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PFBCIA – sweet potato: low-cost AI-powered phenotyping platform from prompt engineering to climate justice: thermal stress

PFBCIA – batata-doce: plataforma de fenotipagem de baixo custo suportada por IA - da engenharia de prompt à justiça climática: estresse térmico

PFBCIA – boniato: plataforma de fenotipado de bajo costo basada en IA, de la ingeniería de prompts a la justicia climática: estrés térmico

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Mariana Rodrigues Fontenelle[1]
Larissa Pereira de Castro Vendrame[2]
Samuel Cordeiro Vitor Martins[3]
Ítalo Moraes Rocha Guedes[4]
Ilvan Medeiros Lustosa Júnior[5]
Carlos Eduardo Pacheco Lima[6]

ABSTRACT: The development of Low-Cost Phenotyping Platforms Supported by Generative Artificial Intelligence (AI) is part of a recently launched research initiative at Embrapa Vegetables in Brasília, Federal District, aimed at creating a National Platform for Adaptation to Climate Change Applied to Family Farming (Clima AF). Through Prompt Engineering and Command Chaining, this stage was designed for the visual assessment of physiological disorders in sweet potato (Ipomoea batatas) tuberous roots in the context of the Climate Emergency. The pipeline consists of four stages: 1 - Definition of an expert persona; 2 - Phenological contextualization and critical root filling period; 3 - Visual anatomical phenotyping; and 4 - Synthesis of the physiological disorders found, with a focus on heat stress. The methodology is available as open access following FAIR principles. The analysis is conducted using minimal information, such as photos that can be taken with everyday devices like smartphones and information about the harvest season. Because it is available as open access, it democratizes information and contributes to achieving climate justice for a socioeconomically vulnerable audience (family farmers).

Keywords: digital phenotyping; FAIR principles; global climate change; family farming; physiologic disorders; large language models.

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[1] Ph.D. in Agricultural Microbiology, Embrapa Vegetables, Samambaia Sul, Distrito Federal, Brazil.
E-mail: mariana.fontenelle@embrapa.br
[2] Ph.D. in Genetics and Breeding, Embrapa Vegetables, Samambaia Sul, Distrito Federal, Brazil.
E-mail: larissa.vendrame@embrapa.br
[3] Ph.D. in Plant Physiology, CNPq Research Productivity Fellow Embrapa Vegetables, Samambaia Sul, Distrito Federal, Brazil. E-mail: samuel.martins@embrapa.br
[4] Ph.D. in Soils and Plant Nutrition, Embrapa Vegetables, Samambaia Sul, Distrito Federal, Brazil.
E-mail: italo.guedes@embrapa.br
[5] Ph.D. in Forest Science, Instituto Federal de Brasília (IFB), Research collaborator at the Centro de Desenvolvimento Sustentável (CDS) da Universidade de Brasília (UnB), Samambaia Sul, Distrito Federal, Brazil.
E-mail: ilvan.junior@ifb.br
[6] Ph.D. in Soils and Plant Nutrition, CNPq Technological Development and Innovative Extension Productivity Fellow Embrapa Vegetables, Universidade Federal de Itajubá Samambaia Sul, Distrito Federal, Brasil.
E-mail: carlos.pacheco-lima@embrapa.br

1 INTRODUCTION

Global climate change (GCC) is undoubtedly one of the issues most critical to humanity, both now and in the future (IPCC, 2021; IPCC, 2023). The last three-year period exceeded the average of 1.50°C (Copernicus, 2026) and, consequently, the first threshold established by the Paris Agreement (IPCC, 2018), raises concern within the scientific community about the true intensity and magnitude of this phenomenon, as current projections may be underestimated.

Family farming in Brazil is defined by Law 11,326 of 2006 and Decree 9,064 of 2017. Family farmers are defined as those who farm in rural areas of up to four fiscal modules, operate and are managed primarily by family labor, and derive at least 50% of their family income from family farms. Small agribusinesses, socio-biodiversity management, fishing activities, and agricultural and livestock operations, as well as indigenous and quilombola communities, for example, can also be characterized as activities related to Family Farming. Most of them are farmers who are highly vulnerable to climate change due to their low per capita income and difficulty in obtaining credit, which limits their ability to adopt resilient and adapted systems. (Lima *et al.*, 2025). Esta observação também é condizente com as informações disponíveis no sexto relatório (AR6) do Painel Intergovernamental sobre Mudanças Climáticas (IPCC) (IPCC, 2021; IPCC, 2023).

The main public policy for family farming adaptation currently in place in Brazil (Climate Adaptation Plan – Family Farming Sector) has as one of its key pillars the development of tools and platforms for applied climate intelligence (Brazil, 2025). This is also stated in the Climate Adaptation Plan – Agricultural Sector, especially on Targets 60 (Establish a Center for Territorial Intelligence within the Ministry of Agrarian Development and Family Farming, ensuring the monitoring of threats, risks, exposure, and vulnerabilities related to climate change in family farming, by 2027) and 64 (Develop and implement an interactive digital tool to provide personalized agrometeorological forecasts and alerts to family farmers by 2031). Therefore, this study aligns with these public policies. This alignment is further reinforced by the Brazilian Artificial Intelligence Plan, which emphasizes the responsible use of AI to address major national challenges, including agriculture, environmental sustainability, social inclusion, and technological sovereignty. In this context, PFBCIA – Sweet Potato represents an applied example of AI for the public welfare, using low-cost generative AI to support climate adaptation and decision-making in family farming systems. Use of Open Science based on the FAIR principles (Findable, Accessible, Interoperable, and Reusable) enables the democratization of the distribution and use of information, as well as the download of methodological tools for use, as available in Lima *et al*. (2026).

Sweet potato (*Ipomoea batatas*) plays a strategic role in food and nutritional security in GCC scenarios. It is highly hardy (Silva *et al*., 2021), has a high concentration of low-glycemic-index carbohydrates, and some cultivars may also have high levels of antioxidant compounds such as beta-carotene and anthocyanins (Silva *et al*., 2026). It is an agricultural crop primarily associated with family farming, providing subsistence and generating employment and income on small rural farms (Pedroso & Ferreira, 2023). However, despite its intrinsic resilience due to its hardiness, the productivity and quality of the tuberous roots are vulnerable to climate extremes, and there must also be a focus on technological development aimed at adapting this crop to climate change.

Despite recent advances in the use of precision agriculture tools, access to conventional phenotyping remains limited, even for scientific activities, due to the high cost of high-resolution sensors, the robust infrastructure required, and the need for specialized labor (Reynolds *et al*., 2019). This also creates a barrier to its use by Technical Assistance and Rural Extension (ATER) agencies, producers, and decision-makers. In this context, the PFBCIA suite being developed by Embrapa Vegetables offers an opportunity to democratize the use of these tools, aligning with the principles of open science (FAIR), the 2030 Agenda, and the IPCC's frameworks for Climate Justice and Just Transition (Fontenelle *et al*., 2025a).

In this methodological article, we propose and describe a first version (v.1.0.0) of the development of a low-cost, AI-supported phenotyping platform for sweet potato cultivation (PFBCIA - Sweet Potato), as technically described by Lima *et al*. (2026). This is a product developed as proof of concept for critical functions through analytical or experimental methods. In this first version, the concepts of Prompt Engineering and Prompt Chaining were utilized with support of Generative AI models for the visual assessment of physiological disorders in sweet potato roots that may occur in GCC scenarios.

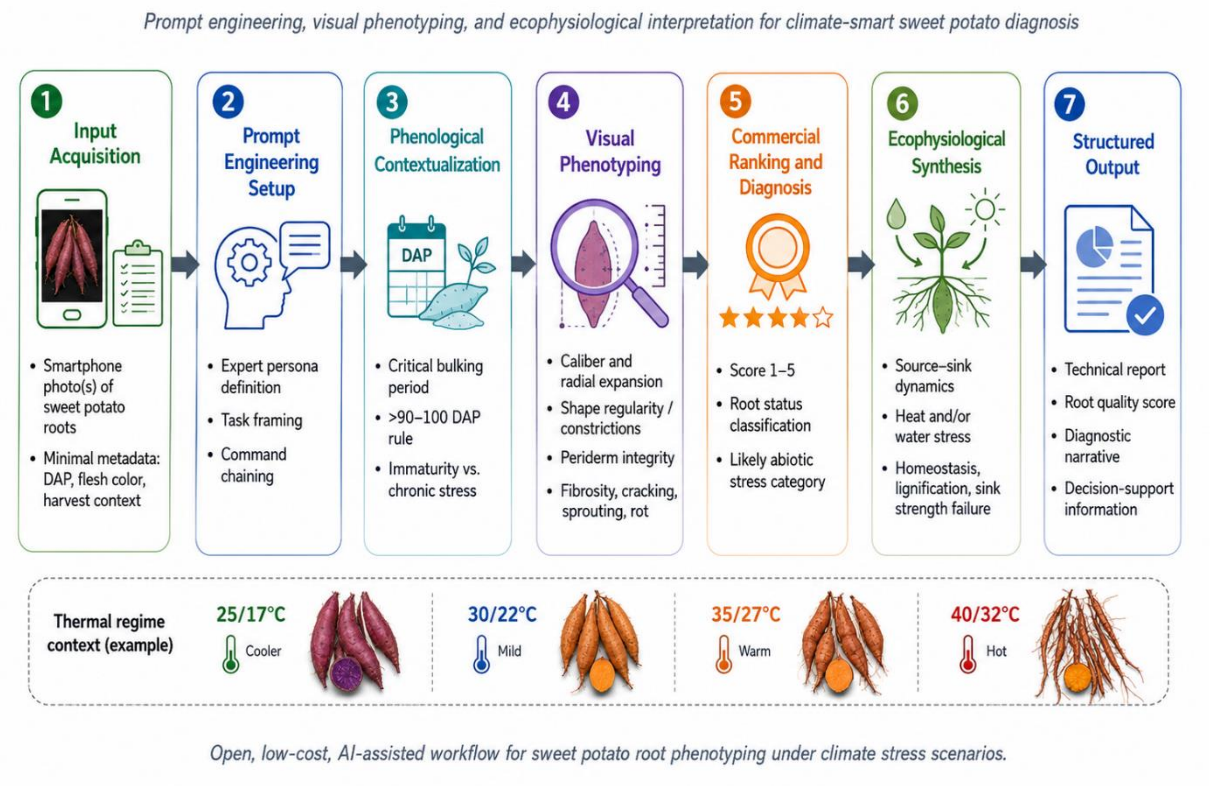
2 MATERIAL AND METHODS

2.1 Methodological Framework

The objective of this innovation was to establish an initial version of a Low-Cost Phenotyping Platform supported by Artificial Intelligence for sweet potato crops, using Prompt Engineering and Prompt Chaining techniques. It was designed as a qualitative proof of concept, constituting a scientific methodology that considers possible physiological disorders occurring in sweet potato tuberous roots under GCC conditions.

Thus, we included the following steps: 1 - conceptual synthesis of abiotic stresses (physiological disorders) resulting from HPS scenarios in sweet potato tuberous roots; 2 - specification of visual targets and eco-physiological descriptors of sweet potato tuberous roots; 3 - definition of the workflow defined by Prompt Engineering and Prompt Chaining **for** analytical guidance of Artificial Intelligence; 4 - Ranking and generation of structured reports. Figure 1 provides a simplified graphical overview of the workflow.

Figure 1 – Core Workflow of the PFBCIA – Sweet Potato Low-Cost Phenotyping methodology proposed.



Source: The authors with support of AI tools

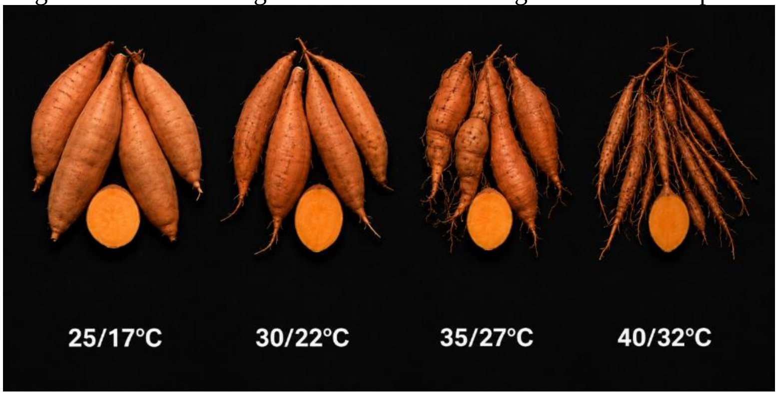
In addition, we evaluated the use of three generative AI models based on large language models (LLMs): ChatGPT (OpenAI), Gemini (Google), and Copilot (Microsoft). To do so, we used three AI-generated images (Figures 2, 3 and 4) as controlled synthetic visual material for proof-of-concept tests, simulating the development of sweet potato tuberous roots under different temperature conditions. These images were created based on the one obtained by K. Raja Reddy, available at Embrapa (2021), with supported of AI tools. Two additional images were also used, showing three tuberous roots simulating symptoms that occur under conditions of high temperatures and water stress, as shown in Figure 5.

The first comparison was quantitative, comparing the rankings assigned by human experts with those generated by the AI models, as well as comparing the AI models with each other using Spearman's rank correlation coefficient and the Mean Absolute Deviation (MAD). The human ranking was based on an analysis conducted by a climate change and agriculture expert, a plant breeder specializing in sweet potato cultivation, and a plant physiologist. For quantitative validation, following the criteria adopted by Fontenelle *et al*. (2025a), we assumed the following thresholds: Spearman's correlation coefficient ≥ 0.85 and MAD ≤ 1.50. The second comparison was qualitative and assessed the capability of the AI models to follow all commands included in the structured prompt through narrative assessment of the generated responses. We also used images with different root flesh colors to verify whether this visual attribute influenced the final analytical result. These synthetic images were not used as experimental evidence of physiological responses, but as controlled visual material to assess the consistency and operational adherence of the AI models to the proposed prompt-engineering protocol.

Figure 2 - First image used in the test - yellow-fleshed sweet potato

Source: The authors with support of AI tools

Figure 3 – Second image used in the test - orange-fleshed sweet potato



Source: The authors with support of AI tools

Figure 4 – Third image used in the test - purple-fleshed sweet potato

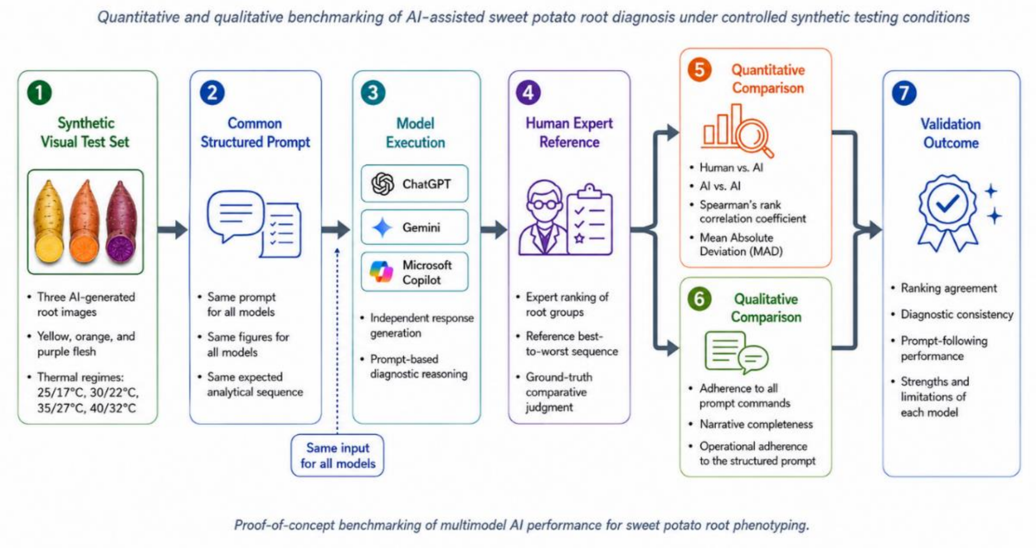
Source: The authors with support of AI tools

Figure 5 – Fourth image used in the test - purple-fleshed sweet potato (Thermal stress)

Source: The authors with support of AI tools

The methodology developed constitutes a modular structure that allows for easy adaptation to other vegetable crops and is part of a larger project aimed at, together with other components, establishing a National Digital Platform for Climate Intelligence for Vegetable Crops. Figure 6, in turn, provides a graphical summary of the proof-of-concept workflow in an educational manner.

Figure 6 - Graphical summary of the proof-of-concept workflow in an educational manner



Source: The authors with support of AI tools

2.2 Prompt Engineering and Prompt Chaining

The prompt engineering and prompt chaining (methodology) techniques proposed and used are described below:

PROMPT 1: PERSONA - Sweet Potato Root Expert: Take on the persona of an Agricultural Engineer and Ecophysiologist, specializing in commercial quality and the development of Sweet Potato Root Expert (Ipomoea batatas). Your focus is on diagnosing the history of abiotic stresses (drought, extreme heat, or water fluctuations) based on the root's final anatomy"; **PROMPT 2: CONTEXT AND PHENOLOGY (**Upload the image to be analyzed; (Report crop age - Days After Planting - DAP); PHENOLOGICAL RULE Required - The critical bulking period occurs before 90–100 DAP; If the reported age exceeds 90 DAP and the roots are very thin, fibrous, or lignified, strictly classify as a photoassimilate translocation failure (chronic stress), and not as an immature root); **PROMPT 3: VISUAL PHENOTYPING - Anatomical Attributes (**OBSERVATION - Analyze the roots visible in the image (if there is more than one, describe the predominant patterns or isolate them spatially; Describe: 1) Caliber and Shape: Was there adequate radial expansion (elliptical/oval roots) or are there central constrictions (strangulation) and a filiform/cord-like shape. 2) Periderm (Bark) Integrity: Identify the presence of longitudinal cracks (growth cracks), grooves, or excessively fibrous texture. 3) Secondary Disorders: Signs of premature sprouting or rot); **PROMPT 4: COMMERCIAL RANKING - The Practical Metric (**RANKING - Assign a Commercial Quality and Resilience Score (1 to 5: - Score 5 (Excellent): Smooth root, uniform shape, no cracks. Ideal size. - Score 4 (Good): Slight surface deformations or crookedness. - Rating 3 (Moderate): Visible constrictions (irregular growth) or underdeveloped diameter. - Rating 2 (Poor): Deep longitudinal cracks (cracking) or very thin roots at >90 DAP. - Grade 1 (Fail/Reject): Complete lignification, thread-like roots without starch, or catastrophic physical damage. Mandatory output: Evaluation: [Visual summary of the root]; Diagnosis: [Normal Root / Water Fluctuation Stress / Chronic Sink-Strength Deficit]; Grade: [1-5]); **PROMPT 5: ECOPHYSIOLOGICAL SYNTHESIS - Scientific Justification: (**SYNTHESIS - Summarize the Eco physiological assessment by connecting the phenotype to the environment: 1. If cracks (cracking) are detected: Explain the mechanics of water fluctuation (drying that stiffens the bark, followed by rapid rehydration that ruptures the parenchyma). 2. If thinning/fibrosis is detected: Explain the failure in sink strength due to the inhibition of photosynthesis in the aboveground parts during the bulking phase. 3. If the root is ideal (Grade 5): Confirm the maintenance of homeostasis and carbon flux. Combines the modules into a single logical train of thought (Chain-of-Thought).

Return: [STEP 1 - PHENOLOGICAL CONTEXTUALIZATION]. [STEP 2 - ROOT PHENOTYPING]. [STEP 3 - PERFORMANCE RANKING]. [STEP 4 - ECOPHYSIOLOGICAL SYNTHESIS].); **PROMPT 6 – STRUCTURED REPORT ELABORATION:** Prepare a structured report containing all the information gathered and make it available for download in .txt format

Adapted from Lima *et al*. (2026).

3 RESULTS AND DISCUSSION

The reports prepared exclusively by the AIs for Figures 2 through 5 are presented below in their entirety, though their format has been adapted to the journal's standards:

Prompt application for Figures 2, 3 and 4.

ChatGPT 5

"*STRUCTURED REPORT — APPLICATION OF THE 6 PROMPTS*

Visual diagnosis of sweet potato storage roots (Ipomoea batatas) under a thermal gradient

File generated on: 2026-05-27

***SCOPE: This report is restricted to the application of the six prompts provided by the user to the three attached images - 1. Yellow flesh* (Figure 2); *2. Orange flesh* (Figure 3); *3. Purple flesh* (Figure 4)**

The images show sweet potato storage roots under four thermal combinations: 25/17°C, 30/22°C, 35/27°C, and 40/32°C.

Methodological note: because crop age in DAP was not directly reported, phenological interpretation was conducted assuming that the roots represent material at the final stage of commercial quality assessment. Therefore, very thin, fibrous, or poorly thickened roots were interpreted as a probable failure in photoassimilate translocation/sink strength under chronic stress, and not simply as immature roots.

PROMPT 1 — PERSONA: The analysis was conducted from the perspective of an Agricultural Engineer and Ecophysiologist specializing in commercial quality and the development of sweet potato storage roots (Ipomoea batatas), with a focus on diagnosing previous abiotic stresses, especially extreme heat, drought, and water fluctuations, based on the final anatomy of the roots.

PROMPT 2 — CONTEXT AND PHENOLOGY: The three images indicate an increasing thermal gradient. Across all flesh colors, there is a consistent trend of reduced commercial caliber, increased morphological irregularity, greater presence of elongated/filiform roots, and intensified apparent fibrosity at higher temperatures.

Phenological rule applied: - The critical bulking period of storage roots occurs before 90–100 days after planting; - When final crop age exceeds this interval and the roots remain very thin, fibrous, or lignified, the diagnosis should prioritize chronic failure in photoassimilate translocation and limitation of sink strength, rather than physiological immaturity.

PROMPT 3 — VISUAL PHENOTYPING

IMAGE 1 — YELLOW FLESH

***Treatment 25/17°C:** Caliber and shape: Roots show good radial thickening, predominantly fusiform to oval shape, adequate commercial caliber, and relative uniformity among roots.*

*Periderm integrity: The periderm is visually intact, with no evident deep longitudinal cracks. The surface is relatively smooth, with small natural marks. Secondary disorders: There are no evident signs of premature sprouting, rot, or catastrophic physical damage. **Treatment 30/22°C:** Caliber and shape: Roots still show adequate thickening, but with a slight reduction in uniformity and a subtle tendency toward elongation/crookedness. Commercial caliber remains acceptable. Periderm integrity: The periderm is predominantly intact, with no deep cracks. Surface texture is slightly more irregular. Secondary disorders: There are no clear signs of rot or premature sprouting. **Treatment 35/27°C:** Caliber and shape: Roots show a* *reduction in average caliber, more pronounced irregularity, and the presence of constrictions or discontinuous thickening. Some roots are narrower, indicating limitations in radial growth.*

Periderm integrity: The periderm does not show visible catastrophic cracking, but greater roughness and apparent fibrosity are present. Secondary disorders: There are no evident signs of rot; the main disorder is anatomical irregularity associated with stress. ***Treatment 40/32°C:***

Caliber and shape: Roots are predominantly thin, elongated, and cord-like/filiform, with severe reduction in radial thickening. The pattern suggests marked tuberization failure and low reserve deposition. Periderm integrity: The periderm has a more fibrous appearance, with fine lateral roots and less commercial tissue appearance. Secondary disorders: No evident rot is observed, but there is strong indication of fibrosity and low commercial quality.

IMAGE 2 — ORANGE FLESH

Treatment 25/17°C: *Caliber and shape: Roots are bulky, uniform, and show a good commercial standard. Shape is fusiform/oval, with adequate radial thickening. Periderm integrity: The periderm is relatively smooth and intact, without deep cracks or severe lesions.*

Secondary disorders: No evident signs of premature sprouting or rot are observed. ***Treatment 30/22°C:*** *Caliber and shape: Roots show good caliber and acceptable shape, although with a slight increase in elongation and minor irregularity. The pattern still indicates good physiological performance. Periderm integrity: The periderm is preserved, with no deep longitudinal cracks. Secondary disorders: No marked signs of rot or sprouting are observed.*

Treatment 35/27°C: *Caliber and shape: Roots show greater heterogeneity, with some constrictions and reduced diameter. The pattern is compatible with moderate to high stress during root bulking. Periderm integrity: The periderm shows irregularity of surface, but severe cracking is not dominant. Secondary disorders: No evident rot is observed; the main problem is irregular development.* ***Treatment 40/32°C:*** *Caliber and shape: Roots are very thin, elongated, and numerous, with a markedly fibrous pattern and low radial thickening. There is strong loss of commercial standard. Periderm integrity: The surface appears rougher/fibrous, with lateral roots and a less tuberized structure. Secondary disorders: No visible rot is observed; the dominant anomaly is failure in radial growth associated with severe heat stress.*

IMAGE 3 — PURPLE FLESH

Treatment 25/17°C: *Caliber and shape: Roots show good caliber, commercial shape, and adequate radial expansion. The pattern is robust and relatively uniform. Periderm integrity: The periderm is intact, with no apparent deep cracks. The surface is compatible with good visual quality. Secondary disorders: No signs of premature sprouting or rot are observed.*

Treatment 30/22°C: *Caliber and shape: Roots are still commercially acceptable, but with slight elongation and a small reduction in uniformity. They maintain good reserve accumulation. Periderm integrity: No relevant cracks are observed. The periderm is visually stable. Secondary disorders: Not observed.* ***Treatment 35/27°C:*** *Caliber and shape: Roots show reduced caliber, greater irregularity, and a tendency toward elongation. Some roots show less filling, suggesting limitation in sink strength. Periderm integrity: The surface texture is more irregular, but severe cracking is not a dominant characteristic. Secondary disorders: No evident rot is observed.* ***Treatment 40/32°C:*** *Caliber and shape: Roots are thin, elongated, numerous, and of low caliber. The pattern indicates strong restriction of radial thickening and marked loss of commercial quality. Periderm integrity: The periderm has a more fibrous appearance, with a greater presence of fine lateral roots. Secondary disorders: No evident rot is observed; fibrosity/insufficient development predominates.*

PROMPT 4 — COMMERCIAL RANKING

YELLOW FLESH

25/17°C: *Evaluation: uniform, smooth roots, well expanded radially, with good commercial standard. Diagnosis: Normal Root. Grade: 5.* ***30/22°C:*** *Evaluation: roots still commercially acceptable, with slight irregularity and minor reduction in uniformity. Diagnosis: Normal Root with slight sign of physiological adjustment to increased temperature. Grade: 4.* ***35/27°C:*** *Evaluation: smaller, irregular roots, with constrictions and moderate reduction in caliber. Diagnosis: Chronic Sink-Strength Deficit. Grade: 3.* ***40/32°C:*** *Evaluation: very thin, elongated, fibrous roots with low reserve deposition. Diagnosis: Chronic Sink-Strength Deficit. Grade: 1.*

ORANGE FLESH

25/17°C: *Evaluation: bulky, uniform roots, without cracks and with excellent visual quality.*

Diagnosis: Normal Root. Grade: 5. ***30/22°C:*** *Evaluation: roots with good caliber, showing slight deformation or elongation. Diagnosis: Normal Root with mild thermal limitation. Grade: 4.* ***35/27°C:*** *Evaluation: heterogeneous roots, some constricted, with reduced caliber. Diagnosis: Chronic Sink-Strength Deficit. Grade: 3.* ***40/32°C:*** *Evaluation: thin, fibrous, and strongly underdeveloped roots. Diagnosis: Chronic Sink-Strength Deficit. Grade: 1.*

PURPLE FLESH

25/17°C: *Evaluation: robust, uniform, well-tuberized roots with no apparent damage. Diagnosis: Normal Root. Grade: 5.* ***30/22°C:*** *Evaluation: roots still commercially acceptable,* *with slight elongation and minor loss of uniformity. Diagnosis: Normal Root with mild heat stress. Grade: 4.* ***35/27°C:*** *Evaluation: smaller, irregular, and partially constricted roots.*

Diagnosis: Chronic Sink-Strength Deficit. Grade: 3. ***40/32°C:*** *Evaluation: very thin, elongated, fibrous roots with strong loss of commercial value. Diagnosis: Chronic Sink-Strength Deficit.*

Grade: 1.

PROMPT 5 — ECOPHYSIOLOGICAL SYNTHESIS

[STEP 1 - PHENOLOGICAL CONTEXTUALIZATION]: *The images represent a thermal gradient in which 25/17°C functions as the reference condition for greater physiological homeostasis and better commercial development of storage roots. As temperature increases to 30/22°C, 35/27°C, and 40/32°C, there is progressive loss of anatomical quality, with reduced caliber, greater irregularity, and, at the thermal extreme, thin and fibrous roots.* ***[STEP 2 - ROOT PHENOTYPING]:*** *The predominant visual pattern across the three flesh colors is a transition from oval/fusiform, well-expanded, commercial roots at 25/17°C to smaller, constricted, and heterogeneous roots at 35/27°C, culminating in filiform/fibrous roots at 40/32°C. Deep longitudinal cracks were not observed as a dominant disorder. Therefore, the main hypothesis is not water fluctuation stress with cracking, but chronic limitation of radial growth and reserve accumulation.* ***[STEP 3 - PERFORMANCE RANKING]:*** *Commercial and physiological performance followed a consistent pattern across the three images: 25/17°C: Grade 5 — excellent quality. 30/22°C: Grade 4 — good quality, with slight deformations. 35/27°C: Grade 3 — moderate quality, with constrictions and underdevelopment. 40/32°C: Grade 1 — commercial rejection, with filiform/fibrous roots and low starch/reserve deposition.*

[STEP 4 - ECOPHYSIOLOGICAL SYNTHESIS]: *The absence of severe cracking suggests that the predominant limitation is not mainly associated with abrupt cycles of drying and rehydration that rupture the periderm and storage parenchyma. The observed pattern is more compatible with chronic heat stress during the critical period of storage root formation and bulking. Under elevated temperatures, photosynthesis in the aboveground organs may be inhibited, respiration increases, and the net availability of carbon for storage organs decreases. Consequently, root sink strength is reduced, photoassimilate translocation decreases, radial expansion is limited, and fine/fibrous structures are maintained. At 25/17°C, maintenance of thermal homeostasis favors carbon flow to storage roots, resulting in well-expanded, uniform roots with higher commercial quality.*

PROMPT 6 — STRUCTURED REPORT

Final synthesis: The three images indicate a consistent morphophysiological response of sweet potato to increasing temperature. The 25/17°C condition promotes better balance among vegetative growth, carbon translocation, and formation of commercial storage roots. The 30/22°C condition still maintains acceptable quality, although with minor signs of deformation. The 35/27°C condition marks a moderate stress zone, with loss of caliber and anatomical irregularity. The 40/32°C condition represents severe heat stress, with failure of radial thickening, thin/fibrous roots, and probable functional collapse of sink strength during root bulking.

Diagnostic conclusion: The main disorder observed is not cracking caused by water fluctuation, but chronic sink-strength deficit associated with progressive heat stress. The response is consistent across the three flesh colors, indicating that the thermal effect on commercial quality and tuberization is dominant over flesh color in the images evaluated.

Summary table:

Image/Flesh | Temperature | Main diagnosis | Grade
Yellow flesh | 25/17°C | Normal Root | 5
Yellow flesh | 30/22°C | Normal Root with slight limitation | 4
Yellow flesh | 35/27°C | Chronic Sink-Strength Deficit | 3
Yellow flesh | 40/32°C | Severe Chronic Sink-Strength Deficit | 1
Orange flesh | 25/17°C | Normal Root | 5
Orange flesh | 30/22°C | Normal Root with slight limitation | 4
Orange flesh | 35/27°C | Chronic Sink-Strength Deficit | 3
Orange flesh | 40/32°C | Severe Chronic Sink-Strength Deficit | 1
Purple flesh | 25/17°C | Normal Root | 5
Purple flesh | 30/22°C | Normal Root with slight limitation | 4
Purple flesh | 35/27°C | Chronic Sink-Strength Deficit | 3
Purple flesh | 40/32°C | Severe Chronic Sink-Strength Deficit | 1".

GEMINI

"TECHNICAL AGRONOMIC REPORT: ECOPHYSIOLOGICAL DIAGNOSIS AND VISUAL PHENOTYPING

OF SWEET POTATO ROOTS (Ipomoea batatas) UNDER SIMULATED CLIMATE CHANGE CONDITIONS

PROJECT CONTEXT:

This structured technical report compiles the visual assessment, commercial quality ranking, and ecophysiological synthesis of tuberous roots of sweet potatoes (Ipomoea batatas) exposed to incremental thermal stress regimes. The analysis follows the prompt engineering and command chaining protocols developed for AI-assisted digital phenotyping.

REPORT SPECIFICATIONS: - Target Crop Age: 110 Days After Planting (DAP); - Critical Phenological Threshold: Bulking phase occurs prior to 90-100 DAP. - Roots remaining thin/fibrous at >90 DAP are strictly diagnosed as failures in photoassimilate translocation (chronic stress) and not as immature roots.

SECTION 1: THE ECOPHYSIOLOGICAL EVALUATION PROTOCOL (PROMPTS 1 - 6)

The analysis executes a 6-step cognitive chain-of-thought:

1. PERSONA ASSUMPTION: *Agricultural Engineer and Ecophysiologist specializing in commercial root quality and abiotic stress history.*

2. CONTEXTUAL VALIDATION: *Verification of crop age (110 DAP) against the critical 90-100 DAP bulking window.*

3. VISUAL PHENOTYPING: *Evaluation of root caliber, shape, periderm integrity, and secondary disorders.*

4. COMMERCIAL RANKING: *Scoring from 5 (Excellent/Homeostasis) to 1 (Fail/Lignified).*

5. ECOPHYSIOLOGICAL SYNTHESIS: Scientific justification linking structural degradations to source-sink mechanics and carbon partitioning.

6. STRUCTURED REPORT ELABORATION: *Consolidation of experimental data for technological and extension applications.*

SECTION 2: COMPARATIVE PHENOTYPIC ANALYSIS ACROSS THREE MORPHOTYPES

M01: YELLOW PULP VARIETY (POLPA AMARELA)

Temperature Regime: 25/17°C (Control / Optimum): *- Evaluation: Roots with excellent commercial caliber, highly uniform, smooth periderm, and symmetric oval/elliptical shape; - Diagnosis: Normal Root (Homeostasis fully preserved); - Grade: 5 (Excellent).* ***Temperature Regime: 30/22°C (Mild Thermal Stress):*** *Evaluation: Good overall radial expansion but displaying incipient asymmetric; volume distribution and minor surface irregularities. Elongated adventitious roots are visible at the base, indicating localized moisture seeking; - Diagnosis: Normal Root / Slight environmental fluctuation response; - Grade: 4 (Good).* ***Temperature Regime: 35/27°C (Moderate to Severe Thermal Stress): -***

Evaluation: Markedly underdeveloped caliber with an elongated, cord-like cylindrical; shape. Starch accumulation is restricted, and early signs of surface ribbing are noted. - Diagnosis: Chronic Drain Deficiency (Moderate restriction of sink strength); - Grade: 3 (Moderate); ***Temperature Regime: 40/32°C (Extreme Thermal Stress):*** *- Evaluation: Roots are strictly filiform, thin, and highly fibrous ("stringy"); Complete absence of starch-storing parenchymal expansion. Unmarketable; - Diagnosis: Chronic Drainage Deficit / Lignification due to Severe Abiotic Stress; - Grade: 1 (Fail / Reject).*

M02: ORANGE PULP VARIETY (POLPA LARANJA)

Temperature Regime: 25/17°C (Control / Optimum): *- Evaluation: Perfectly formed, smooth-skinned, oval roots displaying robust radial; expansion. Periderm integrity is flawless without any cracking or secondary growth. - Diagnosis: Normal Root (Homeostasis preserved). - Grade: 5 (Excellent);* ***Temperature Regime: 30/22°C (Mild Thermal Stress):*** *- Evaluation: Adequate starch accumulation and bulk, with very mild shape asymmetry or elongation across individual roots in the cluster. - Diagnosis: Normal Root / Response to mild thermal elevation.*

- Grade: 4 (Good); ***Temperature Regime: 35/27°C (Moderate to Severe Thermal Stress):*** *- Evaluation: Severe phenotypic alteration characterized by prominent central constrictions (strangulation), irregular dumbbell-like growth, and stunted diameter. - Diagnosis: Chronic Drain Deficiency (Dynamic disruption of sink strength). - Grade: 3 (Moderate); Temperature* ***Regime: 40/32°C (Extreme Thermal Stress):*** *- Evaluation: Complete failure of commercial development. Highly fibrous, line-like, woody root structures completely lacking starch accumulation. - Diagnosis: Chronic Drainage Deficit / Lignification due to Abiotic Stress. - Grade: 1 (Fail / Reject).*

M03: PURPLE PULP VARIETY (POLPA ROXA)

Temperature Regime: 25/17°C (Control / Optimum): *- Evaluation: Exceptional uniformity and radial expansion. Deep purple periderm remains pristine and smooth with an ideal elliptical shape. - Diagnosis: Normal Root (Homeostasis preserved). - Grade: 5 (Excellent);* ***Temperature Regime: 30/22°C (Mild Thermal Stress):*** *- Evaluation: High-quality roots with subtle longitudinal stretching or curvature but preserving excellent commercial volume. - Diagnosis: Normal Root / Preserved homeostatic balance under low stress. - Grade: 4 (Good);* ***Temperature Regime: 35/27°C (Moderate to Severe Thermal Stress):*** *- Evaluation: Elongated, cord-like appearance with a noticeably compressed diameter. High density of lateral adventitious roots branching out due to high respiration demands. - Diagnosis: Chronic Drain Deficiency (Moderate). - Grade: 3 (Moderate);* ***Temperature Regime: 40/32°C (Extreme Thermal Stress):*** *- Evaluation: Severe filiform architecture. Extremely slender roots* *that prioritized structural rigidity over carbohydrate storage. Completely unmarketable. - Diagnosis: Chronic Drainage Deficit / Lignification due to Abiotic Stress. - Grade: 1 (Fail / Reject).*

SECTION 3: ECOPHYSIOLOGICAL SYNTHESIS & METABOLIC MECHANISMS

The direct comparison across all three varieties under increasing temperature regimes reveals a uniform physiological vulnerability to heat stress, deeply impacting the source-sink mechanics of Ipomoea batatas:

1. ***SOURCE-SINK STRENGTH INHIBITION:*** *Under the optimum 25/17°C regime, net photosynthesis in the canopy (source) matches the carbohydrate storage capacity of the roots (sink). As temperatures escalate to 35/27°C and peak at 40/32°C, high respiration rates consume photoassimilates prematurely. Simultaneously, excessive heat impairs the phloem loading and unloading mechanisms, halting the downward translocation of sucrose.*
2. ***LIGNIFICATION VS. TUBERIZATION SWITCH:*** *The sweet potato root system possesses a metabolic fork during the early bulking phase (<90 DAP). Under homeostatic conditions, sucrose signals the proliferation of anomalous cambium rings and thin-walled parenchymal cells which capture starch. Under extreme chronic thermal stress (40/32°C), the absence of incoming sucrose, combined with stress-induced hormonal changes (ABA/Ethylene up-regulation), triggers the stele cells to synthesize lignin. This reinforces the root's cell walls to withstand drought and thermal strain, transforming a potential storage organ into a purely absorbent/conductive "stringy" fiber.*
3. ***CONSTRICION AND STRANGULATION MECHANICS:*** *The central constrictions observed predominantly in the 35/27°C treatments (such as in the Orange Pulp variety) represent sub-lethal thermal fluctuations. Periods of intense heat temporarily arrest cambial activity and radial growth, while brief microclimatic relief allows localized cell expansion, creating an irregular, deformed growth axis.*

SECTION 4: CONCLUSION AND CLIMATE RESILIENCE RECOMMENDATIONS: *- Thermal Vulnerability: All three tested germplasms (Yellow, Orange, and Purple pulp) exhibit an alarming decline in commercial viability when continuous day/night temperatures exceed 30/22°C, culminating in zero commercial yield at 40/32°C. - Breeding Goals: Breeding programs must prioritize selecting lines with heat-tolerant phloem transport systems and enzymes (e.g., starch synthase) that remain active above 35°C. -*

Agronomic Interventions: In regions facing climate-induced warming, mitigation strategies such as organic mulching (to reduce soil temperatures), agroforestry shading, and precision pulse irrigation during the critical 45-90 DAP bulking window are vital to preserve root homeostasis.

***END OF REPORT - GENERATED AUTOMATICALLY BY THE DIGITAL PHENOTYPING MODULE V1.0*”**

Prompt application for Figure 5

ChatGPT

“*STRUCTURED REPORT*

Sweet Potato Storage Root Visual Diagnosis Based on Final Root Anatomy

Species: Ipomoea batatas

Assessment focus: Visual diagnosis of abiotic stress history based on storage root morphology, periderm integrity, and commercial quality.

Input material: Comparative image panel containing three treatments: (1) control without thermal stress, (2) moderate thermal stress, and (3) severe thermal stress.

1. ***GENERAL PHENOLOGICAL CONTEXT:*** *The crop age in Days After Planting (DAP) was not provided. Therefore, the phenological interpretation was based exclusively on the visible anatomical and commercial development of the storage roots. The control roots show advanced development, adequate radial expansion, uniform shape, and commercial maturity. This indicates that the roots in the comparative panel are likely at or near a stage in which bulking should already be established. Consequently, reduced diameter, corky patches, deformation, cracking, and periderm rupture are interpreted as stress-related anatomical outcomes rather than simple immaturity.*
2. ***IMAGE 1 – CONTROL – NO THERMAL STRESS:*** *2.1. Evaluation: The storage roots are well formed, smooth, symmetrical, and commercially uniform. They show adequate radial expansion and a regular elongated-elliptical shape. The periderm is intact, continuous, and free of visible longitudinal cracks, grooves, excessive roughness, or fibrotic surface texture. No evident secondary disorders such as premature sprouting or rot are observed. 2.2. Diagnosis: Normal Root. 2.3. Commercial Quality and Resilience Grade: Grade 5 – Excellent. 2.4. Ecophysiological Interpretation: The phenotype is consistent with physiological homeostasis during the storage root bulking phase. Carbon assimilation in the aboveground organs and translocation of photoassimilates*

to the storage roots appear to have been maintained efficiently. The observed root pattern indicates adequate sink strength, stable radial expansion, and preservation of periderm integrity. No anatomical evidence of thermal stress damage is visible.

3. ***IMAGE 2 – THERMAL STRESS – MODERATE STRESS:*** *3.1. Evaluation - The roots show a moderate decline in commercial quality compared with the control. They remain recognizable as storage roots with partial commercial potential, but radial expansion is less uniform. Some roots show tapering, reduced diameter, and mild irregularity in shape. The periderm exhibits irregular corky or superficial cortical patches, rougher surface texture, and slight superficial cracking or external disturbance. 3.2. Diagnosis - Chronic Sink-Strength Deficit. 3.3. Commercial Quality and Resilience Grade - Grade 3 – Moderate. 3.4. Ecophysiological Interpretation - The phenotype suggests moderate impairment of sink strength during the bulking phase. Under thermal stress, the canopy may experience reduced photosynthetic efficiency, increased respiratory demand, and lower net carbon availability for storage root filling. As a result, photoassimilate supply to the storage roots may be insufficient to sustain uniform radial expansion. This explains the reduced diameter, lower uniformity, mild deformation, and moderate loss of external commercial quality. The corky surface patches indicate stress-related disturbance in periderm and cortical tissue development.*
4. ***IMAGE 3 – THERMAL STRESS – SEVERE STRESS:*** *4.1. Evaluation - The roots exhibit severe anatomical and commercial damage. They show marked deformation, strong irregularity of shape, deep longitudinal cracks, darkened areas of the periderm, and visible tissue rupture. The periderm is structurally compromised, and the roots have lost commercial acceptability. The severity of cracking and deformation indicates irreversible impairment of storage root quality. 4.2. Diagnosis - Water Fluctuation Stress, with severe thermal stress acting as a likely predisposing and aggravating factor. 4.3. Commercial Quality and Resilience Grade - Grade 1 – Fail/Reject. 4.4. Ecophysiological Interpretation - The deep cracking pattern is consistent with a water fluctuation stress mechanism, in which periods of limited expansion or tissue hardening are followed by rapid rehydration and internal parenchyma expansion, causing rupture of the outer tissues. However, because the treatment context is severe thermal stress, heat likely acted as a central predisposing factor by disturbing root growth, reducing tissue elasticity, impairing normal periderm development, and increasing structural instability. Therefore, the final phenotype should be interpreted as a combined stress*

outcome, in which severe thermal stress aggravated cracking, deformation, and tissue breakdown.

5. ***COMPARATIVE SYNTHESIS:*** *The three treatments represent a coherent gradient of damage in sweet potato storage roots. The control treatment shows normal development, adequate root filling, smooth periderm, and excellent commercial quality. The moderate thermal stress treatment shows partial reduction in radial expansion, irregular corky patches, mild deformation, and moderate loss of external quality. This pattern is consistent with impaired carbon allocation and weakened sink activity during bulking. The severe thermal stress treatment shows major anatomical disruption, deep cracking, darkening of the periderm, strong deformation, and commercial rejection. This pattern indicates severe structural failure, probably resulting from the interaction between thermal stress and tissue instability associated with water fluctuation dynamics.*
6. ***FINAL CLASSIFICATION SUMMARY:*** *Treatment: Control – No thermal stress; Evaluation: Smooth, uniform, well-developed roots with intact periderm; Diagnosis: Normal Root; Grade: 5 – Excellent. Treatment: Thermal stress – Moderate - Evaluation: Reduced diameter, irregular corky patches, mild deformation, and moderate external quality loss; Diagnosis: Chronic Sink-Strength Deficit; Grade: 3 – Moderate. Treatment: Thermal stress – Severe - Evaluation: Deep cracks, darkened periderm, severe deformation, and structural damage. Diagnosis: Water Fluctuation Stress, aggravated by severe thermal stress. Grade: 1 – Fail/Reject.*
7. ***FINAL CONCLUSION:*** *The image panel provides a clear visual model of the progressive impact of thermal stress on sweet potato storage root quality. Under non-stress conditions, roots maintain normal bulking, regular shape, smooth skin, and high commercial value. Under moderate thermal stress, root filling becomes less uniform, surface disorders appear, and commercial quality declines. Under severe thermal stress, the roots exhibit deep cracking, deformation, darkening, and structural rupture, leading to commercial rejection. Overall, the evidence supports the interpretation that thermal stress can affect sweet potato storage roots through two main pathways: first, by reducing photosynthetic performance and photoassimilate allocation to the storage roots, resulting in chronic sink-strength deficit; and second, by weakening tissue integrity and increasing susceptibility to severe cracking and structural failure, especially when associated with water fluctuation dynamics*".

GEMINI

“ECOPHYSIOLOGICAL & DIAGNOSTIC REPORT: ABSTACT STRESS EVALUATION IN IPOMOEA BATATAS

Document Reference: ECO-PHYS-IB-2026-0601

Target Species: Ipomoea batatas (Sweet Potato)

Analyzed Asset: batata doce estresse térmico.png

Reported Crop Age: 90 Days After Planting (DAP)

Analysis Date: June 1, 2026

Expert/Persona: Agricultural Engineer & Ecophysiologist (Sweet Potato Root Expert)

1. EXECUTIVE SUMMARY & STATUTORY DIAGNOSIS: *Based on a rigorous cross-sectional and macro-anatomical review of the three experimental cohorts presented in 'batata doce estresse térmico.png’ and guided by the strict Phenological Rule of Ipomoea batatas development, this technical verdict is issued: Biological Threshold Status: 90 DAP (End of critical bulking window). Formal Classification: CHRONIC PHOTOASSIMILATE TRANSLOCATION FAILURE (Chronic Stress). Structural Assessment: The severe degradation, lack of radial expansion, and catastrophic tearing seen in the severe treatment group represent an irreversible structural fate, NOT a state of immaturity or delayed development. Commercial Action: REJECTION for premium fresh markets. Lot must be diverted for alternative industrial uses (bioconversion/ethanol) or animal feed.*

2. PHENOLOGICAL CONTEXTUALIZATION & CRITICAL WINDOW LOGIC

The critical bulking period for sweet potato storage roots occurs strictly prior to 90–100 DAP. During this active phase, the primary vascular cambium and anomalous cambia must rapidly divide to produce expansive storage parenchyma cells designed for intense starch accumulation.

At 90 DAP, the storage roots have reached the biological deadline of this ontogenetic window.

- If the roots remain thin, fibrous, or severely deformed at >90 DAP, it proves the phloem unloading mechanism and vascular differentiation were permanently compromised during early-to-mid-season bulking. - Leaving the crop in the ground past this milestone will not result in late bulking; the structural pathway is permanently locked into a survival/lignified state rather than a storage state.

3. SPATIAL ROOT PHENOTYPING & VISUAL FORENSICS

A spatial separation and macro-phenotypic diagnosis of the three treatment cohorts yield the following morphological profiles: COHORT A: Controle - sem estresse térmico (Control Group) - Caliber and Shape: Excellent, uniform radial expansion. All roots display the premium commercial elliptical-to-fusiform (oval) shape. No cord-like or filiform restrictions. - Periderm Integrity: Flawless. Bark is completely smooth, continuous, and free of grooves, blemishes, or structural cracking. - Secondary Disorders: Zero signs of premature sprouting, localized necrosis, or opportunistic rot; COHORT B: Estresse térmico - estresse moderado (Moderate Stress Group) - Caliber and Shape: Distinct reduction in volume and diameter compared to the control. General shape remains elliptical but shows irregular radial expansion and tapering at the tips. - Periderm Integrity: Compromised. Marked by prominent, irregular corky spots (manchas corticosas) and shallow, localized surface micro-cracks. - Secondary Disorders: Early localized tissue degradation beneath the corky lesions; active soft rot or green sprouting is not yet protruding; COHORT C: Estresse térmico - estresse severo (Severe Stress Group) - Caliber and Shape: Catastrophic failure of radial expansion. Roots are severely thin, asymmetric, twisted, and exhibit severe central constrictions. - Periderm Integrity: Completely ruined. Marked by massive, deep, gaping longitudinal growth cracks (rachaduras profundas) and widespread thermal necrosis/browning (escurecimento da casca). - Secondary Disorders: Extremely high risk of secondary opportunistic soil-borne pathogens. Open structural wounds expose internal tissues, accelerating desiccation and tissue rot.

4. COMMERCIAL PERFORMANCE RANKING

Evaluated under the practical metric scale (Grades 1 to 5): Lot 1: Controle (Control) - Evaluation: Smooth root, uniform shape, no cracks, ideal commercial size. Diagnosis: Normal Root. - Grade: 5 (Excellent); Lot 2: Estresse Moderado (Moderate Stress) - Evaluation: Visible surface deformations, irregular growth, underdeveloped diameter. - Diagnosis: Chronic Sink-Strength Deficit (Early Stage Thermal Inhibition). - Grade: 3 (Moderate); Lot 3: Estresse Severo (Severe Stress) - Evaluation: Catastrophic physical damage, deep longitudinal cracks, severely thin/deformed. - Diagnosis: Chronic Sink-Strength Deficit combined with Water Fluctuation Stress. - Grade: 2 (Poor) - REJECTED

5. ECOPHYSIOLOGICAL SYNTHESIS & SCIENTIFIC JUSTIFICATION: *The final anatomical state observed at 90 DAP is the clear mechanical and biochemical record of the plant's interaction with abiotic stressors: A. Mechanics of Catastrophic Cracking (Water Fluctuation Stress) Prolonged high soil temperatures and severe moisture deficits caused the outer periderm and cortical cell layers to mature prematurely and hyper-suberize. This defense response turned the sweet potato skin into an inelastic, rigid shell. When a subsequent rainfall* *or over-irrigation event occurred, water rushed into the internal storage parenchyma, causing an immediate, exponential surge in internal turgor pressure. Because the stiffened bark could no longer stretch to accommodate this radial expansion, the root split open, producing deep, longitudinal fissures; B. Mechanics of Thinning and Fibrosis (Sink-Strength Deficit) The severe diameter restriction in the stressed cohorts stems from thermal inhibition of the source-sink pathway. Extreme temperatures reduce photosynthetic efficiency in the canopy while directly deactivating 'sucrose synthase' and 'starch synthase' enzymes in the root zone. Consequently, incoming sucrose could not be converted into starch granules within the vacuoles. Deprived of carbohydrate flux, the vascular cambium abandoned storage parenchyma differentiation and instead generated highly lignified, structural xylem vessels to prioritize survival, rendering the root woody and fibrous; C. Homeostasis and Carbon Flux Maintenance (Ideal Grade 5 Roots) The control cohort demonstrates optimal physiological homeostasis. Unchecked by thermal or moisture stress, the source canopy maintained stable carbon fixation and a steady downward phloem flux. At the root zone, optimal enzymatic activity seamlessly converted translocated sugars into dense starch reserves within highly elastic parenchyma cells, producing flawless commercial shapes.*

END OF REPORT”.

COPILOT

COPILOT AI did not produce results that adequately reflect the prompt.

The application of the proposed methodology generated effective results when conducted on the ChatGPT and Gemini AIs. However, Copilot failed to return satisfactory results, due to incorrect application of the prompts. This result is consistent with that found by Fontenelle *et al*. (2025) when developing PFBCIA for lettuce seedlings treated with bio-inputs. It is also agreed with those found by Srivastava *et al*. (2023), which, evaluating several LLMs, showed that the performance among them varies depending on the Prompt Engineering and Prompt Chaining used, as well as on the specific characteristics that make up the main features of each LLM.

Both models presented the same general physiological pattern for roots with yellow, orange, and purple pulp (Figures 2 to 4), as well as for the analysis of the physiological disorders presented in Figure 5. Commercial quality is preserved at low temperatures, a slight morphological deterioration is observed at moderately high temperatures, the caliber and anatomical regularity are gradually reduced at intermediate to high temperatures, and commercial quality is lost at the highest temperature with the occurrence of disorders such as depigmentation and cracking. Processes identified included chronic deficit in water absorption capacity, lack of tuberous root development, and cracking caused by abrupt water fluctuations. This suggests that the methodology was useful in achieving a clear visual and ecophysiological interpretation of thermal stress gradients. These analyses are consistent with those expected and cited in materials such as that published by Fernandes *et al*. (2021).

The results show that, qualitatively, the application of the two AIs that returned effective results showed similar performance in detecting physiological disorders induced by extreme heat. The main difference lies in the way the final structured report is presented, with Gemini presenting a more concise document, while ChatGPT presented a more comprehensive text. For innovative outreach purposes, more concise texts are more suitable as they facilitate the interpretation and application of the results. Alves *et al*. (2016) argue that one of the main problems currently observed in rural extension is not the lack of communication, but rather the way in which it is carried out. In this sense, more synthetic and didactically designed materials are essential tools for the effectiveness of the work of Technical Assistance and Rural Extension agencies (ATER). Improving Prompt to return standardized and concise reports is desirable in future versions. The improvement of specific points in structured prompts can be achieved through the adaptation of natural language models, as demonstrated by Zhou *et al*. (2023).

Furthermore, extracting programming codes such as Python scripts can lead to the construction of a platform independent of commercial generative AI, generating greater autonomy and less technological dependence. This will naturally be the next step in technological development. This possibility is highlighted by Muennighoff *et al*. (2024) and is seen by the authors as an opportunity to increase the democratization and widespread use of tools developed using commercial generative AI as support. It also becomes a robust strategy for achieving independent technological development.

The scores assigned by humans to the tuberous roots shown in Figures 2, 3, and 4 were, in all cases: 5, 4, 2, 1. The scores assigned by both AIs were: 5, 4, 3, 1. For Figure 6, the human and ChatGPT evaluations were concordant (5, 3, 1), while Gemini presented the sequence 5, 3, 2. Table 1 shows the values of the Spearman correlation coefficients and the mean absolute deviation obtained for the performance of the two AIs compared to human evaluation. The values were calculated based on the rankings compiled by the AIs and senior researchers.

Table 1. Quantitative agreement between AI-generated rankings and human expert evaluation for sweet potato root visual quality assessment. Analysis performed taking all rankings into account, for Figures 2 through 5.

AIs x Human evaluation	**Spearman correlation coefficients (ρ)**	**Mean Absolute Deviation (MAD)**
ChatGPT vs. Human evaluation	0,9943	0,20

Gemini vs. Human evaluation	0,9887	0,2667

Source: Authors.

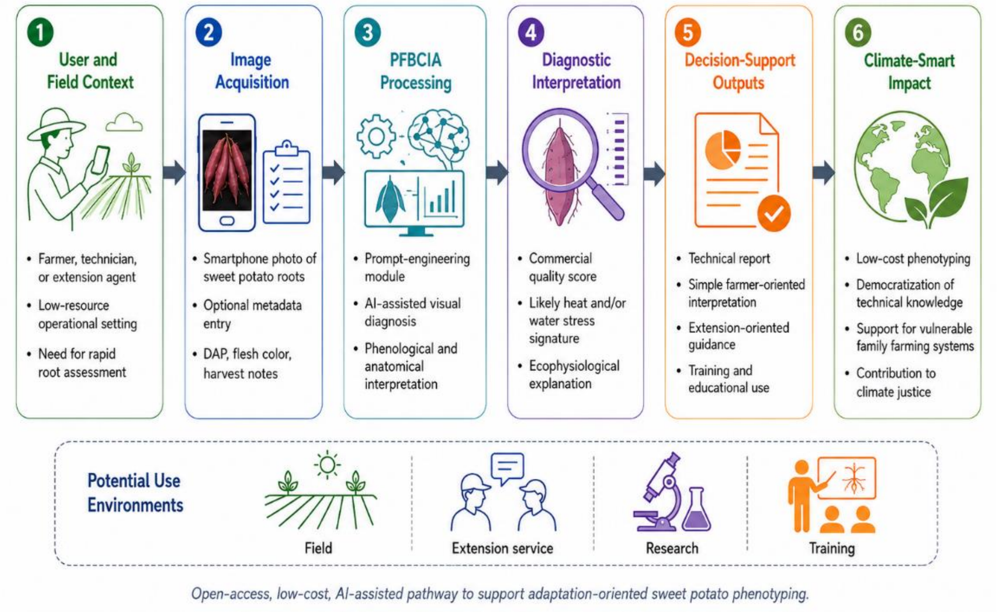
Quantitatively, the AIs that were able to process the prompt effectively demonstrated high consistency and results that were very consistent with human evaluations. The Spearman correlation coefficients for comparing the rankings produced by experts with those generated by applying the prompts to ChatGPT and Gemini, respectively, were $\rho = 0.9943$ and $\rho = 0.9887$. These values, very close to +1, indicate strong agreement in the ranking, with a slight advantage for ChatGPT. The calculated MAD values were MAD = 0.20 and MAD = 0.2667. The values found are well below 1.50, established by Fontenelle *et al.* (2025) as the cutoff score for the performance of the PFBCIAs under development for vegetables by our team, indicating once again a high degree of agreement between the evaluation conducted by experts and that performed by the AI tools. The validation of these same AI models for phenotypic assessment of lettuce seedlings treated with bio-inputs was also reported by Fontenelle *et al.* (2025). Divergent performance of LLMs in different contexts has been widely documented, as can be seen in the work of Zhou *et al.* (2023).

However, it should be noted that this study deals only with the proof of concept, version 1.0.0 of the proposed methodology (and future software currently in the registration phase), and further improvements are still needed to enable its widespread use. As mentioned earlier, one area for improvement is the standardization of output reports. Another point is the validation using real images of tuberous roots harvested under different edaphoclimatic conditions. Nevertheless, the validation of applying this same logical concept to lettuce plants was conducted by Fontenelle *et al.* (2026), who compared data obtained through human evaluation in an experiment simulating future climate conditions and the use of bio-inputs with the performance of an LLM, demonstrating that the development of new PFBCIAs holds a promising future.

The aim is for the PFBCIAs currently under development to become useful tools for democratizing the use of digital technologies for educational and agronomic purposes in different Climate Change scenarios. Details on how this will be achieved can be seen in Figures 7 and 8. The development of technological assets focused on family farming (AF) also positions these assets and ongoing studies as strategies for achieving the IPCC Framework on climate justice and just transition, and they are aligned with the 2030 Agenda and with Brazilian public policies such as the Climate Adaptation Plan – Family Farming Sector. In the latter, the alignment becomes even clearer when we examine Goal 60: Establish a Center for Territorial

Intelligence within the Ministry of Agrarian Development and Family Farming, ensuring the monitoring of threats, risks, exposure, and vulnerabilities related to climate change in family farming by 2027.

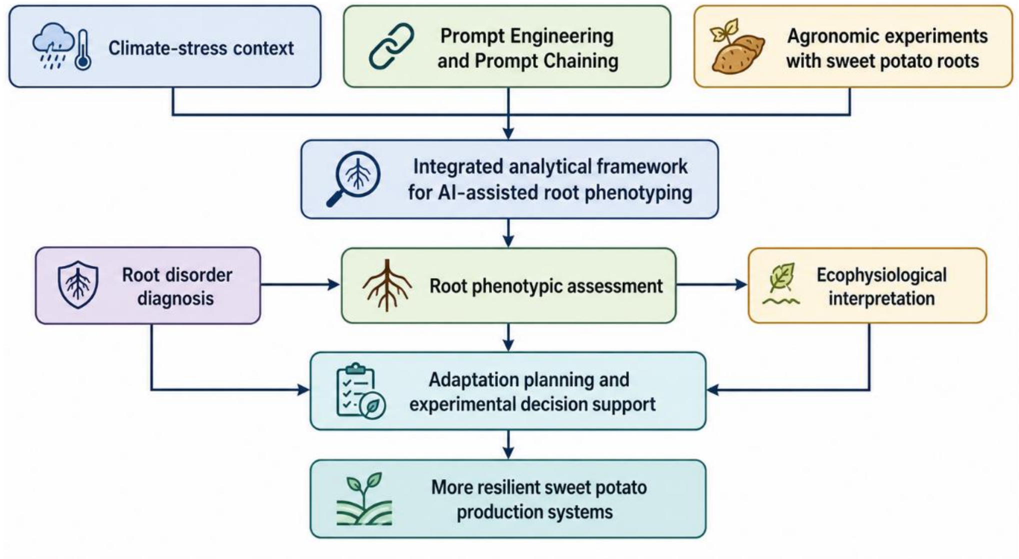
Figure 7. Pratical application pathway of the PFBCIA – Sweet Potato for Climate-Smart Decision Support



Open-access, low-cost, AI-assisted pathway to support adaptation-oriented sweet potato phenotyping.

Source: The authors with support of AI tools

Figure 8. Integrated methodological framework for educational, innovation and agronomic purposes.



Source: The authors with support of AI tools

4 CONCLUSIONS

The PFBCIA - sweet potato has potential for practical use in education, innovation, and agronomy, and has been validated for use with the ChatGPT and Gemini AI models. Its first version was designed to visually assess physiological disorders in sweet potato tubers under heat stress, serving as a tool to help crops adapt to climate change. The open-access approach, following FAIR principles, allows for the generation of reliable agronomic diagnoses using simple inputs such as photos and basic data from the production cycle. As a low-cost tool, it has the potential to democratize technical knowledge in serving family farmers, aligning with the IPCC frameworks on climate justice and just transition, as well as with the 2030 Agenda and the Brazilian legal structure.

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