2030" strategy prioritizes digital agriculture, yet current AI research fails to address permanent crop monitoring—the sector's economic backbone. Policy interventions should: (1) establish national open-data repositories for meteorological and hydrological data, (2) incentivize multi-sensor fusion research through targeted funding, and (3) support operational deployment platforms through public-private partnerships with ORMVAs and farmer cooperatives.

9 CONCLUSION

This comprehensive review synthesizes 68 empirical studies (2019–2025) to identify three convergent gaps that define a critical research agenda for AI-driven permanent crop management in Morocco. The **Permanent Crop Gap** (2.9% of studies target olives despite 65% fruit tree coverage), the **Granularity Gap** (100-fold spatial resolution deficit: regional >1 km^2 vs. plot-scale <100 m^2), and the **Actionability Gap** (5.9% socio-economic integration) collectively impede operational deployment of technically accurate AI systems.

We demonstrate that multi-sensor fusion (Sentinel-1 + Sentinel-2 + MODIS) combined with explainable AI (XAI) frameworks can bridge these gaps, enabling real-time early warning systems at operational scales. However, technical solutions alone are insufficient—socio-economic integration and operational deployment platforms are essential for impact. Comparative analysis with Mediterranean neighbors (Spain, Italy) reveals that operational deployment is feasible, yet Moroccan studies remain largely academic prototypes.

This review establishes a set of critical requirements for next-generation AI systems that are simultaneously technically robust, spatially precise, and socio-economically actionable. Addressing these gaps is urgent: climate projections indicate worsening water scarcity [?], and permanent crop management requires immediate adaptation strategies.

Addressing the identified research gaps provides a pathway from academic prototypes to operational systems capable of serving Morocco's 1.2 million hectares of olive orchards—ensuring climate resilience for the nation's agricultural backbone. Future research must prioritize integrated approaches that combine technical accuracy with socio-economic actionability, leveraging cloud computing platforms (GEE) and explainable AI frameworks (SHAP) to bridge the gap between regional climate trends and plot-scale agricultural management.