

Review Article

The Vulnerability and Resilience of *Phaseolus vulgaris* L. in a Changing Climate with respect to its Physiological, Nutritional, and Genomic Research

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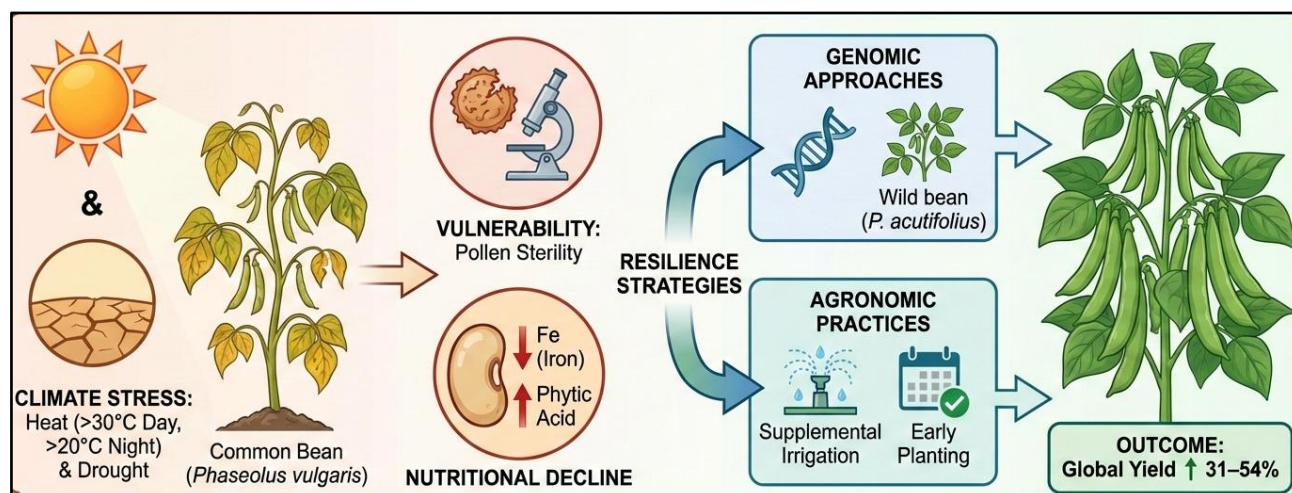
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Abstract- The current paper focuses on the vulnerability of the common bean (*Phaseolus vulgaris* L.) to climate change, summarizing its high sensitivity to temperatures beyond 30°C during the day and 20°C at night which negatively affects the basic physiological process resulting into photosynthesis failure, reproductive damage and flower abortion. Furthermore, combined heat and drought stress have been projected to cause reduction in the bean's nutritional quality, specifically by lowering iron content and increasing anti-nutritional contents like phytic acid by 2050. The paper highlights critical strategies for resilience, including the use of genomic approaches to produce the varieties with traits from wild relatives like the tepary bean (*P. acutifolius*) to improve pollen viability, along with agronomic practices like supplemental irrigation, early planting, and leveraging the bean's ability to enhance nitrogen fixation under elevated CO₂ to increase global yields by a potential by 31 to 54 %.

Keywords- *Phaseolus vulgaris*, Climate Change, Thermal Stress, Pollen Sterility, Genomic Resilience, Nutritional Security

Graphical Abstract



The common bean (*Phaseolus vulgaris* L.) is highly affected by climate change, with its reproduction severely compromised by temperature stress exceeding day and night critical temperature, leading to flower abortion and yield loss. Furthermore, combined heat and drought stress are projected to cause a nutritional decline by 2050, specifically by reducing essential iron content while increasing anti-nutritional phytic acid. To build resilience, the critical strategies involve integrating genomic approaches, such as introgressing heat-tolerant traits from wild relatives like the tepary bean (*P. acutifolius*), with agronomic practices like supplemental irrigation and early

planting. These adaptation measures are projected to secure and potentially increase global common bean yields by 31% to 54%.

1. Introduction

The common bean, scientifically identified as *Phaseolus vulgaris* L., represents one of the most cultivated legume crops for global food security and nutritional stability [1]. However, the existing system of production systems faces severe

limitations, because of abiotic and biotic stress resulting in reducing the yields in low-income countries to often less than 600 kg ha⁻¹ [1]. These prominent reductions in current yields resulted into Chronic food insecurity across countries which are heavily dependent on this legume crop [1]. The increasing global population made a compulsion to rapid increase in yields, placing significant pressure on agriculture, which is challenged by threat of climate change [1]. Although the common bean is suited for increasing food security because of its short growing cycle, ranging from two and a half to three months, along with its adaptability to different cropping methodologies, Common beans remain highly sensitive to climate variability due to the constraints in genetic improvement research [2]. Crucially, the common bean is sensitive to high temperatures, becoming one of the crops most vulnerable to the consequences of climate changes across all major agro-ecological production zones [3,4]

The global scientific community has created awareness about the serious consequences of climate change, specifically highlighting the negative impacts it exerts on crop production globally. [5]. Climate change increasing scenarios has universally resulted into alterations in precipitation patterns, along with widespread increases in temperature and increasing attacks of pests and diseases [3]. These changes have resulted into increased frequencies of fluctuation in weather events, which are globally recognized as the most critical challenges to agricultural [6]. In the African continent, data suggests that temperatures are going to rise at rates exceeding the global average throughout the 21st century [6]. Specially in the regions such as northern and central Uganda which are expected to experience annual average temperature increases of 1.5°C to 2°C by 2030 [7]. Because of these higher temperatures increase in the loss of vital soil moisture can be expected, which in turn will create favorable conditions for the rapid growth and development of agricultural pests and pathogens [8]. Consequently, productivity in the common bean is facing severe and interconnected challenges because of moisture stress, increased incidence of diseases, and insect pest attacks [2]. This is because of realization that the threats are in relation with high temperatures moisture loss from soil while simultaneously promoting biotic stress [6].

1.1 Objective of the Study

This study aim to;

1. To detail the vulnerability of *P. vulgaris* by summarizing the physiological and reproductive collapse caused by temprature and drought stress.
2. To analyze the projected nutritional decline by 2050, specifically highlighting the reduction in essential iron and the corresponding increase in anti-nutritional compounds like phytic acid under climate stress conditions.
3. To outline and integrate critical resilience strategies, including the mobilization of genomic traits from wild relatives (e.g., *P. acutifolius*) and effective agronomic practices (e.g., supplemental irrigation and early planting).
4. To review how the effective implementation of these combined strategies can ultimately lead to a substantial

increase in global common bean yields, projected to be between 31% and 54% in future climate scenarios.

1.2 Research Answers

This study aim to answers

1. How sensitive is the common bean (*Phaseolus vulgaris*) to temperature extremes, and what are the specific resulting physiological and yield impacts ?
2. How is the nutritional quality of common beans, specifically iron and anti-nutritional compounds like phytic acid, projected to be affected by combined heat and drought stress under future climate scenarios ?
3. What critical genomic and introgressive breeding strategies are effective in improving the common bean's resilience, particularly for key traits like pollen viability, using wild relatives like the tepary bean (*P. acutifolius*)?

2. Related Work

Previous research has established that heat stress (HS) is a primary cause of reduced productivity in *P. vulgaris*. Studies have identified critical temperature thresholds beyond which yields are detrimentally affected. Genomic research has highlighted the use of wild relatives, such as the tepary bean (*P. acutifolius*), to introgress heat-tolerant traits. Additionally, biochemical studies have explored the role of melatonin and magnesium in mitigating thermal stress effects.

3. Experimental Method

The methodology for this study follows a systematic review approach to evaluate the impact of climate change on *Phaseolus vulgaris* L. The research process is organized into the following stages.

3.1 Search Strategy and Data Sources

A systematic search was conducted across major scientific databases, including Google Scholar, PubMed, Web of Science, and Scopus. The search aimed to cover literature published primarily within the last two decades i.e. 2005–2025 to ensure contemporary relevance.

3.2 Inclusion and Exclusion Criteria

To ensure contemporary relevance and scientific rigor, the literature search was primarily restricted to peer-reviewed articles. Criteria for inclusion included:

- Studies focusing on the physiological and reproductive response of common beans to temprature stress.
- Research detailing the nutritional changes specifically iron and phytic acid under climate-stressed conditions.
- Genomic and agronomic studies involving resilience strategies like wild relative introgression.

3.3 Data Extraction and Synthesis

From the selected literature, data regarding temperature thresholds, pollen viability percentages, and nutritional concentrations such as iron, zinc, protein, and phytic acid were extracted for comparative analysis.

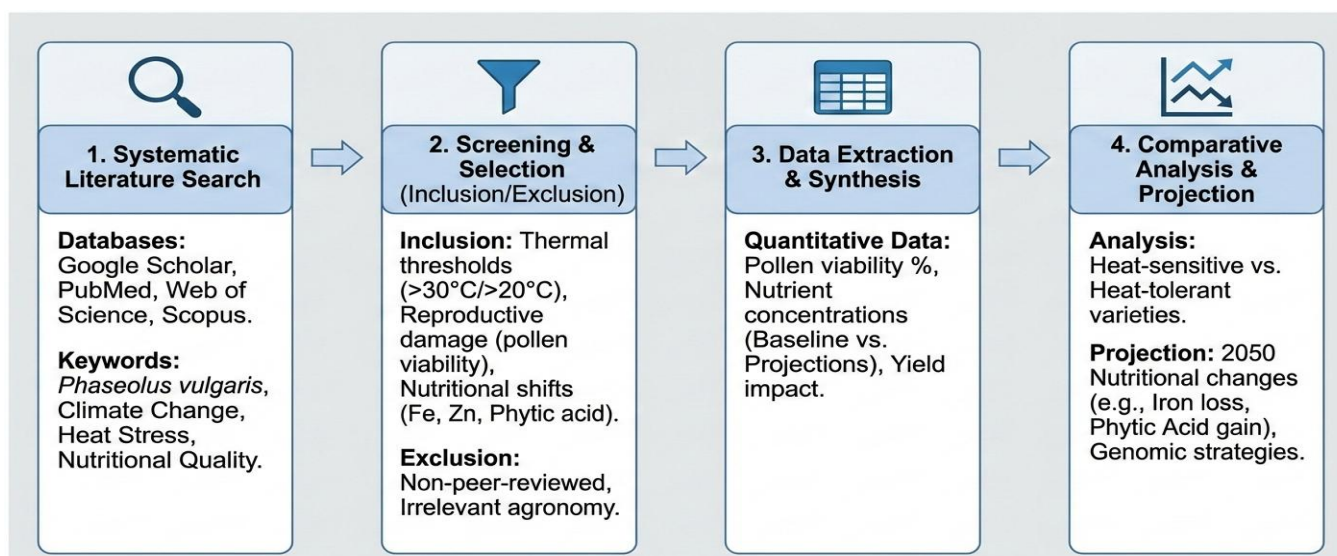


Figure 1: Methodological Workflow of the Systematic Review on the Vulnerability and Resilience of *Phaseolus vulgaris* L. to Climate Change

4. Literature Review

Abiotic stress, particularly heat stress (HS), has proven to be a cause of reduced overall crop productivity in *P. vulgaris* [9]. For the common bean, a specific critical physiological temperature exists, where yields are detrimentally affected when daytime temperatures go beyond 30°C and nighttime temperatures exceed 20°C [4]. The leaf temperature range to ensure healthy plant growth and maximum photosynthetic efficiency falls between 15°C and 30°C under normal atmospheric CO₂ concentrations [2]. High-temperature stress induces a series of harmful effects, which include the abortion or premature abscission of buds, flowers, and immature seeds, which are the direct results into of economic yield loss [4]. Heat stress also has been proven to alter the flowering period and frequently leading to a critical reproductive failure known as asynchrony between the development of the male and female reproductive structures [4]. Furthermore, these increased temperatures stop the essential process such as photo assimilation translocation in leaves and developing seeds, which further on a larger scale limits the process of flowering and seed filling [10]. Adding more increased temperature causes moisture stress which directly results in reduction of stomatal transpiration, which in turn effects the CO₂ diffusion, resulting in decreased photosynthetic efficiency and increased leaf temperature [2]. The results reveal that moisture stress not only stop the plant carbon intake but also reduces cooling of leaves pushing leaf temperatures above the 30°C threshold creating heat-drought stress [2].

Different research papers suggests that the main cause of heat sensitivity in common bean is due to the physiological damage that occurs specifically during the reproductive development of the male structures [11]. In variety of angiosperms, including common bean, the development of the male gametophyte includes the microspores and meiocytes formation, which are highly sensitive and have showed prominent impact because of the thermal stress [4]. This increased temperature decreases the viability of the pollen grain and alter the development of the

pollen tube and its navigation through the female style, ultimately decreasing final yield [11]. Research has also shown that another indehiscence and pollen sterility are among the results observed in plants subjected to heat stress [4].

Research on heat-sensitive Colombian cultivar, Calima, with the novel heat-tolerant breeding line, HTA4, highlighted the severity of this reproductive bottleneck [4]. Under severe heat stress of 31°C day and 24°C night, the heat-sensitive Calima variety showed increased sterility of pollens achieving only 24.9% pollen viability as compared with plant under control condition showed 98.4% viability [4]. Furthermore, the viable pollen produced by Calima failed to successfully attach to the stigma and even germinate under the stress conditions [4]. The HTA4 line, which contains genetic material partially derived from the heat-tolerant tepary bean (*Phaseolus acutifolius* L.) in its pedigree, resulted into increased tolerance, maintaining 71.1% pollen viability under the same stress conditions [3,4]. The mechanism of tolerance in HTA4 was confirmed because of its capacity to develop the functional pollen that sticks successfully to the stigma and forms the functional pollen tubes within the style leading to reproductive success [4]. This observation results into conclusion that male gametophytic is one of the primary physiological barriers [3,4]. Separately, research also suggests that the application of melatonin at a concentration of 100 µM along with magnesium increases the yield and helps in mitigating the effects of heat stress, showing the role of biochemical regulation in heat stress mitigation. [9].

With respect to physiology of leaf, one of the essential defense mechanisms under water stress conditions involves the reduction of photosynthetic carbon metabolism [12]. This closure of photosynthetic pathway is generally linked to the decrease in photochemistry, resulting in lower carbon metabolism over the periods of stress [12]. Increasing drought resistance in *P. vulgaris* must therefore focus more on the process of enhancing the volume of water acquired by the root system, increasing the water use efficiency (WUE), and increasing the mobilization of accumulated carbon reserves

toward the final yield [13]. Certain varieties of common beans, such as Flexo and Giza3, demonstrated superior functioning under heat stress by maintaining higher stomatal conductance and photosynthetic rates [12]. The ability of these particular varieties in controlling their stomata during water stress allowed them to provide crucial physiological stability against thermal stress [12].

Comparative physiological studies have shown two different water use strategies adopted by drought-resistant *Phaseolus* genotypes in response to drought stress [14]. The first strategy utilizes approach which is characterized by the early and gradual closure of stomata [14]. This behavior helps to conserve soil water for the later, essential reproductive phases, such as seed development and pod filling [14]. This strategy resulted in a high Fraction of Transpirable Soil Water (FTSW) threshold of 0.36, which means that stomatal closure is initiated even when soil water is still moderately available [14].

In contrast, the tepary bean (*P. acutifolius*), represented by accession Tep32, used second approach characterized by the prolonged maintenance of stomatal opening [14]. This approach allows the gas exchange for a longer duration, thereby maximizing carbon accumulation which results into increased biomass under stress conditions [14]. The second approach showed a very low FTSW threshold of 0.20, indicating that stomata are only closed when the soil is severely depleted of water, approximately 13 days after the onset of drought condition [14]. This carbon accumulation strategy allows the tepary bean to achieve increased biomass gain under stress when compared to common bean genotypes [14]. Furthermore, the common bean genotype PS showed increased level of phenotypic plasticity, along with reduced stomatal density (SD) and stomatal index (SI) in the middle and basal canopy of leaves under water shortage condition [14]. This water-saving strategy of *P. vulgaris* of reduced stomatal density and conductance has also enhanced host resistance against certain biotic threats, one of them is common bacterial blight [15].

The present increasing concentration of atmospheric carbon dioxide is resulting in to widespread physiological and metabolomic changes across all living organisms, with significant effects on plants [16]. Research on *Phaseolus vulgaris* reported that there is increase in leaf growth due to increased CO₂ level during initial stage of development but later there is subsequently decline as the plant reached maturity [17]. This research suggests that the growth promoting effects of higher CO₂ concentrations primarily restricted to the initial developmental phases of the plant [18]. Research involving increase in CO₂ concentrations by two folds resulted into increased common bean yield with 100% increase in individual pod dry weight and a 10% increase in pod length [19]. However, 9% reduction in the final number of seeds per pod are also seen in the results, indicating a resource allotment conflict or sink limitation [19]. Qualitatively, the soluble sugar content within the beans increased by 41% under elevated CO₂ conditions [19]. The limited overall increase in economic yield and total plant due to higher concentration of CO₂ is specific to age of the plant [19]. The limitation of this research includes that the initial biomass gains due to increased CO₂

Concentration may not necessarily result in an increase in yield security [18].

Predictive models of climate change suggest that crop productivity will decrease due to constraints in the uptake of critical soil resources, specifically water and nitrogen [16]. Increased CO₂ concentrations have been shown to increase the amount of biologically fixed Nitrogen because of the increase in overall plant biomass stimulates greater nitrogen demand [16]. Introducing *Rhizobium leguminosarum* as an inoculant to bean plants cultivated in increased atmosphere CO₂ condition have successfully demonstrated increase in nitrogen fixation along with additional benefit of decreasing the plant's oxidative stress [16]. The natural nodulation process offers better alternative to chemical fertilizers resulting into agricultural practices with greater environmental sustainability [16]. The biological fixation of nitrogen by legumes reduces the use of synthetic fertilizers, which in turn help to reduce use of the fossil fuel consumption associated with their production and application of artificial fertilizers [20]. Apart from nitrogen fixation, legumes also increase the availability of elements like potassium and phosphorus in the soil, thereby reducing the need of chemical fertilizers and decreasing the Green House Gases emissions [20, 21]. The innate ability of legumes to provide natural nitrogen make these crops a resource for both mitigating and adapting to the negative impacts of climate change [20].

Research has shown that higher CO₂ Concentration in environments have resulted in improving the viability and germination capacity of pollen grains [22]. Furthermore, higher CO₂ concentrations generally result in reduction in stomatal frequency, and transpiration rates [22]. However, the experiments in which plants are subjected to Drought and heat stress independent showed opposite morphological response, leading to an increase in stomatal frequency simultaneously reducing the functional stomatal area [22]. The concentrations of atmospheric CO₂ play a very critical role in resources allotment and the trade-offs between carbon assimilation and water conservation [23]. Some outcomes from experiments suggest that higher concentration of CO₂ might actually decrease the drought tolerance capacity, especially when combined with higher temperatures [23].

Studies on Climate change and yields of different crops showed negative impact of climate change on the economic yields of major crops across the entire African continent [6]. The data collected at metrological field sites, especially with respect to drought conditions predicted by 2050, showed a prominent reduction in the yields of various common bean varieties [24]. Furthermore, it has been shown that not only economic yield but also the nutritional quality has decreased to a large extent because of complex climatic conditions. [24].

Results of the experiments showed that under drought conditions due to climate change, the nutritional quality of beans are likely to decrease to a noticeable amount by the 2050 [24]. Specifically, the micronutrient iron was significantly reduced in common bean grains when they are subjected to drought stress conditions [24]. The average concentration of

iron has decreased from 59 ppm to 54 ppm in plants cultivated under drought stress plants [24]. However, the concentrations of total protein and zinc along with the anti-nutritional compounds such as phytic acid and lead has been increased significantly under the same drought stress [24]. The average concentration of zinc is found to be increased from 35 ppm to 39 ppm under drought stress, [24]. Total protein concentration also increased from an average of 326 mg/g to 371 mg/g of dry weight in stressed plants [24]. One of the most important results regarding effect of drought stress on nutritional quality of common beans show that phytic acid, an anti-nutritional compound that actively binds to minerals like iron and zinc, also increased significantly, rising from an average of 0.96% under rainfed conditions to 1.16% under drought stress [24]. This showed that the increase in protein and zinc is effectively counterbalanced by the subsequent loss of iron and the increase in the presence of phytic acid, leading to a net reduction in overall nutritional quality [24]. In spite of the challenges, certain varieties like NUA 59 and NUA 674 showed a promising effect with respect to maintaining the economical yield of beans in the intense drought stress predicted for southeastern Africa post-2050 [24].

In order to attain sustainable economic yield in future the need based genetic improvement in *P. vulgaris* has to be done [1]. Successful incorporation of stress resistant genes can be achieved by using related species such as *P. coccineus*, *P. costaricensis*, *P. dumosus*, and particularly *P. acutifolius* [1]. The development of the heat-tolerant HTA4 line assured that the feasibility of such common bean species [25]. Modern genomic tools, including Next Generation sequencing along with advanced analytical tools like GIS-based modeling and machine learning, are essential in accurately identifying and targeting genetic reservoirs with respect to abiotic stress tolerance [25].

Future directives in plant breeding programs should integrate climate change along with various pathogens and agricultural resistance [26]. Climate change will result not only results in fluctuations in atmospheric concentration of carbon dioxide, temperature, and humidity but also in the physiology, behavior, geographical range, and fecundity of the various vectors, such as whiteflies and aphids along with various pathogens and agricultural pests [26]. The increased temperature has the potential to facilitate the movement and spread of viruses within the host plant by enhancing the activity of myosin motors [27]. Furthermore, the long-term impact of climate change also showed harmful effects *in situ* genetic resources of wild *Phaseolus* species, putting both the wild plant populations and their essential Apidae pollinators in risk of extinction [28;29]. Further reduced pollinator fitness because of changing environmental dynamics will lead to increased extinction risk for wild germplasm [29]. Certain environmental conditions often temperature stress along with water scarcity stress can decrease the severity of diseases like common bacterial blight [15]. This localized disease reduction mechanism is thought to operate via the shifting the mobilization of host resources toward resistance along with existing drought-tolerant mechanisms such as reduced stomatal density and conductance [15]. Predictive modeling has shown that high temperatures in

late winter seasons and the pre-sowing period, combined with low spring precipitations, serve as ideal condition for *begomovirus* incidence in beans [30]. Therefore, it is essential for Integrating climatic changes into early warning systems for improving crop management decisions and mitigating the virus impact [30].

Certain Agronomic practices such as crop rotation and intercropping methods with incorporating legumes are highly effective in enhancing nitrogen availability, improving soil quality, and boosting overall crop yields [20]. The innate ability of legumes for Nitrogen fixation is regarded as one of the climate change mitigation and adaptation strategies, for more environmentally friendly and sustainable land-use models [20]. Apart from their capacity for nitrogen fixation, legumes also increase the bioavailability of potassium and phosphorus in the soil [20]. Thus, reduction in the requirement for synthetic chemical fertilizer can be seen along with the additional benefit in reductions in associated greenhouse gas (GHG) emissions [21]. With respect to direct economical yield specific management practices offer immediate, substantial benefits: when combined with supplemental irrigation and early sowing [31]. The combined method showed an increase in grain yield by 89% during the baseline period, and crucially, maintain high increases of 71% and 56% during the projected 2030s and 2050s climate scenarios, respectively [31]. Further With more than 50% of repetitive sequences, legumes are enriched with resources available for genome modification can also be consider an option for increasing the resistance towards climate change [32]. Also, use of sustainable agricultural management systems could be best in identification of production risks as well as in the planning of activities to mitigate those risks [33]. The implementation of a higher number of adaptation strategies has demonstrates a stronger positive effect on productivity, showing that these strategies are optimal when utilized [6].

4. Results and Discussion

The review of current literature establishes that *Phaseolus vulgaris* exhibits a distinct physiological bottleneck under thermal stress. The critical threshold for yield loss is identified when daytime temperatures exceed 30°C and nighttime temperatures surpass 20°C. Under these conditions, the primary driver of yield decline is reproductive failure, specifically within the male gametophyte. Comparative analysis reveals that heat-sensitive varieties, such as 'Calima', suffer a drastic reduction in pollen viability—dropping from 98.4% under control conditions to just 24.9% under heat stress (31°C Day/24°C night). In contrast, breeding lines like HTA4, which possess introgressed genetics from *P. acutifolius*, demonstrate superior resilience, maintaining 71.1% pollen viability under identical stress parameters. This suggests that reproductive asynchrony and pollen sterility are the dominant physiological barriers to climate adaptation in common beans. Furthermore, it noted that climate stress significantly alters the nutritional profile of the grain, posing a risk to nutritional security. Projections for 2050 indicate that drought stress will induce a "nutritional collapse" in iron content. Data indicates that average iron concentrations in beans grown under drought stress decrease from 59 ppm to 54 ppm. Conversely, the

concentration of phytic acid—an anti-nutritional compound that inhibits mineral absorption—rises significantly from 0.96% in rainfed conditions to 1.16% under drought. Although total protein content (increasing from 326 mg/g to 371 mg/g) and zinc (increasing from 35 ppm to 39 ppm) show upward trends under stress, the bioavailability of these nutrients is likely compromised by the concurrent rise in phytic acid. The review also establish impact of rising atmospheric CO₂. Elevated CO₂ has been shown to enhance initial vegetative growth and nitrogen fixation by stimulating greater biomass and nitrogen demand. Physiologically, higher CO₂ concentrations improve pollen germination capacity and reduce stomatal transpiration rates, potentially mitigating some water stress. However, this "fertilization effect" is often limited by sink capacity; while pod dry weight may increase by up to 100%, the number of seeds per pod often declines by approximately 9%, indicating a resource allocation conflict. For mitigating the effects of climate change and temperature stress, the integration of genomic and agronomic strategies offers a viable pathway to restoring productivity. Agronomic modeling suggests that combining supplemental irrigation with early sowing dates is highly effective. These practices have demonstrated the potential to increase grain yield by 89% relative to baseline productivity and are projected to maintain yield increases of 56% to 71% even under the severe climate scenarios predicted for the 2030s and 2050s. Furthermore, the mobilization of wild genetic resources, particularly from the tepary bean (*P. acutifolius*), serves as a critical reservoir for heat-tolerant traits.

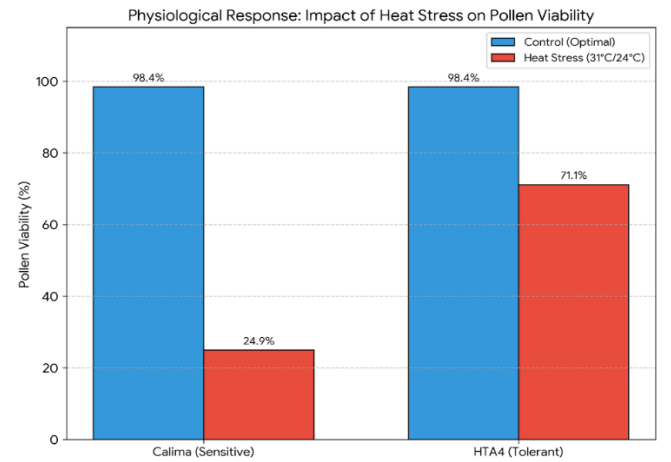


Figure 2. Comparative physiological response of *Phaseolus vulgaris* (Calima) and heat-tolerant line (HTA4) showing the impact of thermal stress on pollen viability percentages compared to control conditions.

Table 1. Pollen viability of *Phaseolus vulgaris* varieties under control and thermal stress.

Sr. No	Variety	Control Pollen Viability (%)	Stress Pollen Viability (%)
1	Calima (Heat-Sensitive)	98.40%	24.90%
2	HTA4 (Heat-Tolerant Line)	98.40%	71.10%

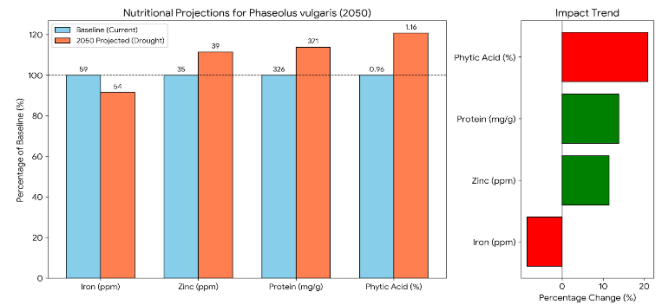


Figure 3. Comparative Analysis of Nutritional Components in *Phaseolus vulgaris* L.: Baseline vs. 2050 Drought Projections.

Sr. No	Nutritional Component	Baseline (Rainfed)	2050 Projected (Drought)	Percentage Change	Nutritional Impact
1	Iron (Fe)	59 ppm	54 ppm	-8.50%	Negative
2	Zinc (Zn)	35 ppm	39 ppm	11.40%	Positive
3	Total Protein	326 mg/g	371 mg/g	13.80%	Positive
4	Phytic Acid	0.96%	1.16%	20.80%	Negatives

Table 2. Nutritional Projections for *Phaseolus vulgaris* L. by 2050 under Climate Stress Scenarios.

5. Conclusion and Future Scope

The comprehensive review of *Phaseolus vulgaris* L. confirms that the species is critically vulnerable to the converging threats of global warming, particularly thermal stress exceeding 30°C and moisture deficits. The evidence points to pollen sterility as the primary physiological mechanism driving yield collapse, while concurrent drought stress threatens to exacerbate "hidden hunger" by reducing essential iron content and increasing anti-nutritional phytic acid levels. Despite these challenges, the species possesses significant adaptive potential. The integration of improved agronomic practices, such as adjusted sowing windows and supplemental irrigation, alongside the genetic introgression of heat-tolerant traits from wild relatives, is projected to secure and potentially increase global yields by 31% to 54%. The innate capacity of legumes to enhance nitrogen fixation under elevated CO₂ further positions them as a sustainable tool for low-input agriculture in a high-carbon future.

Future research scope must prioritize the "genetic modernization" of the common bean through the aggressive use of wild relatives like *Phaseolus acutifolius* and *P. coccineus* to break the current reproductive barriers found in commercial cultivars. Breeding programs must move beyond single-trait selection and utilize GIS-based modeling and next-generation sequencing to develop varieties that are resilient to the compound stresses of heat, drought, and expanding pest ranges. Additionally, future studies should focus on optimizing symbiotic nitrogen fixation efficiency under fluctuating climate conditions to reduce reliance on synthetic fertilizers, thereby aligning food security goals with global climate change mitigation efforts.

Data Availability

Access to the data generated and analyzed during this study is open-source, however proper credit should be given to authors.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the research, authorship, or publication of this article.

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Authors' Contributions

Taufiq Shaikh researched the literature, conceived the study, conducted the systematic search across scientific databases, and wrote the first draft of the manuscript. Nitin Labhane supervised the study, was involved in the critical analysis of genomic and agronomic resilience strategies, and reviewed and edited the manuscript. All authors reviewed and approved the final version of the manuscript.

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