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LOW-COST LETTUCE PHENOTYPING PLATFORMS POWERED BY GENERATIVE AI: DEVELOPMENT, VALIDATION, AND METHODOLOGICAL DEMOCRATIZATION FOR CLIMATE-JUST BRAZILIAN LETTUCE CROPS

PLATAFORMAS DE FENOTIPAGEM DE ALFACE DE BAIXO CUSTO BASEADAS EM IA GENERATIVA: DESENVOLVIMENTO, VALIDAÇÃO E DEMOCRATIZAÇÃO METODOLÓGICA PARA O CULTIVO DE ALFACE NO BRASIL COM JUSTIÇA CLIMÁTICA

PLATAFORMAS DE FENOTIPADO DE LECHUGAS DE BAJO COSTE BASADAS EN IA GENERATIVA: DESARROLLO, VALIDACIÓN Y DEMOCRATIZACIÓN METODOLÓGICA PARA CULTIVOS DE LECHUGA BRASILEÑOS RESPETUOSOS CON EL CLIMA

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ABSTRACT

In this context, low-cost digital technologies capable of democratizing access to technical and scientific tools are essential to enhance the resilience and adaptive capacity of vegetable production systems. This study aimed to develop and validate low-cost lettuce phenotyping platforms powered by generative artificial intelligence (AI), focusing on thermal physiological disorders, using Prompt Engineering and Prompt Chaining as core methodologies. The

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framework comprised: (i) compilation and mapping of climate information and thermal risk/severity for lettuce in Brazil; (ii) identification of key physiological disorders expected under GCC scenarios based on Lima *et al.* (2024) and a systematic literature review; (iii) design of an analytical pipeline using Prompt Engineering and Prompt Chaining for generative Ais; and (iv) extraction of Python scripts and generation of SHA-256 hash codes in Visual Studio Code (VSC), followed by validation through comparison between AI-generated reports and the reference results of Lima *et al.* (2024). The resulting set of scripts reproduced, with high consistency, the patterns reported in the benchmark study and were made publicly available under FAIR principles. These results represent an important tool to accelerate the development of technological solutions for increasing resilience and climate adaptation in Brazilian lettuce production, while remaining replicable and adaptable via open-source code to other regions of the world.

Keywords: Global Climate Change. Adaptation and Resilience. Climate Intelligence. Vegetable Crops. Digital Technologies.

RESUMO

Nesse contexto, tecnologias digitais de baixo custo capazes de democratizar o acesso a ferramentas técnicas e científicas são essenciais para aumentar a resiliência e a capacidade de adaptação dos sistemas de produção de hortaliças. Este estudo teve como objetivo desenvolver e validar plataformas de fenotipagem de alface de baixo custo, baseadas em inteligência artificial (IA) generativa, com foco em distúrbios fisiológicos térmicos, utilizando a Engenharia de Prompts e o Encadeamento de Prompts como metodologias centrais. A estrutura compreendeu: (i) compilação e mapeamento de informações climáticas e risco/gravidade térmica para a alface no Brasil; (ii) identificação dos principais distúrbios fisiológicos esperados em cenários de GCC com base em Lima *et al.* (2024) e uma revisão sistemática da literatura; (iii) projeto de um fluxo analítico utilizando Prompt Engineering e Prompt Chaining para IAs generativas; e (iv) extração de scripts em Python e geração de códigos hash SHA-256 no Visual Studio Code (VSC), seguida de validação por meio da comparação entre relatórios gerados por IA e os resultados de referência de Lima *et al.* (2024). O conjunto de scripts resultante reproduziu, com alta consistência, os padrões relatados no estudo de referência e foi disponibilizado publicamente sob os princípios FAIR. Esses resultados representam uma importante ferramenta para acelerar o desenvolvimento de soluções tecnológicas para aumentar a resiliência e a adaptação climática na produção brasileira de alface, mantendo-se replicáveis e adaptáveis por meio de código-fonte aberto a outras regiões do mundo.

Palavras-chave: Mudança Climática Global. Adaptação e Resiliência. Inteligência Climática. Culturas Hortícolas. Tecnologias Digitais.

RESUMEN

En este contexto, las tecnologías digitales de bajo coste capaces de democratizar el acceso a herramientas técnicas y científicas son esenciales para mejorar la resiliencia y la capacidad de adaptación de los sistemas de producción hortícola. El objetivo de este estudio fue desarrollar y validar plataformas de fenotipado de lechuga de bajo coste basadas en inteligencia artificial generativa (IA), centrándose en los trastornos fisiológicos térmicos, utilizando la ingeniería de prompts y el encadenamiento de prompts como metodologías principales. El marco comprendió:

(i) la recopilación y cartografía de la información climática y el riesgo/gravedad térmica para la lechuga en Brasil; (ii) la identificación de los principales trastornos fisiológicos previstos en escenarios de cambio climático global (GCC) basados en Lima *et al.* (2024) y una revisión sistemática de la literatura; (iii) el diseño de un flujo analítico utilizando Prompt Engineering y Prompt Chaining para IA generativa; y (iv) la extracción de scripts de Python y la generación de códigos hash SHA-256 en Visual Studio Code (VSC), seguida de la validación mediante la comparación entre los informes generados por IA y los resultados de referencia de Lima *et al.* (2024). El conjunto de scripts resultante reprodujo, con gran consistencia, los patrones descritos en el estudio de referencia y se puso a disposición del público bajo los principios FAIR. Estos resultados constituyen una herramienta importante para acelerar el desarrollo de soluciones tecnológicas destinadas a aumentar la resiliencia y la adaptación climática en la producción de lechuga en Brasil, al tiempo que siguen siendo replicables y adaptables a otras regiones del mundo mediante código de código abierto.

Palabras clave: Cambio Climático Global. Adaptación y Resiliencia. Inteligencia Climática. Cultivos Hortícolas. Tecnologías Digitales.

INTRODUCTION

Global warming and global climate change (GCC) are among the greatest contemporary challenges faced by humanity (IPCC, 2021; IPCC, 2023). Copernicus (2026) notes that the last three years have been the warmest on record, and that this three-year period was the first to exceed 1.5°C above pre-industrial levels—the threshold set by the Paris Agreement (IPCC, 2018). Lima *et al.* (2025a), using the ETA-HADGEM2-EM regional model, found that average temperatures (Tmed) could rise by more than 6°C and maximum temperatures (Tmax) by more than 8°C during certain seasons across Brazil, particularly in the Central-West and Northern regions. A widespread increase in temperature is expected to be observed in Brazil throughout the year between the present period and the historical period (Lima *et al.*, 2025a; Lima *et al.*, 2025b).

Particularly severe implications for agricultural crops better adapted to cool and mild temperature, such as lettuce (*Lactuca sativa* L.), even if they have been adapted to the tropical climate (Sala & Costa, 2012), one of the most widely grown and consumed leafy vegetables in Brazil and worldwide (Florindo *et al.*, 2025). Projections for Brazil indicate that future thermal regimes will seriously threaten the viability of conventional lettuce production systems, which are predominantly managed by family farmers and thus highly exposed to climate risks and social vulnerability (Lima et a., 2025a; Lima *et al.*, 2025c).

However, climate intelligence tools designed for agriculture and family farming are still scarce in Brazil, hindering planning and implementation efforts to enhance climate resilience and adaptation in the country (Brazil, 2025a and Brazil, 2025b). Furthermore, R&D equipment, such as phenotyping platforms, remains very expensive and largely inaccessible, especially to smaller innovation centers, as well as to rural extension agents, policymakers, and farmers.

In this context, it is also characterized by the fact that, in addition to being a modern tool based on Artificial Intelligence (AI), it can incorporate work from analysis of photos taken with ordinary cell phones into the IPCC frameworks for climate justice and a just transition. Fontenelle *et al.* (2025a) validated this tool, which was developed using Prompt Engineering and Command Chaining, for the application of phosphorus-supplying bio-inputs to lettuce seedlings by calculating Spearman’s correlation coefficient and the mean absolute deviation (MAD). The tool has been validated for the generative AI models (large language models—LLMs) ChatGPT and Gemini. It may also be important for the democratization of science using public repositories following FAIR principles (Encontráveis - Findable, Acessíveis - Accessible, Interoperáveis - Interoperable).

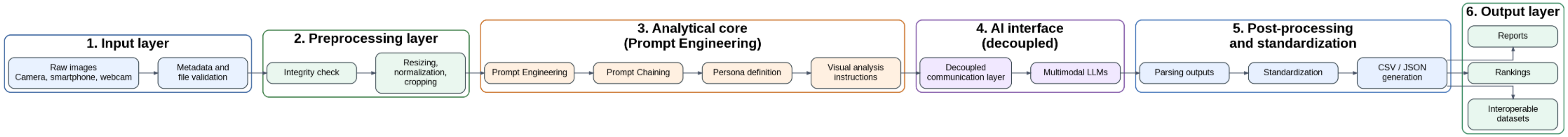
This study aimed to develop and validation of the 1.0.0 version of a low-cost lettuce phenotyping platform powered by generative artificial intelligence (AI), focusing on thermal physiological disorders, using Prompt Engineering and Prompt Chaining as core methodologies.

Material and Methods

A graphical summary of the proposed method for the visual analysis of heat stress caused by high temperatures in lettuce is shown in Figure 1. This constitutes what we call the Low-Cost AI-Supported Phenotyping Platform (PBCIA), which, in this case, is being applied to the lettuce crop (PBCIA-lettuce thermal stress)

Figure 1

Summarized platform architecture of PBCIA – lettuce thermal stress



Source: The authors supported by AI tools

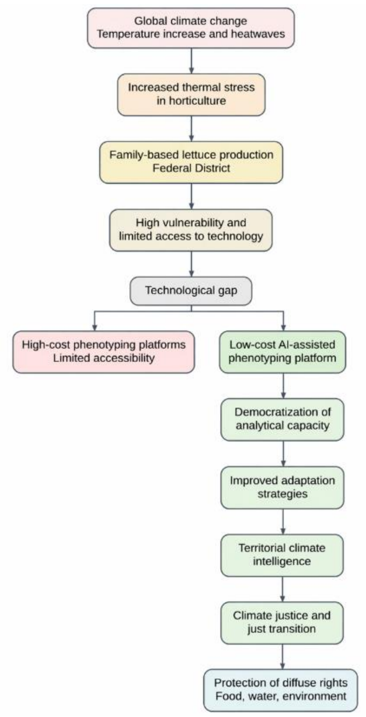
Study Design and Conceptual Framework

This study was conducted to produce results consistent with those found by Lima *et al.* (2024). These results were used to establish the Prompt Engineering and Command Chaining phase, as well as to validate the results. This first development stage, version 1.0.0, was designed to assess physiological disorders in lettuce (Lactuca sativa L.) under thermal stress using Generative Artificial Intelligence and Guided Learning. The conceptual framework consists of the following steps: Plant physiological responses to thermal stress; Occurrence of morphophysiological disorders; Application of biofertilizers versus mineral fertilization and; Use of generative AI (Large Language Models – LLMs) for visual phenotyping

The proposed methodology also follows other four integrated conceptual frameworks: Synthesis of climate and physiological knowledge; Definition of target phenotypic variables; Development of an AI-based analytical pipeline and; Validation against experimental data published by Lima *et al.* (2024). Advantages of using this method are summarized in Figure 1.

Figure 2

Challenges posed by global climate change to family-run lettuce farms and the advantages of adopting the proposed methodology (right) compared to the conventionally used methodology (left).



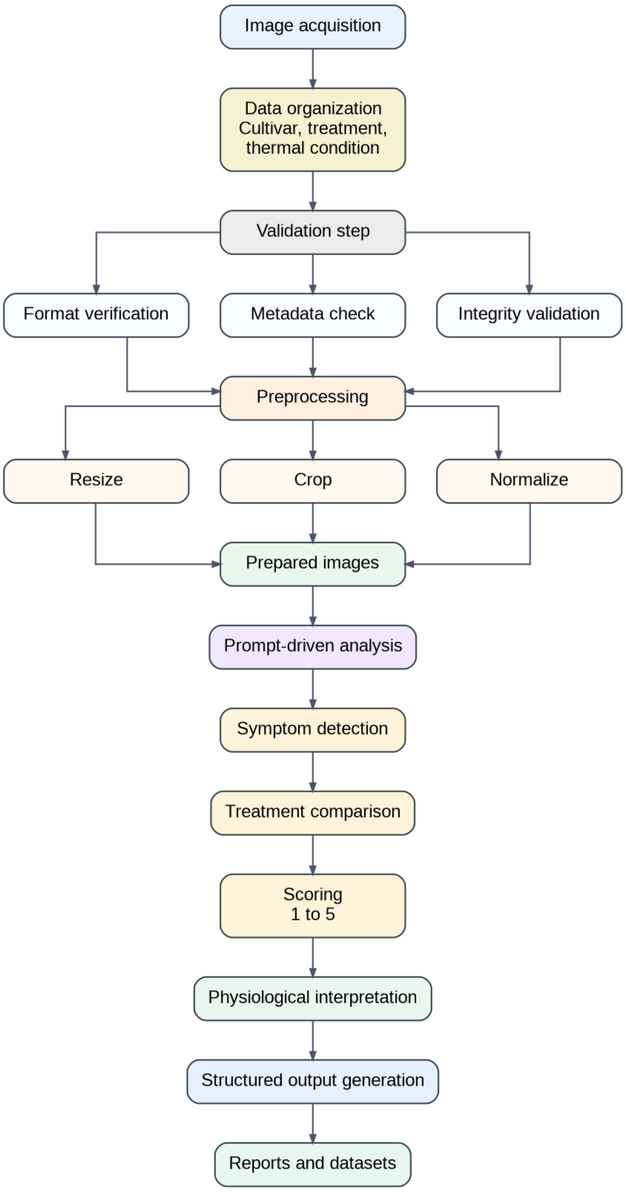
Source: The authors supported by AI tools

Data Acquisition and Preprocessing

Devices such as smartphones and digital cameras were used to take photos, which were made available in accordance with the FAIR principles as outlined in Lima *et al.* (2025d). The preprocessing pipeline followed these steps: integrity verification; metadata validation; image resizing; cropping; and normalization and quality enhancement for high resolution. The image processing and workflow stages are summarized in Figure 3.

Figure 3

A graphical overview of the image processing and workflow used.



Source: The authors supported by AI tools

AI-Assisted Analytical Framework

The analysis utilized Prompt Engineering and Prompt Chaining techniques. The workflow included: Definition of an expert persona (plant physiology specialist); Contextualization of experimental conditions; Specification of analytical objectives; and Structured visual inspection. The analysis also focused on identifying morphophysiological attributes commonly observed during heat stress in lettuce. The attributes analyzed were Leaf coloration and uniformity; Turgor and hydration; Canopy structure; Presence of disorders (chlorosis, necrosis, tip burn, wilting, senescence, bolting). The exact commands used can be found in the preprint published by Lima *et al.* (2025d). A graphical summary of this analytical framework can be found in Figure 4.

Prompt Engineering and Prompt Chaining Used

Prompt 1

Take on the persona of an Agricultural Engineer with a PhD in Plant Physiology and at least 15 years of experience investigating heat stress and physiological disorders in lettuce (*Lactuca sativa*) under tropical environments. You are specialized in evaluating plant responses to biofertilizers and mineral fertilizers, focusing on nutrient balance, thermal tolerance, and chlorophyll maintenance.

Prompt 2

The attached photos show lettuce plants grown under high-temperature stress conditions. In each pair, the left and right pots represent plants subjected to different fertilization sources — one with a biofertilizer and the other with a mineral fertilizer.

Carefully observe and compare the following attributes for each pair:

1. Leaf color intensity and uniformity (deep green indicates chlorophyll stability and nutrient balance; pale green or yellow suggests degradation or nitrogen deficiency);
2. Tissue turgor and hydration status (assess wilting, loss of leaf rigidity, or folding);
3. Leaf morphology and canopy architecture (expansion, deformation, curling, or necrotic margins);
4. Overall vigor and biomass distribution (density and compactness of the head or canopy);
5. Heat stress indicators and visible physiological disorders.

Prompt 3

Identify and describe all visible physiological disorders present in each treatment, classifying them by symptom type. Following categories should be used to describe symptoms:

- Tipburn: necrotic borders or margins typical of calcium or heat stress;
- Chlorosis: diffuse or interveinal yellowing due to chlorophyll degradation or N imbalance;
- Necrosis: brown or blackened areas indicating irreversible cell damage by thermal or oxidative stress;
- Wilting or dehydration: loss of turgidity, leaf curling, or drooping due to high transpiration;
- Leaf abscission or senescence: detachment or drying of basal leaves;
- Bolting or stem elongation: premature reproductive growth induced by high temperature;
- Uneven canopy development: asymmetrical or irregular leaf distribution caused by stress or root inhibition.

For each symptom identified, indicate which treatment exhibits it most severely and provide a brief physiological interpretation of the underlying cause.

Prompt 4

Compare all pairs (biofertilizer vs. mineral) considering the intensity and frequency of physiological disorders, vigor, and tolerance to heat stress. Assign a qualitative performance ranking for each pair:

- 5 = Excellent thermotolerance (vigorous, minimal symptoms);
- 4 = Good (minor chlorosis or slight wilting);
- 3 = Moderate (visible edge burn or localized necrosis);
- 2 = Weak (general chlorosis or partial canopy collapse);
- 1 = Severe stress (widespread necrosis or desiccation).

Then, generate a final integrated ranking summarizing all pairs, identifying which fertilization source (biofertilizer or mineral) conferred greater thermotolerance.

Prompt 5

Summarize the physiological interpretation by addressing:

1. Which treatment (biofertilizer or mineral fertilizer) maintained greater chlorophyll integrity, hydration, and canopy uniformity;
2. Specific physiological disorders were predominant in each treatment;

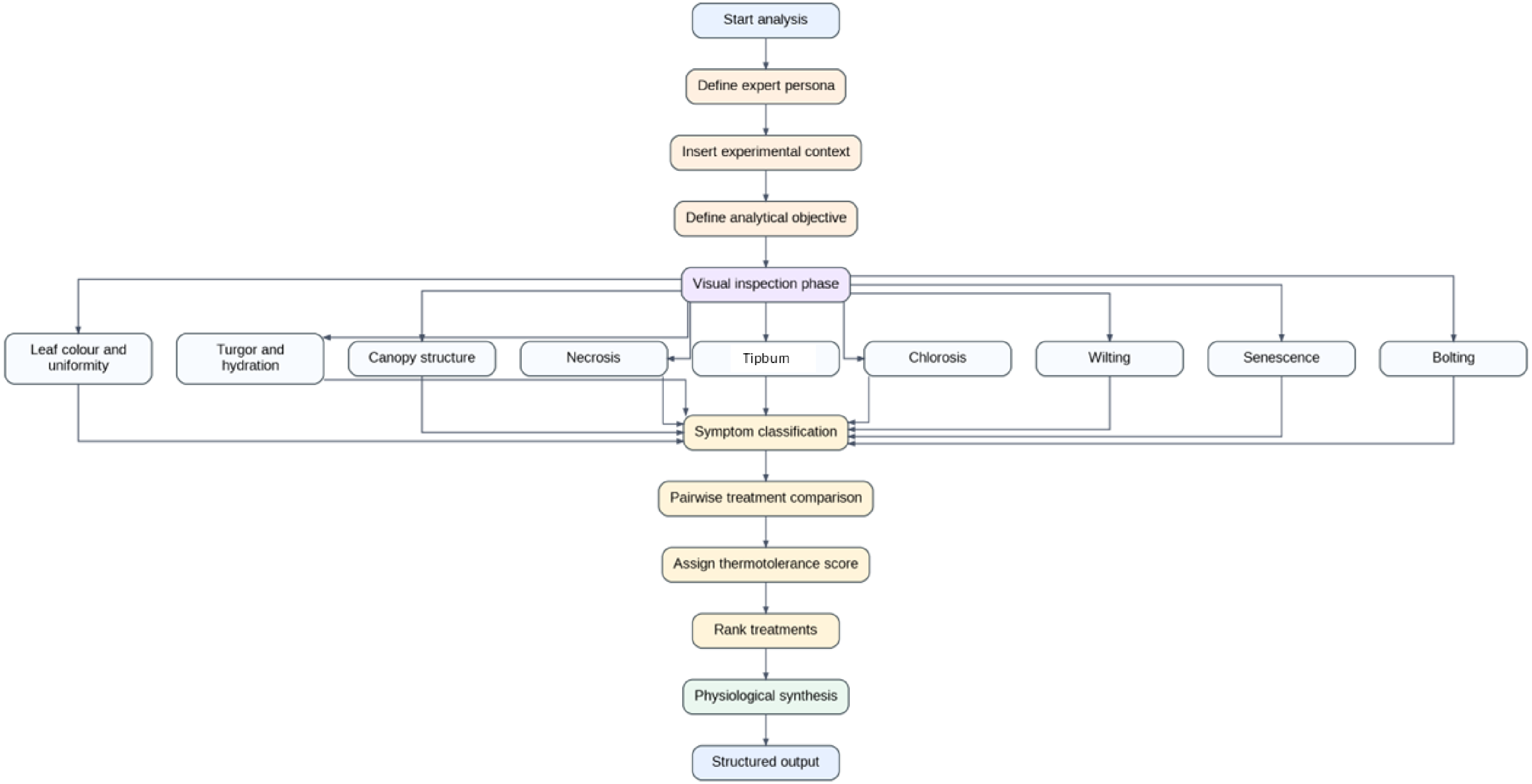
3. How the biofertilizer treatment may have mitigated stress (e.g., via osmotic adjustment, microbial-induced hormonal balance, or antioxidant enhancement);
4. Whether the observed pattern supports the hypothesis that biofertilizers improve lettuce thermotolerance and reduce the incidence of physiological disorders under high temperatures.

How to Use

Enter the prompt for each step of the process, one at a time. When asked by AI, enter the necessary information, as well as the photos to be analyzed as attachments. Wait for the AI to analyze and generate the final report. Initial tests were performed on ChatGPT5, Plus version.

Figure 4

Summary of Prompt Engineering and Prompt Chaining techniques



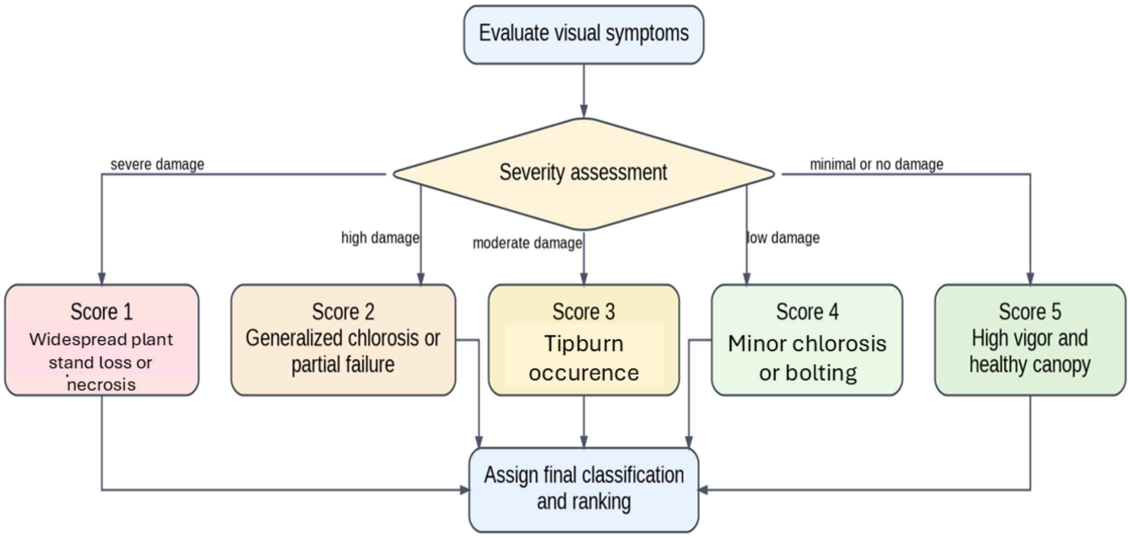
Source: The authors supported by AI tools

Symptom Classification and Scoring System

To obtain a numerical rating of heat tolerance in lettuce, a scale ranging from 1 to 5 was used, as follows: 1 – Severe damage (widespread loss of plant stand and leaf necrosis); 2 – High damage (widespread chlorosis); 3 - Moderate damage (localized necrosis at the leaf margins, characteristic of tipburn); 4 - Minor damage (less pronounced chlorosis and/or slight early wilting); and 5 - No apparent visual damage. Treatments with mineral and organic fertilizers were ranked based on an effective comparison using photos taken from the experiment during the study by Lima *et al.* (2024). Figure 5 graphically illustrates the decision-making process.

Figure 5

Decision-making process for ranking the visual classification of lettuce photos treated with mineral and organic fertilizers under high temperatures.



Source: The authors supported by AI tools

Results Validation

The results were validated through a qualitative comparison of the results obtained using PBFCIA - thermal lettuce with the experimental results reported by Lima *et al.* (2024), since the photos used in this study were taken at the end of the production cycle of that experiment. The images used for analysis by PBFCIA - thermal lettuce were those shown in Figure 6. Figure 7, in turn, provides a graphical overview of the validation process.

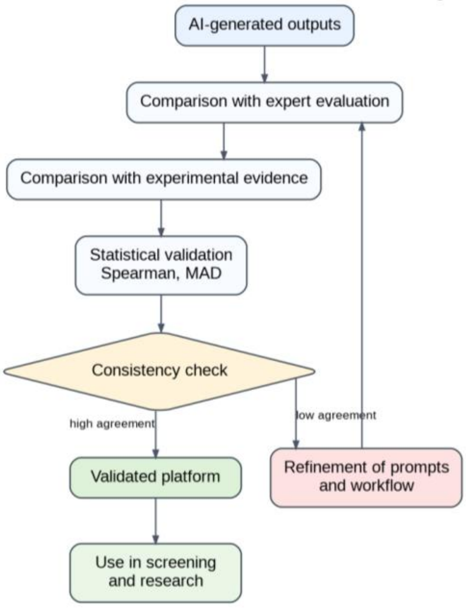
Figure 6

Photos used for development and validation of PBFCIA - thermal lettuce

Source: Lima *et al.* (2024)

Figure 7

Summary of the workflow used for the validation of the PBFCIA - thermal lettuce



Source: The authors supported by AI tools

RESULTS AND DISCUSSION

Results of Applying for the PBFCIA - Thermal Lettuce Model Supported by ChatGPT 5 (v.1.0.0)

Note: The text below, enclosed with quotation marks and in italics, refers primarily to the exact output generated by the AI when prompt engineering was applied.

"*Visual comparative analysis under high temperature stress*

General overview

Across all pairs of lettuce (Lactuca sativa) subjected to high-temperature stress, clear morphological and physiological contrasts were observed between plants treated with ***biofertilizer (left)*** *and those treated with* ***mineral fertilizer (right)****.*

The main differentiating factors involved ***leaf coloration, tissue hydration, canopy uniformity, and the incidence of physiological disorders*** *such as edge burn, necrosis, chlorosis, and dehydration.*

Pair 33 × 64

- ***Biofertilizer (33):*** *Leaves remain greener and broader, with mild marginal chlorosis and limited necrosis restricted to older leaves. Turgidity is partially preserved, suggesting effective osmotic regulation.*
- ***Disorders:*** *slight tipburn and light chlorosis at leaf margins.*
- ***Mineral (64):*** *Noticeable yellowing and marginal necrosis, indicative of calcium deficiency and thermal desiccation. Outer leaves show dehydration and loss of texture.*
- ***Disorders:*** *leaf edge burn, necrosis, wilting.*
- ***Result:*** *Biofertilizer demonstrates* ***higher thermotolerance****.*

Pair 29 × 63

- ***Biofertilizer (29):*** *Pronounced dehydration and basal leaf collapse; canopy partially necrotic but with residual green leaves. Severe heat stress symptoms visible.*
- ***Disorders:*** *necrosis, wilting, senescence.*
- ***Mineral (63):*** *Taller plant with moderate dehydration and basal necrosis, but apical leaves remain turgid and photosynthetically active.*
- ***Disorders:*** *bolting, chlorosis, tipburn.*

- ***Result:*** *Slight advantage for* **mineral treatment**, *possibly due to transient osmotic adjustment.*

Pair 1 × 35

- ***Biofertilizer (1):*** *Vigorous growth, dense and turgid canopy with deep green leaves. No visible necrosis or chlorosis. Excellent maintenance of leaf expansion.*
- ***Disorders:*** *none significant.*
- ***Mineral (35):***
- *Slight chlorosis on outer leaves and minor tipburn, but overall good development.*
- ***Disorders:*** *Tipburn, localized chlorosis.*
- ***Result: Biofertilizer treatment*** *exhibits* ***superior physiological stability*** *under heat.*

Pair 22 × 55

- ***Biofertilizer (22):*** *Healthy canopy with moderate tipburn and slight interveinal chlorosis; overall hydration preserved.*
- ***Disorders:*** *tipburn, light chlorosis.*
- ***Mineral (55):*** *Advanced chlorosis and necrotic patches across leaves; loss of turgidity and leaf curling visible.*
- ***Disorders:*** *necrosis, wilting, chlorosis.*
- ***Result: Biofertilizer*** *maintains better chlorophyll stability and hydration.*

Pair 26 × 58

- ***Biofertilizer (26):*** *Compact plant, moderate chlorosis but high leaf turgor; absence of necrosis in central leaves.*
- ***Disorders:*** *chlorosis (mild), tipburn (localized).*
- ***Mineral (58):*** *Severe necrosis and dehydration, strong bolting response, marked tissue senescence.*
- ***Disorders:*** *necrosis, wilting, bolting.*
- ***Result:*** *Clear advantage for* ***biofertilizer*** *in mitigating heat damage.*

Pair 20 × 54

- ***Biofertilizer (20):*** *Noticeable dehydration and some necrosis but better canopy preservation compared to mineral; turgor partly maintained.*
- ***Disorders:*** *necrosis, wilting.*
- ***Mineral (54):*** *Advanced dehydration, elongated stems (bolting), high tissue necrosis.*
- ***Disorders:*** *bolting, necrosis, chlorosis.*

- ***Result: Biofertilizer** performs better overall, showing less senescence.*

Table 1

Integrated physiological ranking (heat stress tolerance)

Rank	***Pair***	***Better Treatment***	***Main Disorders Observed***	***Performance Level***
1	*1 × 35*	***Biofertilizer***	*None / slight edge burn (mineral only)*	*Excellent*
2	*26 × 58*	***Biofertilizer***	*Mild chlorosis vs. severe necrosis*	*Very good*
3	*22 × 55*	***Biofertilizer***	*Tipburn vs. generalized chlorosis/necrosis*	*Good*
4	*33 × 64*	***Biofertilizer***	*Marginal tipburn vs. dehydration*	*Good*
5	*20 × 54*	***Biofertilizer***	*Moderate necrosis vs. advanced bolting*	*Moderate*
6	*29 × 63*	***Mineral***	*Severe necrosis (biofert.) vs. moderate bolting*	*Moderate*

Source: The authors supported by AI tools

Overall Ranking (Best to Worst Thermotolerance)

1. ***Biofertilizer (pairs 1, 26, 22, 33, 20)***
2. ***Mineral (pair 29 only shows advantage)***

Physiological interpretation

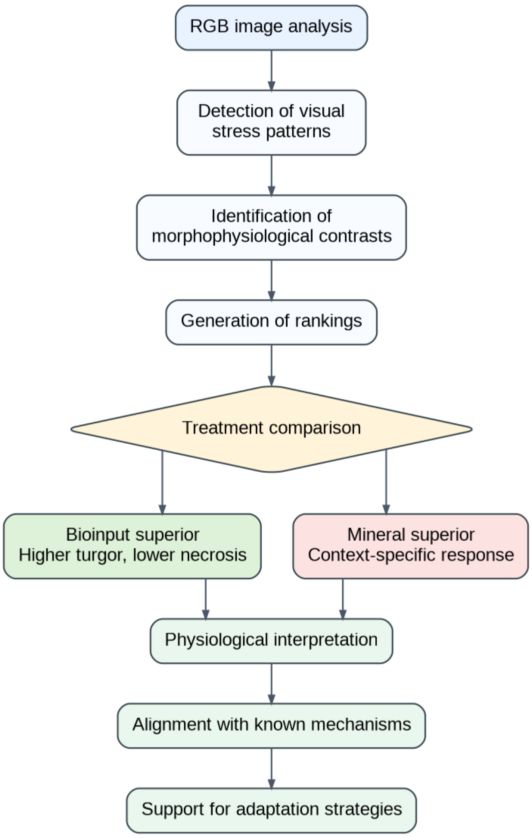
*The biofertilizer-treated plants consistently displayed **greater leaf turgor, deeper green coloration, and reduced necrotic or desiccated tissue**, indicating **enhanced thermotolerance** and more efficient **osmotic and antioxidant regulation** under high temperature.*

*In contrast, mineral-fertilized plants exhibited **greater calcium-related edge burn, accelerated bolting, and widespread necrosis**, consistent with **oxidative stress and nutrient imbalance** under heat.*

*These results strongly support the hypothesis that **biofertilizers confer superior heat resilience in lettuce**, primarily by improving root–shoot signaling and maintaining physiological homeostasis under stress".* Figure 8 provides a graphical summary of the results obtained.

Figure 8

Flowchart illustrating the process of obtaining and applying results using the PBFCIA method - thermal lettuce.



Source: The authors supported by AI tools

Validation and Discussions

Lima *et al.* (2025a) shows a significant increase in Tmed and Tmax projected for Brazil through 2100, which could, if no adaptation measures are taken, make lettuce cultivation unviable in most areas and regions of the country. These results are consistent with those found by Pereira *et al.* (2024), who, by evaluating the stability of different lettuce cultivars in terms of heat tolerance in various environments—such as open fields and greenhouses—during different seasons of the year, showed that low heat tolerance is the primary abiotic stress this crop will face as a result of global warming. They further argue that situations involving higher temperatures are likely to become common in the future, causing significant socioeconomic damage, and reinforce the notion of lettuce crops' vulnerability to heat and the need to adopt adaptation strategies such as plant breeding. The adoption of digital tools such as climate intelligence platforms—like as the one discussed here—is cited as an effective means of adaptation and one of the priorities for the sectoral Climate Plans for Agriculture and Livestock and for Family Farming (Brazil, 2025a and Brazil, 2025b), and is therefore in line with the state of the art in Brazilian public policy.

The potential for reducing abiotic stress using bio-inputs stems from the presence of plant growth-promoting microorganisms (PGPMs). This group of microorganisms, also known as efficient microorganisms, can produce compounds capable of modulating processes that aid in the growth of cultivated plants. An example of these compounds are auxins (IAA), which can activate root growth and increase apical dominance and plant growth, as well as control gravitropism and phototropism (Alatzas, 2013; Santos *et al.*, 2020; Bomfim *et al.*, 2024). Biofertilizers based on arbuscular mycorrhizal fungi (AMF), for example, have been reported to mitigate the adverse effects of high temperatures on soybeans by facilitating nutrient uptake, optimizing photosynthesis, increasing osmotic adaptation, improving antioxidant function, and maintaining superior reproductive capacity (Fontenelle *et al.*, 2025b).

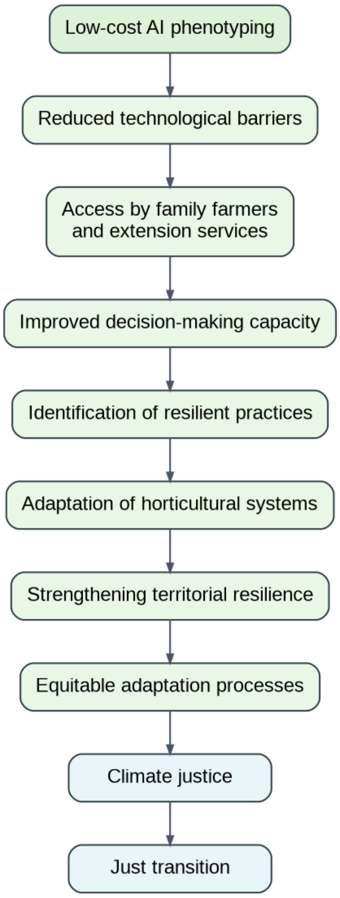
Additional formulations containing endophytic microorganisms also show promise for mitigating abiotic stresses and environmental extremes projected in GCC scenarios (Tang *et al.*, 2022). Symbiosis with AMF and the regulation of hormones such as abscisic acid, auxins, gibberellins, jasmonates, and strigolactones can regulate root growth and stomatal closure in over 80% of terrestrial plants. There are also the effects of plant growth-promoting rhizobacteria (PGPR) on colonization and symbiosis, hormonal status, phytochemical release, antioxidant efficacy, ionic homeostasis, water balance, gene expression, biocontrol, and bioremediation—areas currently identified as promising fields in biotechnology for enhancing climate adaptation and resilience (Tang *et al.*, 2022). Studies have also shown that consortia based on AMF and other PGPR in biodiverse agricultural production systems improve land-use efficiency, contributing to the sustainable development of agriculture under conditions of water and mineral scarcity (Pérez-Bernal *et al.*, 2025).

With regard to the validation of the application of the tool under discussion, Fontenelle *et al.* (2025a), through experimental tests using bio-inputs, conventional statistics, and mean and visual ranking, validated the use of the generative AI models ChatGPT (Spearman’s correlation coeficiente -ρ - = 0.90 and Mean Absolute Deviation – MAD) = 1.17) and Gemini ($\rho = 0.86$ and MAD = 1.50) for use as a low-cost phenotyping platform for lettuce seedlings. The thresholds established by the authors were $\rho \geq 0.85$ and MAD ≤ 1.50, demonstrating the superior performance of ChatGPT, which was therefore selected for use in this study. AI Copilot, however, performed below expectations (ρ = 0.42 and MAD = 3.71) and is not, in principle, validated for such visual analysis. The results obtained in this study are also consistent, but more detailed, of those came from the experiment conducted by Lima *et al.* (2024), from which the photos used in this study were sourced. These authors found, upon analyzing lettuce growth under simulated temperature conditions in worst-case scenarios of GCC, that most of the 11 cultivars evaluated exhibited low levels of marketable yield, as evidenced by the occurrence of tipburn, chlorosis, necrosis, bolting and stand loss. Furthermore, they found that the Hortbio® biofertilizer could mitigate the negative effects of high temperatures. Fontenelle *et al.* (2025b), based on a comprehensive literature review conducted using the PRISMA method, clearly demonstrated that the use of regenerative systems and nature-based solutions—such as the use of bio-inputs—are effective strategies for adapting agricultural crops to climate change.

Since this study is primarily applicable to family farming (the group most vulnerable to climate change) and follows the FAIR principles of open science, it is linked to the frameworks of climate justice and just transition, as cited by Fontenelle *et al.* (2025a; 2025b) and summarized graphically in Figure 9.

Figure 9

A brief overview of the relationship between this study and the IPCC frameworks on climate justice and a just transition.

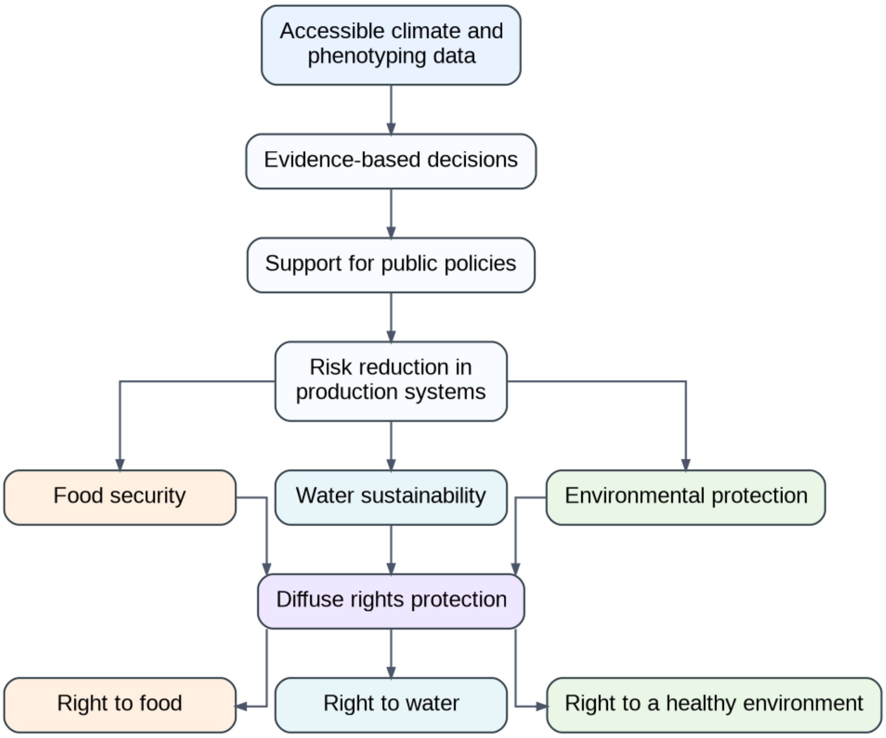


Source: The authors supported by AI tools

This study also aligns with the 2030 Agenda and with its SDGs 2 and 13, as well as with diffuse rights, particularly the right to an equilibrated environment, as enshrined in Article 225 of the Brazilian Constitution and subsequent laws. This point is also described graphically and summarized in Figure 10.

Figure 10

A brief overview of the relationship between this study and the diffuse rights.



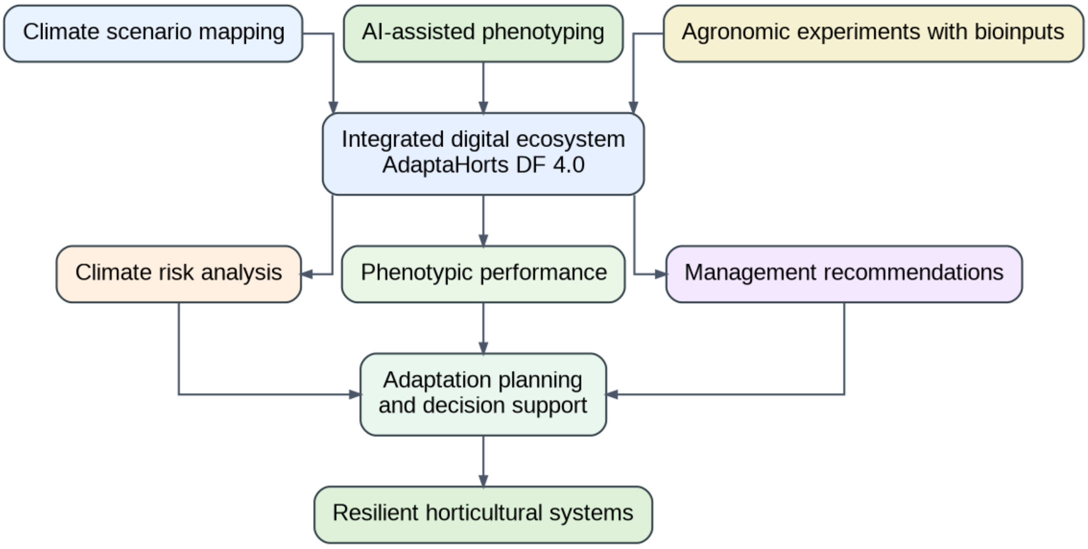
Source: The authors supported by AI tools

Conclusions and Perspectives

PFBCIA - Thermal letucce, in its initial version, has the potential to serve as a reusable methodological infrastructure capable of integrating low-cost phenotyping platforms supported by generative AI and climate indices into a single workflow accessible to different teams and activities. Figure 11 highlights that this platform can be integrated with other activities and projects, such as AdaptaHorts DF 4.0. Furthermore, it can be converted into Python scripts that serve as the engine and foundation for incorporating new crop types, stress conditions, and regions. More advanced versions are expected to be developed in the coming years, along with the establishment of a digital ecosystem to help family farms adapt to climate change, promoting climate justice and a just transition.

Figure 11

Prospects for integrating the PFBCIA - Thermal Lettuce project with other climate change research currently being conducted by the team with AI tools. One example for the AdaptaHorts DF 4.0 Climate Intelligence Platform.



Source: The authors supported by AI tools

Statement on the Use of Artificial Intelligence (AI) Tools

The authors report that AI tools were used to assist with writing and translation, methodology development and application, and the creation of figures.

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