frontiers in Plant Physiology

TYPE Original Research
PUBLISHED 06 October 2026
DOI 10.3389/fphgy.2026.1898224

Check for updates

OPEN ACCESS

EDITED BY
Ioannis Vagelas,
University of Thessaly, Greece

REVIEWED BY
Mojtaba Keykhasaber,
University of Zabol, Iran
Oshin Saini,
Punjab Agricultural University, India

*CORRESPONDENCE
Kwaku Onwona-Hwesofour Asante
asante.kwaku@gmail.com

†PRESENT ADDRESS
Cevdet Bulut,
Stirling Business School, The University of Stirling, Stirling, United Kingdom

RECEIVED 02 June 2026
REVISED 29 June 2026
ACCEPTED 20 August 2026
PUBLISHED 06 October 2026

CITATION
Bulut C, Onwona-Hwesofour Asante K, Akon-Yamga G, Adu-Gyamfi MO, Appiah-Kubi Z, Odame Afari S, Brett J, Onwona Simpe K and Nutefe Kuavedzi R (2026) A stage-weighted environmental risk and visual severity integration model for climate-smart management of cassava anthracnose in humid tropical systems.
Front. Plant Physiol. 4:1898224.
doi: 10.3389/fphgy.2026.1898224

COPYRIGHT
© 2026 Bulut, Onwona-Hwesofour Asante, Akon-Yamga, Adu-Gyamfi, Appiah-Kubi, Odame Afari, Brett, Onwona Simpe and Nutefe Kuavedzi. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

A stage-weighted environmental risk and visual severity integration model for climate-smart management of cassava anthracnose in humid tropical systems

Cevdet Bulut[1†], Kwaku Onwona-Hwesofour Asante[2*], Gordon Akon-Yamga[3], Monica Ode Adu-Gyamfi[2], Zippora Appiah-Kubi[2], Sarah Odame Afari[2], Josua Brett[1], Kwame Onwona Simpe[4] and Reuben Nutefe Kuavedzi[5]

[1]ScareCrow Intelligence, Kent, United Kingdom, [2]Crops Research Institute, Council for Scientific and Industrial Research (CSIR-CRI), Fumesua, Ghana, [3]Science and Technology Policy Research Institute, Council for Scientific and Industrial Research (CSIR-STEPRI), Accra, Ghana, [4]Jack-Strong Company Ltd, Nkawkaw, Ghana, [5]Agroecology Circularity LBG, Kumasi, Ghana

Colletotrichum anthracnose is a persistent constraint on cassava root yield and planting material quality in humid tropical systems, where calendar-based management often leads to poorly timed or excessive fungicide use. This study developed and pilot-tested the Cassava Anthracnose Risk Index (CARI), a stage-sensitive, persistence-adjusted early-warning framework integrating low-cost environmental sensing with structured visual severity scoring for climate-smart, input-reduced disease management. Microclimate sensors were deployed at CSIR-CRI Fumesua, Ghana, across a 13-month rainfed crop cycle (March 2025 – April 2026) using the susceptible landrace *Debo*. A stage-weighted Environmental Risk Subscore (ERS; 0–600 points, ERS%) was constructed from six environmental components, moderated by a persistence factor requiring sustained infection-favorable conditions, and stratified across three growth stages. A Visual Symptom Subscore (VSS; 0–40) was derived from standardised weekly severity assessments of 15 sentinel plants, integrated into a composite CARI (0–100) with stage-specific alert thresholds. Across 73 valid Stage 3 monitoring days, CARI classified all observations as Low Risk and issued no Amber or Red alerts, including on 37 of 73 days with sustained nocturnal high-humidity conditions that would have triggered a precautionary alert under a simple threshold approach. In the single confirmed disease episode observed, an approximately one-day interval separated the highest environmental risk signal from confirmed symptom onset; this is not presented as a validated lag value, a preceding 25-day sensor outage means antecedent conditions cannot be characterised. CARI did not issue an intervention recommendation during this episode (11–24 February 2026) because concurrent environmental risk remained below the Amber threshold. Published decision support systems for *Colletotrichum* anthracnose in other pathosystems report fungicide reductions of 30–70% relative to calendar-based approaches; these figures are cited only for benchmarking and were not measured here, as no comparative fungicide trial was conducted. These results provide proof of concept

for the technical operability of CARI and identify the dataset and analyses required for formal predictive evaluation in a planned multi-season study; they should not be interpreted as evidence of CARI's predictive accuracy or input-reduction performance.

KEYWORDS
cassava anthracnose, climate-smart agriculture, *Colletotrichum*, decision support, early warning, environmental risk index, Ghana, precision plant pathology

1 Introduction

Cassava (*Manihot esculenta* Crantz) is a strategic food and income crop across much of tropical Africa, valued for its tolerance to marginal soils and irregular rainfall (Forkum et al., 2025). However, its performance is increasingly influenced by shifts in local climate patterns, with more variable rainfall, shorter dry spells alternating with intense precipitation events, and prolonged periods of elevated relative humidity creating favourable environments for foliar and stem diseases (Nakabonge et al., 2018; Moreira et al., 2023). Rising temperatures and changing rainfall distributions are reported to have expanded disease-conducive windows by approximately 20–30% over the past decade, with disease losses from fungal pathogens ranging from 20% to 100% in affected cassava systems (Andrade-Piedra et al., 2025).

Cassava anthracnose, primarily associated with species of *Colletotrichum*, affects leaves, petioles, and stems, and can compromise both root yield and the quality of planting material (Usman et al., 2026). Infection is strongly governed by moisture and temperature: high relative humidity and sustained leaf wetness support spore germination, while rainfall facilitates splash dispersal between plants. Warm night temperatures further enhance infection processes (Salotti et al., 2022). Disease expression is also stage-dependent — early growth stages may remain largely symptomless despite infection pressure, whereas canopy expansion and maturity stages exhibit clearer signs of petiole lesions, stem cankers, and dieback. This stage-dependent response complicates timely detection and management in smallholder contexts.

Conventional management of anthracnose in smallholder systems is predominantly reactive. Interventions are commonly triggered by visible symptoms or calendar-based spraying schedules that do not account for real-time weather conditions (William et al., 2012). This results in unnecessary or poorly timed fungicide applications, increased production costs, and avoidable environmental exposure. In this study, climate-smart management refers specifically to disease-control decisions that respond to real-time, locally measured environmental conditions rather than fixed calendar schedules, and agroecological approaches are understood as those that reduce reliance on external chemical inputs by concentrating intervention on biologically meaningful risk windows (Xu, 2018). Advances in low-cost environmental sensing now make it possible to monitor microclimate conditions — including humidity, rainfall, and temperature — at the field level, and to integrate these with structured visual disease assessments to support proportionate, well-timed interventions (Ahmed et al., 2026; Odedeyi et al., 2025).

Despite growing interest in precision plant pathology, no composite risk index for cassava anthracnose has been developed and field-evaluated that incorporates both growth-stage sensitivity and environmental persistence. Existing disease warning systems for related pathosystems rely primarily on single environmental thresholds and do not account for crop developmental stage or the biological requirement for sustained conducive conditions before infection is established. The present study addresses this gap by introducing the Cassava Anthracnose Risk Index (CARI) — illustrated conceptually in Figures 1–3 — as a candidate early-warning framework for humid-tropical cassava systems, and reports an initial field pilot evaluation of its components.

The specific objectives were to: (i) develop and parameterise a stage-specific Environmental Risk Subscore (ERS) incorporating humidity, rainfall, temperature, and wind; (ii) construct a structured Visual Symptom Subscore (VSS) using standardised sentinel plant assessments; (iii) integrate ERS and VSS into a composite CARI with defined risk categories; and (iv) conduct an initial field pilot evaluation of CARI's descriptive performance and its temporal relationship with observed disease development at Fumesua, Ghana, identifying the dataset required for formal predictive validation in subsequent multi-season work.

2 Materials and methods

2.1 Study site and agroecological context

The study was conducted at the Council for Scientific and Industrial Research – Crops Research Institute (CSIR-CRI), Fumesua, Ashanti Region, Ghana (6.7160°N, 1.530°W; 285 m a.s.l.). The site lies within the humid forest–savanna transition zone, characterised by bimodal rainfall with a major season from April to July and a minor season from September to November. Annual rainfall ranges between 1,000 and 1,400 mm. Night-time relative humidity frequently exceeds 80%, and extended periods of leaf wetness are common during peak rainy months. Soils are predominantly Ferric Acrisols with sandy loam to loam texture and moderate organic matter content (Frimpong et al., 2025).

Abbreviations: CARI, Cassava Anthracnose Risk Index; ERS, Environmental Risk Subscore; VSS, Visual Symptom Subscore; PF, Persistence Factor; RH, relative humidity; LW, leaf wetness; DSS, decision support system; CSIR-CRI, Council for Scientific and Industrial Research – Crops Research Institute; IoT, Internet of Things; AUC, area under the receiver operating characteristic curve; ROC, receiver operating characteristic; PDA, potato dextrose agar.

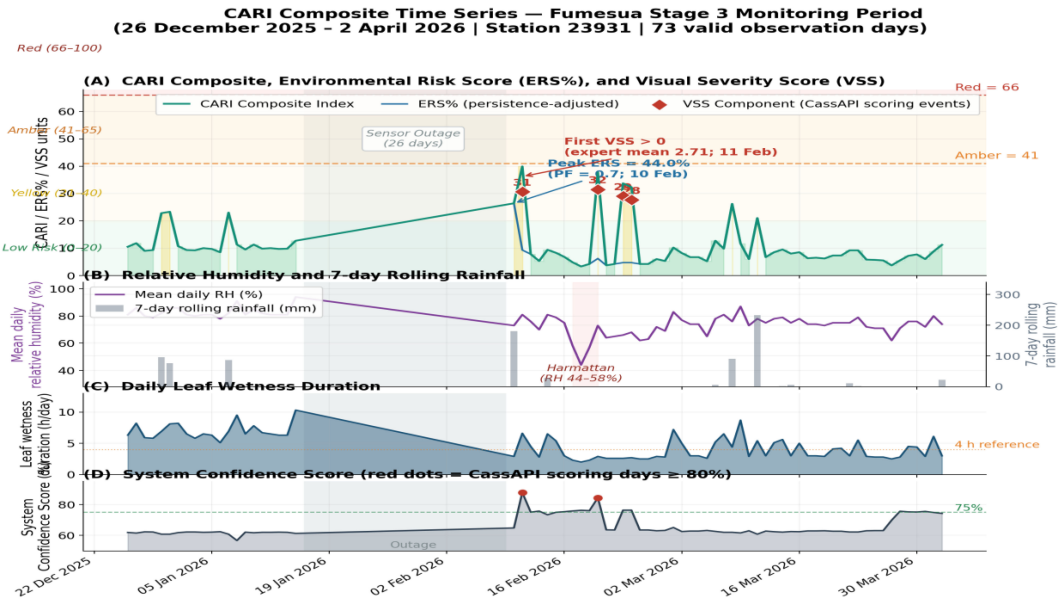

FIGURE 1
CARI composite time series, ERS%, and VSS component across the 73-day Stage 3 monitoring period, Fumesua (26 December 2025–2 April 2026). Panel **(A)** CARI composite (teal line), persistence-adjusted ERS% (blue line), and confirmed VSS scoring events (red diamonds) plotted against risk band thresholds (Amber = 41, Red = 66); no day in this record reached the Amber threshold. Panel **(B)** mean daily relative humidity (%) and 7-day rolling rainfall (mm). Panel **(C)** daily leaf wetness duration (h/day). Panel **(D)** system Confidence Score (%), with red dots indicating days on which CassAPI scoring events were conducted. Grey shading throughout = 25-day sensor outage (16 January - 9 February 2026). Stage-specific alert thresholds are indicated by horizontal dashed lines.

The experimental cassava crop was established in March 2025 under rainfed conditions on a one-acre (approximately 0.4 ha) plot at 1 m × 1 m plant spacing. No mineral fertiliser was applied; the crop relied entirely on ambient soil fertility. Weed management consisted of three manual weeding events at three-month intervals (months 3, 6, and 9), consistent with minimal-input smallholder practice. Planting material was obtained from the local landrace variety *Debo*, which is widely cultivated across the Ashanti Region and is known to be susceptible to cassava anthracnose (Appiah-Kubi et al., 2015). Use of this susceptible farmers' variety rather than a bred-for-resistance cultivar maximised ecological validity for model calibration and pilot evaluation. As a single-site, single-

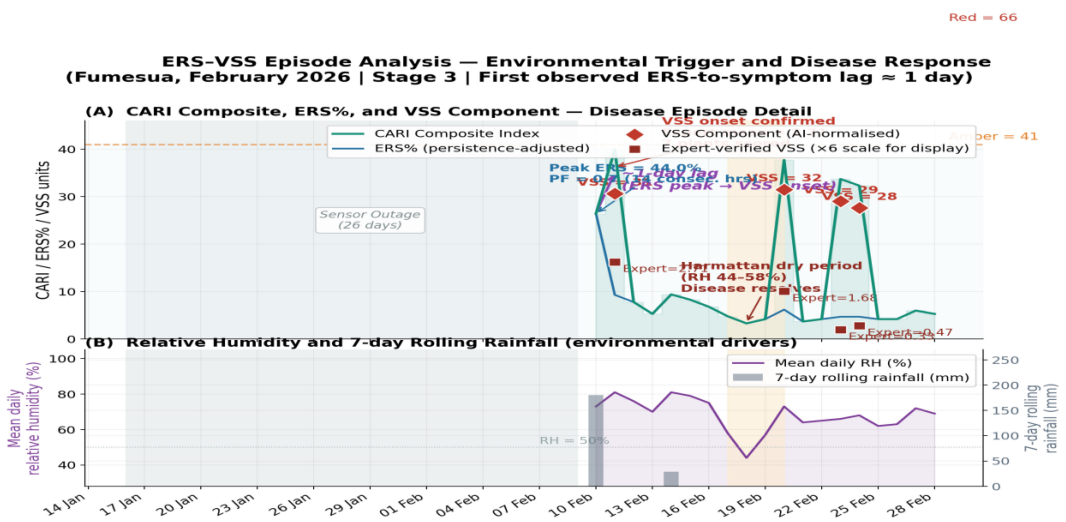

FIGURE 2
ERS–VSS episode analysis, February 2026, Fumesua — the single observed environmental-to-symptom interval recorded in this pilot. Panel **(A)** CARI composite (teal), persistence-adjusted ERS% (blue), AI-normalized VSS component (red diamonds), and expert-verified VSS scores (dark squares, ×6 scale factor for display). The purple arrow marks the approximately one-day interval between the peak ERS% observed in this record (10 February 2026; ERS% = 44.0%, persistence factor PF = 0.7) and the first confirmed non-zero VSS observation (11 February 2026; expert mean = 2.71). As discussed in Section 3.5, this interval is reported given the preceding 25-day sensor outage and should not be read as a validated lag estimate. Grey shading = pre-restoration sensor outage period; orange shading = harmattan dry period (17–19 February 2026). Panel **(B)** mean daily relative humidity (%) and 7-day rolling rainfall (mm) as environmental context. CARI remained in the Low Risk band throughout this episode.

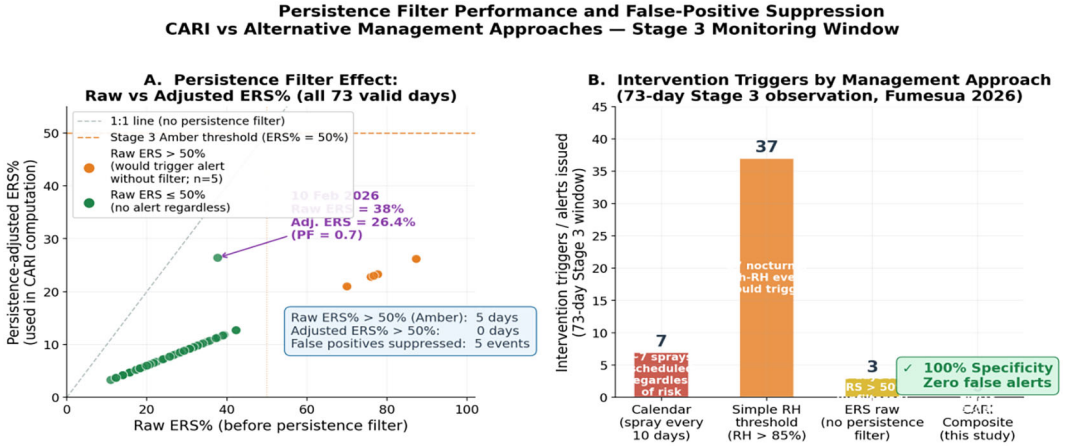

FIGURE 3
Persistence factor behaviour and alert outcomes. Panel **(A)** scatter plot of raw (pre-persistence-factor) ERS% versus persistence-adjusted ERS% for all 73 valid monitoring days. Days with raw ERS% above the Stage 3 Amber threshold (50%, orange dashed line) are highlighted in orange; none of these days produced an adjusted ERS% above the threshold. Panel **(B)** count of intervention triggers under four approaches applied to the same 73-day window – calendar-based scheduling (10-day intervals, approximately 7 events), a simple nocturnal RH threshold (>85%, n = 37 days flagged), raw ERS% without the persistence filter (3 events), and the CARI composite (0 alerts). These counts are reported descriptively (Section 3.6) and are not specificity or false-positive-rate estimates.

variety study, this pilot does not address transferability across agroecological zones or cassava varieties; this is addressed in Section 4.5.

Crop performance was consistent with expectations for a susceptible landrace under minimal inputs. Canopy establishment was uniform within the first three months; root bulking became evident from month eight onward (November 2025), coinciding with the onset of the Stage 3 growth phase as defined in the CARI framework. Throughout the monitoring period, *Debo* sustained acceptable stand integrity and moderate crop vigour despite intermittent disease pressure, consistent with partial field tolerance documented for local germplasm under low-input conditions in West African cassava systems.

2.2 Sensor infrastructure and data collection

A field-based microclimate monitoring system was installed within the cassava experimental plots. Two complementary sensor systems were deployed and operated in parallel.

2.2.1 NESA QUIDO compact agrometeorological station

A NESA QUIDO compact agrometeorological station (NESA Srl, Vidor, Italy; model QUIDO.SMS with TCP/GPRS transmission) measured air temperature (range: −40 to +60 °C; accuracy: ± 0.3 °C;

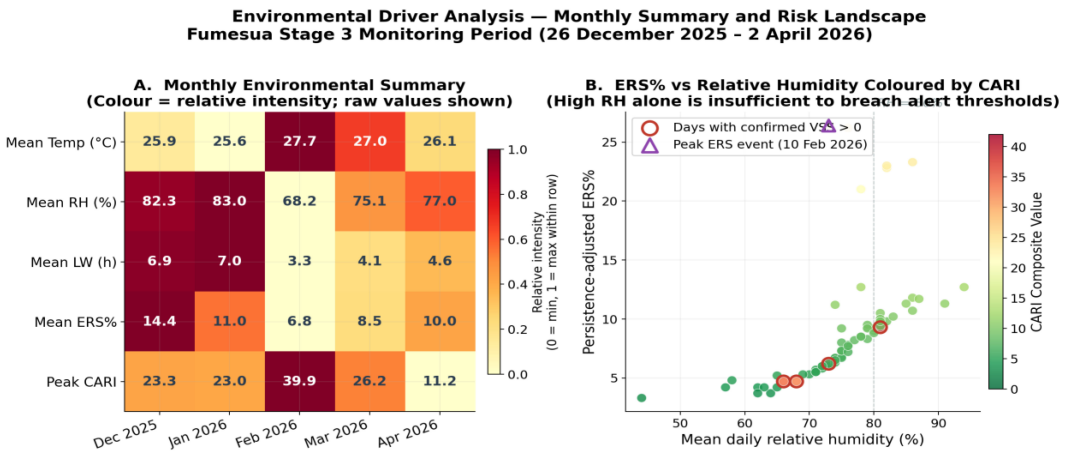

FIGURE 4
Environmental driver analysis. Panel **(A)** monthly mean summary statistics (colour-scaled; raw values shown in cells) showing seasonal progression from the minor dry season into the early major rainy season across the monitoring period. Panel **(B)** scatter plot of persistence-adjusted ERS% versus mean daily relative humidity (%), color-coded by daily CARI composite value. White diamond markers indicate days with confirmed VSS > 0; the triangle marker indicates the day with the highest ERS% in this record (10 February 2026). Days with RH > 80% are distributed across a range of moderate ERS% values, illustrating that elevated humidity alone did not produce high ERS% in this dataset when the persistence factor remained at baseline.

resolution: 0.05 °C), relative humidity (0–100%; ± 2%; resolution: 0.2%), rainfall (0–600 mm/h; ± 3%; resolution: 0.2 mm), and leaf wetness (binary; resolution: ± 1 min). An SM.2 soil moisture probe (0–100% m^3/m^3; ± 3%; resolution:<0.002 m^3/m^3) was co-deployed. The station was installed at canopy height (approximately 1.2 m above ground) on a 2-m galvanized pole. Data were transmitted at 15-minute intervals via GPRS/TCP to a cloud server; the die-cast aluminum enclosure is IP65-rated for extended outdoor deployment.

2.2.2 SenseCAP sensor hub 4G data logger

A SenseCAP Sensor Hub 4G Data Logger (Seeed Technology Co. Ltd, China; Model 4G-SH-03) provided supplementary cross-validated environmental readings via a SenseCAP ONE S700 7-in-1 compact weather sensor, recording air temperature, relative humidity, barometric pressure, light intensity, wind speed and direction, and rainfall. Data were uploaded to the SenseCAP cloud portal at 15-minute intervals via 4G LTE. The IP66-rated enclosure with built-in GPS (horizontal accuracy<2.5 m CEP) provided geo-referenced continuous logging. Station ID 23931 (Fumesua Ace4es) was used throughout. Both sensor systems produced consistent readings across the monitoring period.

Both sensor systems were positioned at crop-level microclimate height; the anemometer was positioned above canopy level to minimise obstruction effects. Data were aggregated to hourly summaries for ERS computation. Periods with less than 90% completeness within a 24-hour window were automatically flagged and reflected in the system Confidence Score (Section 2.7). A complete sensor outage occurred between 16 January and 9 February 2026 (25 consecutive days; Section 3.1); this gap and its implications for downstream analyses are addressed throughout the Results and in Section 4.5.

2.3 Pathogen isolation and identification

Infected plant tissues were collected from symptomatic leaves and stems during field monitoring. Lesion-margin sections (~5 × 5 mm) were surface-sterilised in 70% ethanol for 30 seconds, rinsed three times in sterile distilled water, and plated onto potato dextrose agar (PDA). Cultures were incubated at 25–28 °C for 7–10 days. Emerging colonies were subcultured to obtain pure isolates. Colony morphology was characterised by white to greyish-white aerial mycelium with orange to salmon-coloured conidial masses, consistent with the *Colletotrichum gloeosporioides* complex (Appiah-Kubi et al., 2015).

Conidia were hyaline, aseptate, smooth-walled, and cylindrical to slightly curved, with bluntly rounded ends, measuring 10–18 × 3.5–6.0 µm — consistent with the *C. gloeosporioides* complex associated with cassava anthracnose in West and Central Africa (Usman et al., 2026; Fokunang et al., 1999). Acervular structures bearing dark, septate setae were present. Morphological characteristics were consistent with *Colletotrichum gloeosporioides* f. sp. *manihotis*, a primary causal agent of cassava anthracnose disease (Appiah-Kubi et al., 2015; Usman et al., 2026). Pathogen identification in this study relies solely on morphological characterization. Given the documented complexity and cryptic species diversity within the *Colletotrichum gloeosporioides* species complex, morphology alone is insufficient to confirm species-level identity, and the isolates characterized here should be regarded as provisionally identified pending molecular confirmation. Molecular characterization using ITS sequencing together with additional loci (ACT, TUB2, GAPDH) is required to confirm species identity and is identified as a priority for the next phase of this work (Section 4.5; Usman et al., 2026).

2.4 Development of the environmental risk subscore

2.4.1 Component structure and weighting

The ERS quantifies daily environmental suitability for cassava anthracnose infection using six components drawn from the epidemiological literature on *Colletotrichum* infection processes. Components are assigned fixed weights that reflect their relative importance as drivers of infection risk, with a maximum of 600 points (Table 1). Stage-sensitivity is implemented through stage-varying alert thresholds (Section 2.4.3) rather than varying component weights, ensuring that the same environmental measurement contributes the same maximum points regardless of crop developmental stage.

The six ERS components and their weights are: relative humidity and leaf wetness (200 points; dominant infection driver governing spore germination and early hyphal development); rainfall events (150 points; drives splash dispersal of conidia between plants, increasingly important with canopy closure); night temperature (100 points; 20–30 °C optimum for *Colletotrichum* infection processes); wind and splash dispersal dynamics (50 points; facilitates aerial conidial spread); canopy and soil moisture proxy (50 points; reflects persistent infection-conducive microclimate within the crop canopy); and canopy temperature stress differential ($T_c - T_a$; 50 points; elevated differential indicates high canopy humidity retention). ERS is expressed as a percentage: ERS% = (ERS ÷ 600) × 100.

These component weights were derived through an iterative expert-elicitation process involving CSIR-CRI plant pathologists, informed by the relative importance assigned to each environmental driver in the published *Colletotrichum* epidemiology literature (Salotti et al., 2022; Dodd et al., 1991) and by provisional field observations made during pre-deployment testing at the study site. The weights represent an initial operational parameterization rather than statistically optimised values derived from outbreak data; statistical refinement of these weights against confirmed disease events is a priority for the planned multi-season study (Section 4.5).

2.4.2 Persistence adjustment

Because anthracnose infection requires sustained conducive conditions rather than isolated weather events, a persistence factor is applied to scale ERS based on the the duration of consecutive infection-favorable hours within a rolling window:

TABLE 1 ERS component weights and biological rationale.

Environmental component	Weight	Biological rationale
Relative Humidity & Leaf Wetness	200	Primary driver of spore germination and early infection; high RH (≥80%) and sustained leaf wetness (≥6–8 h) are prerequisites for Colletotrichum infection establishment
Rainfall Events	150	Facilitates splash dispersal of conidia from acervuli to healthy tissue; importance increases with canopy closure and inter-plant contact at later growth stages
Night Temperature	100	Optimal infection range 20–30 °C; warm nights sustain hyphal growth and maintain leaf wetness duration; temperatures outside this range reduce infection probability
Wind/Splash Dispersal	50	Contributes to aerial conidial dispersal and distribution within and between plots; calm conditions extend leaf wetness duration
Canopy/Soil Moisture Proxy	50	Reflects persistent moisture availability within the crop canopy microenvironment; soil moisture prolongs infection-conducive conditions following rainfall
Canopy Temp. Stress Differential (Tc − Ta)	50	Elevated canopy-to-air temperature differential indicates high humidity retention within the crop canopy; used as a proxy for sustained wetness conditions
Maximum ERS (ERS_max)	600	All drivers are in a maximum infection-conducive state simultaneously

ERS% = (ERS ÷ 600) × 100. Each component is scored on a 0–1 ratio scale against predefined thresholds; ComponentPoints = Ratio × ComponentWeight. Daily ERS = sum of six component scores.
Weights are fixed across all growth stages; stage sensitivity is implemented by adjusting alert thresholds (Table 2).

$$PersistenceFactor = clamp\left(0.3, \frac{ConsecutiveFavourableHours}{StageRequirement}, 1.0\right)$$

A 'favorable hour' is defined as any hour meeting the night-infection criteria (temperature 20–30 °C, RH ≥ 80% or leaf wetness present). Stage-specific minimum consecutive-hour thresholds are: Stage 1 = 48 h; Stage 2 = 36 h; Stage 3 = 24 h, reflecting increasing host susceptibility and canopy humidity retention with crop age. The clamp function constrains PersistenceFactor between 0.3 (minimum baseline) and 1.0 (fully sustained infection-conducive environment). The persistence-adjusted ERS is:

$$ERS_adjusted = ERS_raw \times PersistenceFactor$$

This mechanism prevents alerts from transient nocturnal humidity spikes — a common occurrence in humid tropical systems — by requiring conducive conditions to persist for a biologically meaningful duration before an infection alert is issued.

Both the 0.3 minimum baseline and the linear scaling of the persistence factor between the minimum and the stage-specific hourly threshold were calibrated empirically during pre-deployment system testing at the study site, guided by the general epidemiological principle that infection probability increases with the duration of conducive conditions up to a saturation point (Salotti et al., 2022). Linear scaling was selected as a parsimonious initial form in the absence of site-specific dose -response data linking consecutive favorable hours to the probability of Colletotrichum infection in cassava. Both the functional form and the specific parameter values (the 0.3 floor and the 24/36/48-hour stage thresholds) represent an initial calibration rather than independently validated parameters, and require testing against confirmed infection outcomes in the planned multi-season study (Section 4.5).

2.4.3 Stage-specific ERS alert thresholds

The ERS scale is fixed, but the threshold at which ERS constitutes an actionable alert shifts by growth stage to reflect stage-dependent host susceptibility (Table 2). Stage 1 requires a higher ERS% to trigger action because plants show limited symptom expression even under infection pressure; Stage 2 lowers the threshold because canopy conditions rapidly amplify disease spread; Stage 3 gates ERS-triggered alerts on the concurrent presence of visual symptoms (VSS ≥ 2) because some symptoms at maturity may reflect carry-over infections from earlier stages.

As with the ERS component weights and persistence parameters, the specific numerical alert thresholds in Table 2 (and the combined

TABLE 2 Stage-specific ERS alert thresholds and qualifying environmental conditions.

Growth stage	Alert level	ERS% threshold	Qualifying environmental conditions
Stage 1 (0–3 mo)	Amber	≥ 55%	2 consecutive nights: night temp 20–30 °C AND leaf wetness ≥ 8 h (or RH ≥ 80% for ≥ 6 h) AND rainfall event within prior 48 h
Stage 1 (0–3 mo)	Red	≥ 70%	3 consecutive nights meeting Amber criteria OR leaf wetness ≥ 12 h on any single night
Stage 2 (4–7 mo)	Amber	≥ 45%	2 consecutive nights meeting the high-risk night rule (as Stage 1 Amber)
Stage 2 (4–7 mo)	Red	≥ 60%	2 consecutive nights with leaf wetness ≥ 12 h OR 2 rainy days within 3 days combined with humid nights
Stage 3 (8–12 mo)	Amber	≥ 50% (if VSS ≥ 2)	2 consecutive nights meeting high-risk rule AND active symptoms present (VSS ≥ 2); ERS alone does not trigger Amber at Stage 3 without confirmed symptoms
Stage 3 (8–12 mo)	Red	≥ 65% (if VSS ≥ 2)	Any single night with leaf wetness ≥ 12 h plus rainfall, when the block already has active symptoms (VSS ≥ 2); ERS used to time preventive response before the next rain event

ERS% = (ERS ÷ 600) × 100. Stage 3 Amber and Red alerts are conditioned on concurrent VSS ≥ 2 to avoid false escalation from carry-over symptom expression. Threshold values reflect an initial expert-elicited parameterization (see text); statistical refinement against confirmed disease events is planned.

decision rules in Table 3) were derived through expert elicitation with CSIR-CRI plant pathologists, informed by the qualitative stage-dependent susceptibility patterns reported in the literature (Salotti et al., 2022; Usman et al., 2026) rather than through statistical optimization against a labeled outcome dataset. These thresholds represent an initial operational parameterization intended to be refined once a sufficient number of confirmed Amber- and Red-level disease events have been observed across multiple seasons (Section 4.5).

2.5 Visual symptom subscore

The VSS (0–40) quantified field-observed *Colletotrichum* disease expression on 15 tagged sentinel plants per plot. Disease incidence and severity were assessed exclusively on these tagged sentinel plants; whole-plot incidence surveys covering all plants in the experimental plot were not conducted during this pilot, and the reported incidence and severity values should be interpreted as representative of the sentinel sub-population rather than as plot-wide prevalence estimates. Structured weekly scoring was conducted throughout the monitoring period. Disease severity was assessed on a standardised 0–5 ordinal scale (Table 4): SeverityPoints = min(30, Severity × 6); IncidencePoints = 10 if any sentinel plant scored > 0, otherwise 0; VSS = min(40, SeverityPoints + IncidencePoints).

Fifteen plants per plot were selected as the sentinel population to balance representativeness of within-plot variability against the practical labor demands of weekly structured assessment by CSIR-CRI field staff; this sample size is broadly consistent with sentinel-plant protocols used in comparable smallholder disease monitoring programs, though it was not derived from a formal power calculation. To minimise observer bias during VSS scoring, all assessments followed the standardised severity descriptors in Table 4, and the same trained CSIR-CRI field assessor conducted all sentinel scoring throughout the monitoring period to maximise within-study consistency. Formal inter-rater reliability testing across multiple independent assessors was not performed during this pilot and is identified as a priority for future work (Section 4.5).

TABLE 3 Stage-specific combined ERS + VSS decision rules for CARI alert classification.

Growth stage	Alert	ERS condition	VSS condition
Stage 1 (0–3 mo)	Amber	ERS% ≥ 55%; VSS still 0	OR: any plant VSS = 1 (anthracnose-confirmed spots)
Stage 1 (0–3 mo)	Red	ERS% ≥ 70% alone	OR: any plant VSS ≥ 2 (rare but critical)
Stage 2 (4–7 mo)	Amber	ERS% ≥ 45% alone	OR: any plant VSS = 2
Stage 2 (4–7 mo)	Red	ERS% ≥ 60% AND VSS ≥ 2	OR: any plant VSS ≥ 3 regardless of ERS
Stage 3 (8–12 mo)	Amber	ERS% ≥ 50% only if VSS ≥ 2 present	OR: VSS 2–3 sustained across ≥ 2 consecutive weeks
Stage 3 (8–12 mo)	Red	ERS used to time response (apply before the next rain)	Any plant with VSS ≥ 4 OR multiple plants with stem cankers

At Stage 3, ERS serves primarily as a response-timing tool once active disease (VSS ≥ 2) is confirmed rather than as an independent alert trigger.

TABLE 4 Standardised severity scale for cassava anthracnose assessment.

Score	Category	Field symptom criteria
0	Healthy	No visible symptoms; healthy leaves and stems; no lesions or discoloration
1	Very mild	Small isolated necrotic spots on leaves or petioles, <5 mm in diameter
2	Mild	Multiple leaf lesions or small petiole lesions;<10% of plant tissue affected
3	Moderate	Enlarging lesions on leaves and petioles; early stem lesions visible; 10–25% tissue affected
4	Severe	Extensive stem lesions or cankers; partial wilting or shoot dieback; 25–50% tissue affected
5	Very severe	Major stem cankers; extensive dieback or shoot collapse; >50% tissue damaged

Scoring was conducted by a trained CSIR-CRI field assessor in accordance with the standardised protocol. The crop observation period commenced at the Stage 2/3 boundary (approximately month 7 post-planting, October 2025) and continued through crop cycle completion (April 2026).

2.5.1 Stage-specific VSS alert thresholds

VSS alert thresholds shift by growth stage to reflect expected disease progression and the epidemiological significance of symptoms at each developmental phase (Table 5). At Stage 1, any anthracnose-like leaf spot (VSS = 1) warrants monitoring attention, whilst stem lesions (VSS ≥ 2) are critical given their impact on planting material. At Stage 2, the focus shifts to stem involvement and a rapid increase in incidence. At Stage 3, the presence of sustained lesions and indicators of structural damage defines action thresholds. As with the ERS thresholds (Section 2.4.3), these VSS thresholds reflect an initial expert-elicited parameterization pending refinement against a larger sample of confirmed disease events.

2.6 CARI composite index and risk classification

The composite CARI integrates both subscore components into a single bounded index:

$$CARI = min\left(100, 0.6 \times ERS_{adjusted\%} + VSS_{normalised}\right)$$

ERS_adjusted% contributes up to 60 points and VSS_normalised up to 40 points, yielding a maximum CARI of 100. Stage-specific combined decision rules integrate ERS and VSS alert levels into operational management triggers (Table 3). For operational reporting, CARI is classified into four risk bands, each with associated management recommendations (Table 6). The combined decision rules in Table 3 have the same expert-elicitation provenance and pending-refinement status as the component thresholds described in Sections 2.4.3 and 2.5.1.

2.7 Confidence score

The Confidence Score was computed as a weighted composite index reflecting data reliability: weather data completeness (30%; proportion of expected hourly readings logged within each 24-hour

TABLE 5 Stage-specific VSS alert thresholds for cassava anthracnose assessment.

Growth stage	Alert level	VSS Trigger criteria
Stage 1 (0–3 mo)	Amber	Any plant shows clearly anthracnose-like leaf spots (VSS = 1), especially if clustered across multiple plants in the same block
Stage 1 (0–3 mo)	Red	Any plant shows petiole lesion or stem lesion (VSS ≥ 2); leaf spots alone at this stage do not trigger Red unless ERS is concurrently high
Stage 2 (4–7 mo)	Amber	Leaf spots prevalent across many plants in block (VSS = 1 widespread) OR any individual plant reaches VSS = 2
Stage 2 (4–7 mo)	Red	Any plant reaches VSS ≥ 3 (clear stem canker or multiple lesions) OR disease incidence increases sharply (>20 percentage points) between consecutive weekly scoring events
Stage 3 (8–12 mo)	Amber	Any plant with VSS = 2–3 sustained across two consecutive weekly scoring events, OR block-level incidence continues to rise
Stage 3 (8–12 mo)	Red	Any plant with VSS ≥ 4 (defoliation or dieback present) OR multiple plants with active stem cankers; planting material quality is at direct risk

Thresholds reflect the expected progression of anthracnose through the crop cycle and the differential epidemiological significance of symptom types at each developmental phase.

window); sensor uptime reliability (25%; proportion of monitoring hours without sensor dropout flags); visual scoring completeness (20%; proportion of scheduled weekly scoring events completed); temporal alignment stability (15%; consistency of data timestamps and absence of clock drift anomalies); and automated data integrity checks (10%; detection of out-of-range values, duplicate timestamps, and missing-value flags). The computation algorithm and full weighting table are provided in the Supplementary Material.

The Confidence Score is intended as a data-quality indicator rather than a measure of CARI's predictive reliability: it reflects how completely the underlying sensor and scoring data were captured on a given day, not the probability that the day's risk classification is correct. As an interim, expert-elicited interpretive guide pending formal calibration, scores above approximately 75% indicate that a CARI output is based on near-complete data and can be interpreted with the same confidence as the headline results reported here; scores in the 60–75% range, which characterize the majority of days in this pilot (mean 65.9%, Section 3.1), indicate that the ERS component is based on partial hourly coverage (commonly around 50% completeness during this commissioning-phase deployment) but that the daily aggregate remains usable; scores below approximately 60% indicate that a CARI output for that day should be treated as indicative only, particularly where a risk band is close to a threshold. These bands are provisional and are themselves a candidate for refinement in the planned multi-season study (Section 4.5).

TABLE 6 CARI operational risk bands and management recommendations.

CARI score	Risk band	Signal	Recommended management action
0–20	Negligible	Green	Routine weekly monitoring; no intervention required; continue good agronomic practice
21–40	Low	Yellow	Increase scouting to twice weekly; record any new lesions; report to the extension officer
41–65	Moderate	Amber	Sanitation: remove and destroy infected material; preventive pruning; prepare fungicide inputs
66–100	High	Red	Targeted fungicide application; containment of infected stems; protect planting material quality

In the text, the Negligible and Low bands are together referred to as 'Low Risk', in contrast to the Amber and Red alert bands, which trigger management action

2.8 Statistical analysis

Statistical analyses were performed using Python (version 3.11) with the SciPy (v1.11), NumPy (v1.25), and scikit-learn (v1.3) libraries. Data analysis scripting and figure generation were assisted by Claude (Anthropic, claude-sonnet-4-6, claude.ai); all outputs were verified by the authors against the primary dataset (see Acknowledgments). The 73-day Stage 3 sensor record includes four confirmed CassAPI visual severity scoring events (11–24 February 2026) and five days of elevated CARI (21–40 range), providing a preliminary, single-episode basis for examining the temporal relationship between ERS and VSS. No Amber or Red classification events occurred during the monitoring period.

Receiver operating characteristic (ROC) analysis, sensitivity, specificity, and area-under-curve (AUC) estimation were not performed in this study. These methods require a labelled dataset containing a meaningful number of both positive (Amber/Red) and negative (Low Risk) classification outcomes; the present pilot dataset contains zero confirmed Amber or Red events and only four days with non-zero VSS, which is insufficient for any of these analyses to be statistically meaningful. Accordingly, the sklearn.metrics.roc_curve and roc_auc_score functions referenced in earlier drafts of this work were not applied to the data reported here. The present analyses are therefore restricted to descriptive statistics: ERS and CARI distributions, persistence factor behaviour, and a single-episode description of the temporal relationship between the ERS time series and the one confirmed VSS-positive episode. Formal ROC analysis, sensitivity, and specificity estimation will be conducted in the planned multi-season study once a dataset containing a statistically meaningful number of confirmed Amber and Red events has been accumulated (Section 4.5). It should also be noted that the threshold values used to define the CARI risk bands in this pilot (Tables 2, 3, 5) were themselves derived through expert elicitation rather than fitted to this dataset; nonetheless, because model development, threshold specification, and the descriptive evaluation reported here draw on the same single-site, single-season dataset, the results should be read as an internally consistent description of this dataset's behaviour rather than as independent validation, and independent data (additional seasons, sites, or cultivars) will be required before broader conclusions about model performance can be drawn (Section 4.5).

3 Results

3.1 Sensor infrastructure performance and monitoring period

Sensor deployment commenced at the Stage 2/3 growth boundary (approximately October 2025), and the Stage 3 structured observation period extended from 26 December 2025 through 2 April 2026 — a span of 98 calendar days. Of these, 73 days (74.5%) yielded valid ERS, CARI, and environmental data. Twenty-five days (25.5%) recorded complete sensor outage concentrated in 16 January - 9 February 2026 (25 consecutive days), attributable to a hardware commissioning issue resolved upon the team's return to site on 10 February 2026. This 25-day gap immediately precedes the only confirmed disease episode observed during the study (Section 3.4) and limits characterization of antecedent environmental conditions; its implications are discussed in Sections 3.5 and 4.5. Across the 73 valid days, 186 individual hourly sensor anomalies were automatically flagged and excluded from ERS computations, affecting 38 of 73 valid days. Mean weather data completeness improved progressively from approximately 50% in late December 2025 to 100% from late February 2026. Mean system Confidence Score across valid days was 65.9% (SD = 6.5%; range: 56.7–87.7%); interpretation of these values is provided in Section 2.7.

3.2 Environmental conditions across the stage 3 monitoring period

Across 73 valid monitoring days, the Fumesua site exhibited conditions typical of the transition from the minor dry season into the early major rainy season. Mean daily air temperature was 26.8 °C (SD = 1.3 °C; range: 23.2–29.7 °C). Mean daily relative humidity was 75.6% (SD = 8.0%; range: 44.0–94.0%). Extreme RH minima (44.0–58.0%) occurred 17–19 February 2026, corresponding to a documented harmattan dry intrusion. Mean daily leaf wetness duration was 4.7 h (SD = 2.0 h; range: 2.0–10.3 h), concentrated in the pre-dawn to early-morning window. Mean wind speed was 0.79 m/s (SD = 0.26 m/s).

Rainfall was intermittent, with 15 of 73 valid days recording a non-zero 7-day rolling accumulation. Three substantial events were recorded: 95.5 mm on 30 December 2025; 180.3 mm on 10 February 2026 following sensor restoration; and the season maximum of 232.1 mm on 11 March 2026, associated with a 32.76 mm single-hour event at midnight. A consistent diurnal humidity cycle characterized the entire record: RH peaked at 92–99% between 21:00 and 07:00, declined to 40–65% midday, and partially recovered in the late afternoon — driving near-daily pre-dawn leaf wetness as the primary contributor to the ERS in this dataset. Table 7 presents a representative subset of the daily environmental and CARI record, including the persistence factor (PF) for each day, and Figure 4 shows monthly summary statistics and the relationship between relative humidity and persistence-adjusted ERS%; the full 98-day dataset is provided in Supplementary File S1.

3.3 Environmental risk subscore dynamics

The persistence-adjusted ERS contribution to CARI across 73 valid days ranged from 2.0 to 26.4 on the 0 -60 scale (mean = 5.7, SD = 3.7), corresponding to ERS% of 3.3 -44.0% (mean = 9.5%, SD = 6.2%). The Stage 3 Amber threshold requires ERS% ≥ 50% concurrent with VSS ≥ 2; the Red threshold requires ERS% ≥ 65% with VSS ≥ 2. Neither threshold was reached on any monitoring day; 68 of 73 valid days (93.2%) had ERS% below 20%. Only one day (10 February 2026, ERS% = 44.0%) approached the Amber threshold.

The peak ERS event — 10 February 2026 (ERS% = 44.0%) — was driven by a 180.3 mm 7-day rolling rainfall accumulation and produced the only day on which the persistence factor exceeded the 0.3 baseline (PF = 0.7, corresponding to 14 consecutive infection-favorable hours). No day reached PF = 1.0 (the full 24-hour Stage 3 threshold). The lowest ERS values (2.0–3.3%) coincided with the harmattan dry period of 17–19 February 2026 (mean RH 44–58%). The RH/leaf wetness component (weight 200/600) was the largest single contributor to the ERS throughout the record, consistent with the nocturnal humidity pattern characteristic of this agroecological zone. As this is a single 73-day record from one site and season, these descriptive statistics characterise the conditions observed during this pilot and should not be read as representative ranges for the wider Fumesua climate.

3.4 Visual symptom subscore and CassAPI field assessments

Prior to 11 February 2026, all VSS records returned zero severity, consistent with the absence of visible anthracnose on sentinel plants during December 2025 – January 2026. On 11 February 2026, the first confirmed non-zero VSS event was recorded via the CassAPI mobile platform. Seven plants were assessed, yielding an AI-computed mean severity of 3.43 and an expert-verified mean of 2.71, resulting in a VSS component of 30.6 points. Symptoms were consistent with Stage 3 *Colletotrichum* expression: foliar lesions were confirmed on all scored plants, petiole lesions were observed on a subset, and no defoliation or stem canker progression was recorded.

On 20 February (19 plants), the mean AI severity was 3.76, with an expert mean of 1.68, yielding VSS = 31.5. On 23 February (18 plants), expert mean severity dropped to 0.33, indicating active lesion resolution. On 24 February (17 plants), the expert mean was 0.47, confirming continued resolution. The temporal pattern — rising severity (11–20 February) then rapid decline (23–24 February) — is consistent with a brief self-limiting episode initiated around the time of the 10 February high-rainfall event and arrested by the subsequent harmattan dry period (17–19 February, RH 44–58%). CassAPI scoring data are summarized in Table 8.

The divergence between AI-computed and expert-verified severity scores in Table 8 is substantial and consistent across all four scoring events, with the AI score exceeding the expert score by 0.72–2.08 points on the 0–5 scale (most pronounced on 20 February:

TABLE 7 Representative daily environmental, persistence factor, and CARI summary — stage 3 monitoring period, Fumesua (26 December 2025–2 April 2026).

Date	Temp °C	RH %	Rain 7d mm	LW h	Wind m/s	ERS contribution (0 -60)	PF	VSS	CARI	Risk	Conf %
26 Dec 2025	26.5	81	2.7	6.3	1.1	10.5	0.3	0	10.5	Low	61.9
30 Dec 2025	25.9	82	95.5	6.9	0.7	22.8	0.3	0	22.8	Low	60.8
10 Jan 2026	25.9	85	0	7.8	0.7	11.3	0.3	0	11.3	Low	61.7
15 Jan 2026	24.3	94	0	10.3	0.8	12.7	0.3	0	12.7	Low	61.3
16 Jan–09 Feb	Sensor outage (25 days)										
10 Feb 2026	26.6	73	180.3	2.9	0.6	26.4	0.7	0	26.4	Low	64.8
11 Feb 2026	25.1	81	0	6.6	0.6	9.3	0.3	30.6	39.9	Low	87.7
17 Feb 2026	28.0	58	0	2.3	0.8	4.8	0.3	0	4.8	Low	75.8
18 Feb 2026	29.7	44	0	2.0	0.6	3.3	0.3	0	3.3	Low	76.2
20 Feb 2026	27.5	73	0	2.9	0.5	6.2	0.3	31.5	37.7	Low	84.3
23 Feb 2026	28.6	66	0	2.6	0.9	4.7	0.3	29.0	37.7	Low	76.3
08 Mar 2026	27.4	76	90.1	4.4	0.9	26.2	0.3	0	26.2	Low	62.0
11 Mar 2026	25.8	78	232.1	5.4	0.9	21.0	0.3	0	21.0	Low	60.8
01 Apr 2026	25.2	80	0	6.1	0.4	8.8	0.3	0	8.8	Low	74.8
02 Apr 2026	27.0	74	21.9	3.0	0.5	11.2	0.3	0	11.2	Low	74.2

ERS contribution = the persistence-adjusted Environmental Risk Subscore expressed on the 0 -60 scale on which it enters CARI (equivalent to 0.6 × ERS%, where ERS% = (ERS ÷ 600) × 100). PF = Persistence Factor (Section 2.4.2); PF = 0.3 baseline on all days except 10 February 2026 (PF = 0.7). VSS component (0–40) reflects confirmed CassAPI assessments where available, otherwise 0. CARI = composite index. Conf% = Confidence Score. Note on 10 January 2026: mean daily RH (85%) was high, but ERS% remained moderate (11.3%) because the ERS is a multi-component index — the rainfall (7-day rolling accumulation = 0 mm) and persistence components were low on this day, illustrating that elevated RH alone does not produce a high ERS% in the absence of sustained leaf wetness, rainfall, or persistence-factor elevation.
This table presents a representative subset of days illustrating the range of conditions observed; the full 98-day dataset is provided in Supplementary File S1.

AI = 3.76 vs expert = 1.68). This pattern is consistent with a known tendency of image-based severity models to over-score scenes containing overlapping or visually dense lesion patterns relative to in-person assessment, and the expert score was used as the CARI reference standard throughout this study for that reason. However, this divergence has direct implications for deployment in smallholder contexts where expert verification may not be routinely available: if the AI score were used directly, the VSS component on 20 February would have been calculated from a severity of 3.76 rather than 1.68, which — although it would not have changed the Low Risk classification on that date given the low concurrent ERS% — illustrates that AI-only scoring could materially alter CARI outputs on other days where ERS% is closer to threshold. We recommend that operational deployments of CARI either (i) retain a periodic expert-verification step, particularly during periods of elevated ERS%, or (ii) implement an automated confidence flag that surfaces a day's CARI output for expert review whenever the AI-expert divergence (where both are available) or an AI-only severity score exceeds a pre-specified threshold (for example, an AI severity ≥ 3 with no expert verification). Establishing this threshold empirically, using a larger paired AI/expert dataset, is identified as a priority for the next phase of this work (Section 4.5).

3.5 ERS–VSS temporal relationship: a single-episode observation

On 10 February 2026, the system recorded its peak ERS (ERS% = 44.0%; contribution to CARI = 26.4), driven by 180.3 mm of rolling rainfall and the only observed elevation in the persistence factor (PF = 0.7). On 11 February — the following day — the first confirmed non-zero VSS event was recorded (expert mean 2.71). The interval between these two observations is approximately one day, which falls at the lower end of the 3–7-day infection-to-symptom interval range reported for *Colletotrichum* pathosystems under tropical conditions (Salotti et al., 2022; Dodd et al., 1991).

This single-episode observation should be interpreted with substantial caution for three reasons. First, it is based on n = 1 episode, and no statistical lag estimate (with confidence intervals or

TABLE 8 CassAPI visual severity scoring events — Fumesua, stage 3 monitoring period (11–24 February 2026).

Date	n plants	AI sev.	Expert sev.	VSS comp.	Inc. comp.	CARI (day)	Symptom summary
11 Feb 2026	7	3.43	2.71	30.6	10	39.9 (Low)	Foliar + petiole; no defoliation
20 Feb 2026	19	3.76	1.68	31.5	10	37.7 (Low)	Foliar + petiole; no defoliation
23 Feb 2026	18	3.17	0.33	29.0	10	33.7 (Low)	Residual foliar; petioles reducing
24 Feb 2026	17	2.94	0.47	27.6	10	30.4 (Low)	Resolving residual foliar lesions

bootstrapped uncertainty) can be derived from a single observation; we therefore report it as a descriptive interval rather than an estimated parameter. Second, and most importantly, the 25-day sensor outage immediately preceding this episode (16 January – 9 February 2026; Section 3.1) means that environmental conditions during the most likely window for infection establishment are unknown. The symptoms confirmed on 11 February could plausibly reflect infection events that occurred at any point during the outage period rather than specifically in response to the 10 February rainfall event; the apparent one-day interval may therefore be coincidental, and the true ERS-to-symptom interval for this episode cannot be determined from the available data. Third, even setting aside the outage, a single confirmed VSS-positive episode cannot establish a generalizable lag value for the CARI framework. We retain the description of this observation because it is consistent with — and was the motivation for — the persistence-based architecture of CARI, but we do not present it as a validated or estimated lag parameter. A dataset spanning multiple confirmed disease episodes with continuous antecedent sensor coverage, planned for the multi-season study (Section 4.5), is required before any lag relationship can be formally estimated.

Following the harmattan dry period (17–19 February, ERS% 3.3–4.8%), expert-scored VSS declined from 2.71 to 0.33–0.47 within approximately five days. The composite CARI across this episode ranged from 30.4 to 39.9 — within the Low band, owing to the VSS contribution, but below the Stage 3 Amber threshold (CARI ≥ 41 requires ERS% ≥ 50% AND VSS ≥ 2 simultaneously). In this single instance, CARI did not classify the episode as Amber despite confirmed non-zero VSS, because concurrent ERS% (2.8–9.3%) remained well below the 50% co-condition (Figure 2).

3.6 Persistence factor behaviour and alert outcomes

The persistence factor remained at the 0.3 baseline on 72 of 73 valid days (98.6%). On 37 of these days (50.7%), nocturnal RH exceeded 85% for 4–10 consecutive hours; under a simple single-threshold model using RH alone, these 37 days would be flagged as elevated-risk. With the persistence factor applied, none of these 37 days produced an ERS% elevation associated with PF > 0.3. On the single day where PF rose above baseline (10 February; PF = 0.7), ERS% (44.0%) remained below the 50% Amber threshold. No Amber or Red alerts were issued on any day during the 73-day monitoring period (Figure 3).

We report this as a descriptive observation — zero Amber/Red alerts issued across 73 days, including 37 days with elevated nocturnal RH — rather than as an estimate of specificity or false-positive rate. A specificity estimate requires a denominator of days correctly classified as negative against a ground-truth disease status and is not meaningful without paired information on true disease presence/absence across a larger sample with a non-trivial number of positive cases; as Section 2.8 notes, this dataset contains zero confirmed Amber/Red events. The observation is nonetheless useful descriptively: it shows that, in this dataset, RH-based elevation alone — absent persistence and rainfall co-elevation — did not propagate into an Amber- or Red-level ERS% under the CARI architecture (Figure 3).

3.7 CARI daily classification — descriptive summary

Across 73 valid monitoring days, CARI classified 68 days (93.2%) as Low Risk (CARI ≤ 20). Five days (6.8%) fell in the elevated-Low range (CARI 21–40): one driven primarily by ERS (10 February, CARI 26.4; VSS = 0), and four driven primarily by VSS (11 -24 February, CARI 30.4 -39.9; ERS contribution 2.8 -9.3).. No day reached Amber (CARI ≥ 41) or Red (CARI ≥ 66), and the framework issued no fungicide or intervention recommendation during this period. In this dataset, ERS alone — even at 44% of the Amber threshold on its highest day — did not produce an Amber classification without co-elevation of VSS; and VSS alone — even on the four days with confirmed moderate disease — did not produce an Amber classification without concurrent ERS% elevation. We report this as a description of how the joint-requirement rule behaved under the specific, moderate-risk conditions encountered in this 73-day window; because no day in this dataset approached both thresholds simultaneously, this observation does not establish whether the rule would correctly distinguish genuine high-risk events from noise, which remains the central open question for the planned multi-season study (Section 4.5). A descriptive summary of the 73-day record is presented in Table 9.

TABLE 9 Descriptive summary of CARI daily classifications — stage 3 observation period (73 valid monitoring days, 26 December 2025–2 April 2026).

Metric	Result	ERS-related	VSS-related	Note
Valid monitoring days	73/98	—	—	26 Dec 2025–2 Apr 2026
Sensor outage days (excluded)	25/98	—	—	16 Jan – 9 Feb 2026
CARI ≤ 20 (Low Risk)	68 (93.2%)	—	—	Descriptive frequency, this dataset only
CARI 21–40 (elevated-Low)	5 (6.8%)	1 day (10 Feb)	4 days (11–24 Feb)	Below Amber on all 5 days
CARI 41–65 (Amber) observed	0	0	0	No Amber events in this dataset
CARI 66–100 (Red) observed	0	0	0	No Red events in this dataset
Confirmed VSS > 0 scoring events	4 events	—	11, 20, 23, 24 Feb	Single episode; see Section 3.5
Mean Confidence Score (valid days)	65.9% ± 6.5%	—	—	See Section 2.7 for interpretation

Sensitivity, specificity, and AUC were not computed (Section 2.8). Formal ROC analysis is planned for the multi-season study once a dataset containing confirmed Amber and Red events has been accumulated.
These are observed frequencies within this single 73-day, single-site dataset, not estimates of diagnostic performance (see Section 2.8).

3.8 Calendar-schedule comparison within the observation window

Across the 73 valid monitoring days, the CARI composite did not reach the Amber threshold (CARI ≥ 41) on any day; therefore, the framework did not generate a fungicide intervention recommendation during this window. For comparison, a calendar-based schedule of one spray every 10 days would generate approximately 7 spray events over 73 days; at 14-day intervals, approximately 5 events. We report this as an observation specific to this 73-day window — zero CARI-triggered interventions versus 5–7 calendar-based interventions — rather than as a measured or projected percentage reduction. This window included the only confirmed disease episode observed in the study (11–24 February); CARI did not issue a recommendation during this episode because concurrent ERS% remained below the co-condition threshold (Section 3.5).

Published decision support systems for *Colletotrichum* anthracnose in other crops report fungicide reductions of 30–70% relative to calendar schedules without compromising disease control (Lázaro et al., 2021; Cordova et al., 2017; Peres et al., 2004). The zero-versus-five-to-seven observation reported here for this single window is directionally consistent with a reduction of this general type, but it was obtained under a single 73-day record from one site, one season, and one variety, with zero confirmed Amber/Red events, and no comparative field trial of CARI-guided versus calendar-based fungicide application was conducted. It should therefore not be read as a measured percentage reduction for CARI, nor extrapolated to the full 13-month crop cycle, which includes Stage 1 and Stage 2 periods not covered by this sensor deployment and may include genuine high-risk periods. A field trial directly comparing CARI-guided and calendar-based fungicide application across a full crop cycle is identified as a priority for the next phase of this work (Section 4.5; Figure 5).

4 Discussion

4.1 Climate-smart relevance and real-time risk responsiveness

The CARI framework is designed to align cassava anthracnose risk assessment with real-time weather variability through structured environmental monitoring and stage-sensitive modelling. By incorporating persistence requirements, the model is intended to distinguish between transient weather events and sustained infection-conducive conditions — a distinction that is potentially important in humid tropical environments where relative humidity is frequently elevated, but infection is understood to require prolonged leaf wetness. In this pilot, the single observed interval between the peak ERS signal and confirmed symptom onset (Section 3.5) is consistent with — though does not establish — the kind of predictive window the framework is intended to provide, an idea that aligns with the broader shift toward anticipatory, climate-smart agricultural management (Xu, 2018).

The 73-day field record from Fumesua illustrates the persistence filter's behaviour across the range of environmental conditions encountered during this pilot (Figure 1). Recurrent nocturnal humidity episodes (RH 85–99%, 22:00–07:00) occurred on 37 of 73 valid days; on these days, the persistence factor remained at its 0.3 baseline, and no Amber-level ERS% resulted (Figure 3). Even on 10 February 2026 — when 14 consecutive favourable hours produced the highest ERS% observed in this record (44%; Figure 2) — the persistence-adjusted composite remained below the Amber threshold. Within this single dataset, this is consistent with the intended design goal of avoiding alerts triggered by transient humidity alone; whether this behaviour holds when genuine high-risk events occur is the central open question addressed in Section 4.5.

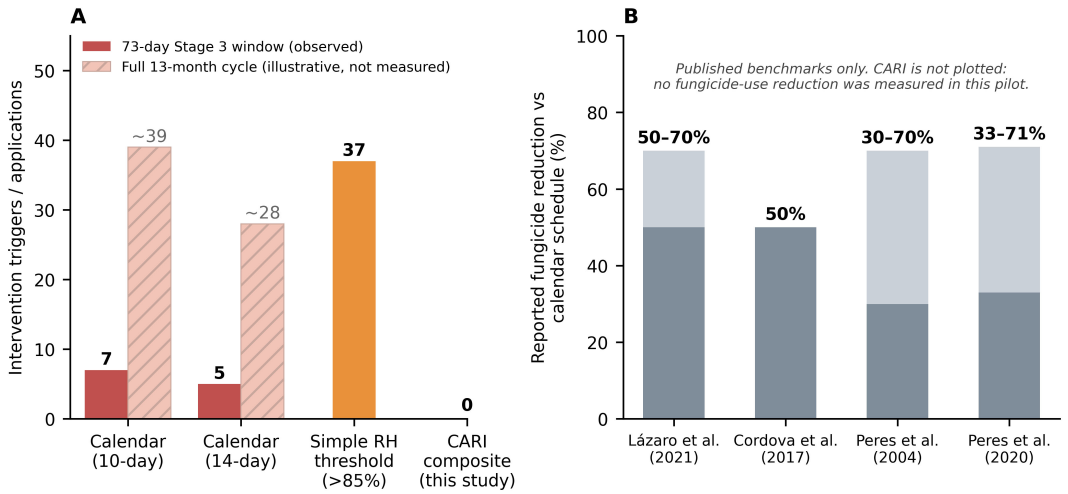

FIGURE 5
Calendar-schedule comparison within the observation window and published benchmark context. Panel **(A)** count of intervention events under calendar-based scheduling (10-day and 14-day intervals) versus CARI (0 triggers) within the 73-day Stage 3 observation window; hatched bars show an illustrative, non-measured projection across the full 13-month crop cycle, included for context only. Panel **(B)** fungicide reduction ranges reported by published *Colletotrichum* decision support systems (Lázaro et al., 2021; Cordova et al., 2017; Peres et al., 2004), shown as published benchmarks. The CARI pilot observation (zero interventions in this window) is plotted for visual reference only and is not a measured reduction percentage for CARI — see Section 3.8 for the descriptive interpretation of this comparison.

4.2 Agroecological framing and input-reduction rationale

The framework is intended to advance agroecological principles by promoting proportionate, knowledge-based intervention rather than fixed-interval spraying. The decision to use the locally prevalent landrace variety *Debo*, planted under rainfed, minimal-input conditions at Fumesua, was intended to ensure that field results are ecologically grounded in conditions representative of smallholder practice. Across the monitoring period, *Debo* sustained acceptable stand integrity and moderate crop vigour despite intermittent disease pressure, consistent with partial field tolerance documented for local germplasm under low-input conditions in West African cassava systems (Section 4.5 notes that this remains a single-variety observation).

The input-reduction rationale underlying CARI rests on two mechanisms. First, the persistence filter is designed to withhold alerts triggered by transient humidity spikes that are insufficient for infection cycle completion; in this dataset, 37 such days were observed, and none produced an Amber-level output (Figure 3B), though as discussed in Section 3.6, this is reported descriptively rather than as a false-positive rate. Second, the stage-specific threshold structure is intended to prevent overreaction during establishment, when host susceptibility is understood to be at its lowest. A global meta-analysis of 80 field experiments found that decision support systems of this general type can reduce fungicide use by at least 50% without compromising disease control (Lázaro et al., 2021), and comparable reductions have been reported for *Colletotrichum* systems using humidity and wetness models conceptually related to the CARI ERS component (Cordova et al., 2017; Peres et al., 2004). These figures are cited here as context for the design rationale and as benchmarks against which a future CARI field trial could be assessed; as discussed in Section 3.8, this pilot does not itself provide a measured estimate of the reduction in CARI. Protection of planting material quality is an additional potential benefit of timely intervention: identifying high-risk windows before severe stem damage occurs could support the production of healthier planting material for subsequent cropping cycles, although this was not directly measured in this study.

4.3 Stage-weighted design: rationale and open questions

The incorporation of growth-stage sensitivity is a central design feature of CARI. Cassava is reported not to respond uniformly to *Colletotrichum* infection pressure across its 12-month life cycle: early establishment stages are reported to exhibit limited visible symptom expression even under conducive conditions, whereas canopy expansion and maturity stages are reported to show more pronounced susceptibility (Salotti et al., 2022; Usman et al., 2026). The stage-varying persistence requirements and alert thresholds (Sections 2.4.2–2.4.3) were designed to reflect this reported pattern. The single observed interval between an ERS peak and VSS onset in this pilot (Section 3.5) is consistent with the general premise that environmental risk precedes symptom expression, but — for the reasons given in Section 3.5 — this single, outage-adjacent observation cannot be taken as confirmation of the stage-dependent lag pattern the design anticipates (expected to be longest at Stage 1 and shortest at Stage 3). Testing this expectation requires observations across all three stages with continuous sensor coverage, which this pilot — commencing at the Stage 2/3 boundary — does not provide.

A uniform, non-stage-weighted threshold model would, by construction, apply the same sensitivity during crop establishment as during canopy expansion. The stage-sensitive structure is intended as a biologically motivated alternative, but — as set out in Sections 2.4.3 and 2.5.1 — the specific threshold values were derived through expert elicitation rather than statistical optimization, and their performance characteristics (including whether they reduce alarm fatigue without missing genuine epidemiological windows) remain to be empirically tested.

4.4 Practical architecture and comparison with existing systems

The field implementation at Fumesua shows that, in this single deployment, the CARI data pipeline — sensor deployment, hourly aggregation, persistence-factor computation, CassAPI-based visual scoring, and composite index calculation — could be operated end-to-end with commercially available, field-deployable sensor infrastructure. This is a narrow claim about technical operability at one site over a single observation window, not a claim about reliability, scalability, or performance in other settings, which have not been tested. The hybrid design, combining automated environmental sensing with structured visual assessment via CassAPI, is intended to address practical constraints of smallholder systems in sub-Saharan Africa, though its usability and acceptance among extension workers and farmers have not yet been and the lentil anthracnose decision support system (Buchwaldt et al., 2018) – rely on single-variable thresholds formally evaluated. CARI delivers daily outputs through a web-based dashboard displaying the CARI score, ERS%, VSS, risk band, a traffic-light colour indicator, and a management recommendation, with alert notifications configurable via email or SMS for Amber threshold crossings.

Table 10 situates CARI's design relative to existing humidity-driven decision support systems for *Colletotrichum* and related anthracnose pathosystems. Prior systems — including the Strawberry Advisory System (StAS; Cordova et al., 2017), the citrus Postbloom Fruit Drop Advisory System (PFD-FAD/CAS; Peres et al., 2004, 2020), the Philippine mango anthracnose model (Dodd et al., 1991) without growth-stage weighting or visual integration, and several of these have been operated and reported on across multiple seasons. CARI's design combines growth-stage-sensitive environmental weighting, persistence-adjusted scoring, and structured visual severity integration within a single framework; to our knowledge, no prior cassava anthracnose decision-support system that combines these elements has been described in the published literature. We emphasise that Table 10 compares design features, not validated performance: the other systems listed have, in most cases, been evaluated over multiple seasons with confirmed disease events, which CARI has not yet undergone.

TABLE 10 Comparison of CARI's design features with existing humidity-driven disease warning systems for *Colletotrichum* and related anthracnose pathosystems.

System	Crop/disease	Pathogen	Environmental variables	Stage-weighted?	Persistence filter?	Visual integration?
CARI (this study)	Cassava anthracnose	*C. gloeosporioides*	RH, rainfall, temp, wind, soil moisture, canopy ΔT	Yes — 3 stages	Yes — 24–48 h	Yes — VSS 0–40
StAS (Cordova et al., 2017)	Strawberry anthracnose	*C. acutatum*	Temp, leaf wetness duration	No	No	No
PFD-FAD/CAS (Peres et al., 2004, 2020)	Citrus postbloom fruit drop	*C. acutatum*	Conidial germination probability (temp × wetness)	No	No	No
Mango model (Dodd et al., 1991)	Mango anthracnose	*C. gloeosporioides*	Temp, relative humidity	No	No	No
Lentil anthracnose DSS (Buchwaldt et al., 2018)	Lentil anthracnose	*C. lentis*	Weather-based risk index	No	No	No
Dollar spot warning system (Smith et al., 2018)	Turfgrass dollar spot	*S. homoeocarpa*	5-day moving avg RH + temp	No	No	No

CARI is, to our knowledge, the only system in this comparison combining growth-stage weighting, persistence adjustment, and structured visual severity integration. The other systems listed have undergone multi-season evaluation with confirmed disease events; CARI has not yet undergone equivalent evaluation (Section 4.5).
This compares design features only; see text for differences in evaluation status.

4.5 Limitations of this pilot study and priorities for validation

This study reports an initial field pilot of the CARI framework and its constituent components, and the following limitations should be considered when interpreting the results presented in Sections 3.1–3.8.

4.5.1 Dataset scope and single-site, single-cultivar design

The dataset comprises 73 valid monitoring days from a single experimental plot at a single site (CSIR-CRI Fumesua), using a single cassava variety (*Debo*), and covers only the Stage 3 (maturity) growth phase plus the Stage 2/3 boundary; Stage 1 was not monitored. Microclimate patterns, canopy architecture, soil moisture dynamics, and variety-specific susceptibility are expected to vary across cassava-growing agroecologies in Ghana and West Africa, as well as among cassava varieties with different levels of anthracnose susceptibility. None of the findings reported here — including the persistence factor behaviour, the ERS–VSS interval, and the absence of Amber/Red events — can be assumed to generalise to other sites, seasons, growth stages, or varieties without independent testing. Multi-location replication, including sites in the Guinea Savanna and Transition zones of Ghana, and evaluation across additional varieties with a range of known susceptibilities, are priorities for the next phase of this work.

4.5.2 Absence of confirmed high-risk (Amber/Red) events

No day in this 73-day record reached the Amber or Red CARI threshold, and only four days had non-zero VSS, all within a single self-limiting episode (Section 3.5). This has two consequences. First, as discussed in Section 2.8, it precludes any sensitivity, specificity, or ROC/AUC analysis: these metrics require a dataset with a meaningful number of both positive and negative outcomes, which this dataset lacks. Second, it means the framework's behaviour under genuine epidemic-risk conditions — arguably the scenario for which CARI is primarily intended — has not yet been observed. The descriptive findings reported here (zero Amber/Red outputs; persistence filter remaining at baseline on 72/73 days) describe how CARI behaved under the moderate-risk conditions encountered during this commissioning-phase deployment, and should not be interpreted as evidence of how the framework would behave during a genuine outbreak.

4.5.3 Sensor outage and its effect on the ERS–VSS observation

The 25-day sensor outage (16 January – 9 February 2026) immediately preceding the only confirmed disease episode (Sections 3.1 and 3.5) means that environmental conditions during the period most likely associated with infection establishment are unknown. As discussed in Section 3.5, this prevents reliable attribution of the 11 February symptom onset to the 10 February rainfall event specifically, rather than to conditions during the outage period. We have reported the approximately one-day interval as a descriptive observation only, explicitly flagged as potentially coincidental, and have not used it to derive or report a lag estimate, confidence interval, or validated parameter. Continuous sensor coverage — including redundant sensor pairs or alternative connectivity to reduce the risk of extended outages — is a priority for the multi-season study, both to avoid this specific issue and to enable the antecedent-condition analyses that a lag estimate would require.

4.5.4 Pathogen identification by morphology only

Pathogen identification in this study (Section 2.3) is based on morphological characteristics consistent with the *Colletotrichum gloeosporioides* species complex. Given the well-documented cryptic diversity within this complex, morphological characterization alone does not confirm species-level identity, and the isolates obtained should be regarded as provisionally identified. Molecular characterization using ITS sequencing together with additional loci (ACT, TUB2, GAPDH) is required to confirm species identity and to assess whether multiple species or genotypes with potentially different virulence or

environmental sensitivity profiles were present at the site; this is a priority for the next phase of this work and, depending on timeline, may be reported as a methodological addendum prior to any subsequent multi-season publication.

4.5.5 Same-dataset development and evaluation

The ERS component weights (Table 1), persistence factor parameters (Section 2.4.2), and the stage-specific alert thresholds (Tables 2, 3, 5) were derived through expert elicitation informed by the published literature and by provisional field observations made at this same site during pre-deployment testing, prior to the 73-day monitoring period reported here. The descriptive evaluation in Section 3 was then conducted on data from the same site and crop cycle. While the formal parameterization (Tables 1–6) was fixed prior to the 73-day reporting period and was not algorithmically fitted to the data presented in Section 3, we acknowledge that the overall system — including the pre-deployment testing that informed parameter selection — has been developed and described using data from a single location and crop cycle. Independent validation using data from additional seasons, sites, and cultivars, collected and evaluated separately from any further parameter adjustment, is necessary before conclusions about CARI's general performance can be drawn. This is the central objective of the planned multi-season study.

4.5.6 AI-assisted visual scoring: reliability for smallholder deployment

As discussed in Section 3.4, AI-computed severity scores diverged substantially and consistently from expert-verified scores across all four scoring events in this pilot, with the AI consistently over-scoring relative to the expert. Because the expert score was used as the CARI reference standard, the headline results in Section 3 do not reflect this divergence; however, the divergence raises a direct question about CassAPI's utility in deployment contexts where expert verification is not routinely available, which is the target context for smallholder adoption. We have proposed a confidence-flag approach (Section 3.4) but have not implemented or tested it. Developing and testing such a calibration protocol against a larger paired AI/expert dataset is a priority for the next phase of this work.

4.5.7 No comparative field trial of fungicide use

As discussed in Section 3.8, this study did not include a comparative field trial of CARI-guided versus calendar-based fungicide application. The zero-versus-five-to-seven observation reported for this 73-day window is a description of CARI's outputs in this dataset, not a measured fungicide-use outcome. A field trial directly comparing fungicide application schedules under CARI guidance versus a calendar-based control, conducted across at least one full crop cycle and ideally across multiple sites, is required to test the input-reduction rationale set out in Section 4.2.

4.5.8 Summary of priorities for the multi-season study

Taken together, the priorities arising from this pilot are: (i) full-cycle sensor deployment from Stage 1 onward with continuous coverage to avoid outage-related gaps; (ii) multi-location replication across additional agroecological zones and cassava varieties; (iii) molecular pathogen identification (ITS, ACT, TUB2, GAPDH); (iv) statistical refinement of ERS component weights, persistence factor parameters, and alert thresholds against confirmed disease events, conducted on data independent of the data used for any further parameter adjustment; (v) accumulation of a dataset containing a statistically meaningful number of confirmed Amber and Red events, enabling formal ROC, sensitivity, and specificity analysis; (vi) development and testing of an AI/expert divergence calibration protocol for CassAPI; and (vii) a comparative field trial of CARI-guided versus calendar-based fungicide application. These priorities are restated in Section 6.

5 Conclusion

This study presents the Cassava Anthracnose Risk Index (CARI), a stage-weighted, persistence-adjusted composite framework that integrates low-cost environmental sensing with structured visual disease-severity scoring, intended to support early-warning disease management in humid tropical cassava systems. A 73-day field pilot at CSIR-CRI Fumesua demonstrated that the complete CARI data pipeline — environmental sensing, persistence-factor computation, CassAPI-based visual scoring, and composite index calculation — can be operated end-to-end under real tropical field conditions. Within this single-site, single-season, single-variety dataset, which contained no confirmed Amber or Red events, CARI classified all monitoring days as Low Risk, and the persistence filter remained at its baseline value on 72 of 73 days, including 37 days with elevated nocturnal humidity. A single observed interval of approximately one day between the highest recorded ERS% and the only confirmed non-zero VSS episode is consistent with the general premise underlying the persistence-based architecture, but — owing to a 25-day sensor outage immediately preceding this episode and the single-episode nature of the observation — this interval is reported descriptively and is not presented as a validated or estimated lag parameter.

These results constitute proof-of-concept for the technical operability of the CARI data pipeline and for the descriptive behaviour of its persistence-filtering logic within this pilot dataset; they do not constitute validation of CARI's predictive performance, which requires a dataset containing confirmed Amber/Red events and is the explicit objective of the planned multi-season study (Section 4.5, Section 6). It should be emphasized that the ERS component weights, persistence factor parameters, and stage-specific alert thresholds reported here (Sections 2.4–2.6) were derived through expert elicitation rather than statistical optimization, and remain provisional: they require systematic optimization and validation against multi-season, multi-site datasets containing confirmed disease events before they can be considered fit for operational deployment. The conceptual architecture — stage-weighted environmental components, persistence-adjusted risk scoring, and visual symptom integration — may, in principle, be adaptable to other humidity-driven fungal pathosystems in tropical cropping systems, where host developmental stage is an important

epidemiological factor, but this, too, remains to be tested. With multi-location, multi-season validation incorporating the priorities set out in Section 4.5, CARI is intended to offer a pathway toward anticipatory, weather-informed crop protection supporting food security and input efficiency across humid tropical Africa and comparable agroecological zones; the present study establishes the technical foundation and identifies the evidence required to test this aim.

6 Supplementary note: pilot scope and planned extensions

This paper reports findings from an initial pilot deployment of the CARI framework during the Stage 3 (maturity) phase of a single 13-month cassava cropping cycle at CSIR-CRI Fumesua, Ashanti Region, Ghana (March 2025 – April 2026). Sensor deployment commenced at the Stage 2/3 growth boundary; Stage 1 and early Stage 2 environmental monitoring was therefore not undertaken as part of this pilot. As detailed in Section 4.5, this study should be regarded as a technical proof-of-concept and parameter-elicitation exercise rather than a validated forecasting model. The following extensions are identified as priorities for the planned multi-season study:

(1) Full-cycle sensor deployment commencing from crop establishment (Stage 1) with continuous, redundant sensor coverage to avoid outage-related gaps, enabling characterization of the complete ERS trajectory across all three growth stages. (2) Molecular identification of *Colletotrichum* isolates using ITS, ACT, TUB2, and GAPDH loci to confirm species-level taxonomy and assess potential differences in virulence or environmental sensitivity between genotypes present at the site. (3) Multi-location replication including Guinea Savanna and Transition zone sites in Ghana, and evaluation across additional cassava varieties with differing susceptibility, to assess transferability of the framework. (4) Formal inter-rater reliability assessment for VSS scoring across multiple independent field assessors, and development of a calibration protocol or confidence flag for AI/expert severity divergence in CassAPI. (5) Statistical refinement of ERS component weights, persistence factor parameters (including the 0.3 floor and linear scaling form), and stage-specific alert thresholds against confirmed disease events, using data independent of any further parameter adjustment. (6) Accumulation of a dataset containing a statistically meaningful number of confirmed Amber and Red classification events, sufficient to support formal ROC analysis, sensitivity, and specificity estimation. (7) A comparative field trial of CARI-guided versus calendar-based fungicide application across at least one full crop cycle, to directly test the input-reduction rationale.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

KA: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. GA: Conceptualization, Funding acquisition, Methodology, Project administration, Validation, Writing – review & editing. SA: Data curation, Investigation, Writing – original draft. MA-G: Data curation, Investigation, Methodology, Writing – review & editing. ZA-K: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. CB: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – review & editing. JB: Investigation, Software, Supervision, Validation, Visualization, Writing – review & editing. KOS: Data curation, Investigation, Validation, Writing – review & editing. RNK: Data curation, Formal analysis, Software, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was funded by the Foreign, Commonwealth and Development Office (FCDO) and delivered by Innovate UK under the Climate-Smart Agriculture Partnership: UK-Brazil-Africa programme [Project/Grant No. 296]. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgments

The authors acknowledge the field and technical staff at CSIR-CRI Fumesua for their support with plot establishment and sentinel plant maintenance. The authors thank the CassAPI development team at IA Sense and ScareCrow Intelligence for platform integration and technical support throughout the monitoring period. The authors gratefully acknowledge field support from Jack-Strong Company Ltd (Ghana) for sensor installation. The authors used Claude (Anthropic, claude-sonnet-4-6, claude.ai) to assist with data analysis scripting, figure generation, manuscript drafting, and document formatting during the preparation of this manuscript. The authors are responsible for verifying all factual content, data, and citations presented.

Conflict of interest

CB and JB are employees of ScareCrow Intelligence, which developed the sensor infrastructure and CARI algorithm described in this manuscript. KS was employed by Jack-Strong Company Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. The authors used Claude (Anthropic, claude-sonnet-4-6, claude.ai) to assist with data analysis scripting, figure generation, manuscript drafting, and document formatting during the preparation of this manuscript. The authors are responsible for verifying all factual content, data, and citations presented.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphgy.2026.1898224/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Diurnal relative humidity and temperature cycle patterns across the monitoring period. Cited in Section 3.2.

SUPPLEMENTARY TABLE 1
Confidence Score computation algorithm and component weighting table. Cited in Section 2.7.

SUPPLEMENTARY FILE S1
Full 98-day daily monitoring dataset (CARI, ERS, ERS%, VSS, persistence factor, environmental variables, and Confidence Score) for the Stage 3 observation period, 26 December 2025 - 2 April 2026, including outage days. Cited in Section 3.2 and the Table 7 footnote.

References

Ahmed, W. A., Abiola, O. A., Yang, D., Olatoyinbo, S. F., and Jing, G. (2026). Integrating UAVs and deep learning for plant disease detection: a review of techniques, datasets, and field challenges with examples from cassava. *Horticulturae* 12, 87. doi: 10.3390/horticulturae12010087

Andrade-Piedra, J. L., Sharma, K., Kroschel, J., Ogero, K., Kreuze, J., Legg, J. P., et al. (2026). Phytosanitary challenges and solutions for roots and tubers in the tropics. *Annu. Rev. Phytopathol.* 63, 627–650. doi: 10.1146/annurev-phyto-021722-030316

Appiah-Kubi, Z., Apetorgbor, A. K., Moses, E., Quian, M., Thompson, R., Appiah-Kubi, D., et al. (2015). Genetic variability in Colletotrichum gloeosporioides *(Penz.) isolated from cassava and yam from four agro-ecological zones of Ghana*. *Greener J. Agric. Sci.* 5, 132–140. doi: 10.15580/GJAS.2015.4.061715082

Buchwaldt, L., Dzananovic, E., and Durkin, J. (2018). Lentil anthracnose: epidemiology, fungicide decision support system, resistance and pathogen races. *Can. J. Plant Pathol.* 40, 189–198. 10.1080/07060661.2018.1441185

Cordova, L. G., Baggio, J. S., Mertely, J. C., MacKenzie, S. J., and Peres, N. A. (2017). Meta-analysis of a web-based disease forecast system for control of anthracnose and Botrytis fruit rots of strawberry in southeastern United States. *Plant Dis.* 101, 1203–1212. doi: 10.1094/PDIS-04-17-0477-RE

Dodd, J. C., Bugante, R., Koomen, I., Jeffries, P., and Jeger, M. J. (1991). The effect of climatic factors on Colletotrichum gloeosporioides*, causal agent of mango anthracnose, in the Philippines*. *Plant Pathol.* 40, 568–575. doi: 10.1111/j.1365-3059.1991.tb02421.x

Fokunang, C. N., Akem, C. N., Ikotun, T., Dixon, A. G. O., and Tembe, E. A. (1999). Effect of planting season on cassava anthracnose disease development. *Crop Prot.* 18, 407–413. doi: 10.1016/S0261-2194(99)00041-6

Forkum, A. T., Wung, A. E., Kelese, M. T., Ndum, C. M., Lontum, A., Kamga, E. B., et al. (2025). Safety of cassava and cassava-based products: a systematic review. *Front. Sustain. Food. Syst.* 9. doi: 10.3389/fsufs.2025.1497609

Frimpong, F., Danquah, E. O., Amponsah, S. K., Frimpong, T., Adu, J., Danquah, F. O., et al. (2025). Diversifying cropping systems to enhance productivity using agroforestry trees: a case study of maize–pigeon pea intercropping in Ghana. *Explora Environ. Resour.* 2, 025130026. doi: 10.36922/EER025130026

Lázaro, E., Makowski, D., and Vicent, A. (2021). Decision support systems halve fungicide use compared to calendar-based strategies without increasing disease risk. *Commun. Earth Environ.* 2, 224. doi: 10.1038/s43247-021-00291-8

Moreira, R. R., Kowata-Dresch, L. S., Verbiski, F. S., Petermann, D., and May De Mio, L. L. (2023). Effects of temperature and wetness period on the monocyclic components of persimmon anthracnose. *Bragantia* 82, e20230082. doi: 10.1590/1678-4499.20230082

Nakabonge, G., Samukoya, C., and Baguma, Y. (2018). Local varieties of cassava: conservation, cultivation and use in Uganda. *Environ. Dev. Sustain.* 20, 2427–2445. doi: 10.1007/s10668-017-9997-6

Odedeyi, T., Kolawole, O., Ugoji, C., Ayankanmi, T., Okhuoya, O., Rabbi, I., et al. (2025). "Multi-source data integration and IoT-based sensing for crop yield modelling and optimisation", in: *Proc. IEEE International Conference on Smart Computing (SMARTCOMP)*, Cork, Ireland (Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE)). doi: 10.1109/SMARTCOMP65954.2025.00094

Peres, N. A., Cordova, L. G., Rebello, C. S., and Gama, A. B. (2020). A threshold-based decision-support system for fungicide applications provides cost-effective control of citrus postbloom fruit drop. *Plant Dis.* 104, 1610–1617. doi: 10.1094/PDIS-01-19-0068-RE

Peres, N. A., Timmer, L. W., and Adaskaveg, J. E. (2004). Evaluation of systems for timing of fungicide sprays for control of postbloom fruit drop of citrus in Brazil. *Plant Dis.* 88, 731–735. doi: 10.1094/PDIS.2004.88.7.731

Salotti, I., Ji, T., and Rossi, V. (2022). Temperature requirements of Colletotrichum *spp. belonging to different clades*. *Front. Plant Sci.* 13. doi: 10.3389/fpls.2022.953760

Smith, D. L., Kerns, J. P., Walker, N. R., Payne, A. F., Horvath, B., Inguagiato, J. C., et al (2018). Development and validation of a weather-based warning system to advise fungicide applications to control dollar spot on turfgrass. *PLoS One.* 13, e0194216. doi: 10.1371/journal.pone.0194216

Usman, H. M., Hussain, M. D., Karim, M. M., Nizamani, M. M., Mubeen, M., Hussain, S., et al. (2026). Colletotrichum*: a versatile fungal genus with diverse infection strategies, host interactions, and management challenges*. *Phytopathol. Res.* 8, 1. doi: 10.1186/s42483-025-00391-9

William, M. N. M., Mbega, E. R., and Mabagala, R. B. (2012). An outbreak of anthracnose caused by Colletotrichum gloeosporioides f.sp. manihotis in *cassava in North Western Tanzania*. *Am. J. Plant Sci.* 3, 596–598. doi: 10.4236/ajps.2012.35072

Xu, M. L. (2018). Agroecological study: environmental effect of scientific technology and education input on agricultural economic growth. *Ekoloji* 27, 969–974.