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Adaptive and compensatory mechanisms of Imazamox-tolerant sorghum (*Sorghum bicolor* L.) under combined herbicide and climatic stress

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Abstract

Herbicide-tolerant crops are often regarded as physiologically stable under chemical stress; however, tolerance does not necessarily preclude the activation of adaptive and compensatory mechanisms. The present study aimed to assess the adaptive responses of imazamox-tolerant sorghum (*Sorghum bicolor* L.) to increasing doses of the herbicide Pulsar 40 (imazamox) by analyzing growth dynamics and key structural elements of productivity. A three-year field experiment was conducted under rainfed conditions in South Central Bulgaria during 2023–2025. Plant height, panicle length, grain mass per panicle, and vegetative biomass were evaluated to identify compensatory responses under herbicide stress. The results revealed that moderate herbicide doses induced temporary growth suppression followed by partial compensatory enhancement of reproductive structures, while excessive doses led to incomplete compensation and reduced productivity. Interannual variability, supported by monthly temperature and rainfall records for April–September, highlighted the role of climatic conditions in modulating adaptive responses. The findings demonstrate that imazamox-tolerant sorghum exhibits dose-dependent adaptive and compensatory mechanisms, emphasizing the importance of optimal herbicide management to support crop resilience and yield stability.

Keywords: Sorghum; Herbicide Stress; Adaptation; Compensatory Growth; Productivity Elements; Rainfed Conditions

1. Introduction

Plant adaptation to abiotic stress is a complex and dynamic process involving morphological, physiological and developmental adjustments that enable survival and reproduction under suboptimal conditions [1]. In modern agricultural systems, herbicide application represents a controlled but significant stress factor, even in crops classified as herbicide-tolerant [2]. While tolerance allows crop survival, it does not necessarily eliminate sublethal effects that may alter growth patterns, resource allocation, and productivity.

Sorghum (*Sorghum bicolor* L.) is recognized as one of the most stress-resilient cereal crops, characterized by high ecological plasticity and the ability to compensate for adverse conditions through flexible biomass allocation and reproductive adjustment [3,4]. These properties make sorghum particularly suitable for rainfed systems exposed to strong interannual climatic variability.

The introduction of imazamox-tolerant sorghum hybrids has expanded post-emergence weed control options. However, ALS-inhibiting herbicides, including imazamox, may still induce physiological and morphological stress when applied at elevated doses, particularly when chemical stress co-occurs with drought and high temperatures [5]. Such stress may affect vegetative growth, panicle architecture, grain filling, and the balance between vegetative and reproductive development.

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Compensatory mechanisms in crops may include temporary growth inhibition, recovery of reproductive traits, redistribution of assimilates, and prioritization of grain formation [6]. These mechanisms are especially relevant under rainfed conditions, where chemical stress interacts with climatic constraints and may either enhance or limit crop recovery [7]. Despite their agronomic importance, adaptive and compensatory responses of herbicide-tolerant sorghum under combined chemical and climatic stress remain insufficiently documented.

The objective of this study was to evaluate adaptive and compensatory mechanisms of imazamox-tolerant sorghum in response to increasing herbicide doses by analyzing growth and productivity-related morphological traits over three consecutive growing seasons, while explicitly accounting for the contrasting temperature and rainfall regimes during the vegetation period.

2. Materials and Methods

2.1. Experimental site, climatic background and growing seasons

The study was conducted during the 2023–2025 growing seasons at the experimental field of the Agricultural University of Plovdiv, South Central Bulgaria. The experiments were carried out under rainfed conditions on alluvial-meadow soil.

To support interpretation of crop responses, monthly mean temperatures, maximum temperatures and rainfall sums were summarized for the vegetation period (April–September) and compared with the long-term reference values (1981–2010) (Table 1). The three years differed in both thermal regime and precipitation distribution, creating contrasting stress environments for sorghum growth and compensation potential, particularly during early vegetative development (May–June) and reproductive stages (July–August).

Table 1 Monthly climatic conditions during the sorghum vegetation period in the Plovdiv region (April–September) and long-term reference (1981–2010)

Month	Mean T (°C) 1981–2010	Mean T (°C) 2023	Max T (°C) 2023	Rain (mm/m²) 1981–2010	Rain (mm/m²) 2023
IV	12.2	12.3	25.0	39	58.0
V	17.2	16.3	27.4	320	65.1
VI	20.9	22.0	32.6	36	79.0
VII	25.0	27.2	40.9	5	25.0
VIII	25.0	26.3	37.9	5	31.0
IX	18.3	21.7	34.7	65	19.0
Month	**Mean T (°C) 1981–2010**	**Mean T (°C) 2024**	**Max T (°C) 2024**	**Rain (mm/m²) 1981–2010**	**Rain (mm/m²) 2024**
IV	12.2	16.2	31.2	39	32.0
V	17.2	16.9	29.5	320	83.0
VI	20.9	26.3	37.3	36	2.0
VII	25.0	27.6	39.2	5	24.0
VIII	25.0	26.8	37.7	5	12.0
IX	18.3	21.1	35.2	65	17.0
Month	**Mean T (°C) 1981–2010**	**Mean T (°C) 2025**	**Max T (°C) 2025**	**Rain (mm/m²) 1981–2010**	**Rain (mm/m²) 2025**
IV	12.2	12.0	17.8	39	55.9
V	17.2	17.1	22.5	320	113.2
VI	20.9	24.5	31.4	36	10.9

VII	25.0	27.5	34.5	5	17.0
VIII	25.0	24.6	31.5	5	26.0
IX	18.3	21.4	27.7	65	12.9

(Note: Rain values are presented as mm/m^2, consistent with field records.)

2.2. Plant material and treatments

The imazamox-tolerant sorghum hybrid **Sentinel IG** was used. The experimental design was a randomized block with four replications. Treatments included:

- **A1** – Untreated control
- **A2** – Farm control
- **A3** – Pulsar 40 (imazamox) at 120 ml da^{-1}
- **A4** – Pulsar 40 at 240 ml da^{-1}
- **A5** – Pulsar 40 at 480 ml da^{-1}

Herbicide application was performed at the 3–4 leaf stage.

2.3. Evaluated parameters

Adaptive and compensatory responses were assessed using the following parameters:

- Final plant height (cm),
- Panicle length (cm),
- Grain mass per panicle (g),
- Vegetative biomass (stems + leaves, g $plant^{-1}$).

All measurements were performed on air-dried plant material.

2.4. Data analysis

Mean values were calculated for each treatment and year. Adaptive and compensatory trends were evaluated by comparing treated variants with untreated and farm controls, and interannual variability was interpreted in the context of recorded monthly temperature and rainfall.

3. Results and Discussion

3.1. Growth suppression and adaptive response (final plant height)

Across all experimental years, increasing herbicide doses resulted in a gradual reduction in final plant height (Table 2). At the recommended dose (120 ml da^{-1}), height reduction was limited, whereas higher doses led to more pronounced suppression.

Table 2 Final plant height of sorghum (cm)

Treatment	2023	2024	2025
A1	62.4	65.1	60.3
A2	70.6	69.2	67.1
A3	66.8	63.9	64.2
A4	63.1	61.0	60.5
A5	59.7	58.1	56.8

The climatic background provides essential context for these differences. In 2024, June was extremely hot (mean 26.3°C) with almost no rainfall (2 mm), followed by high temperatures in July–August and low rainfall (24 and 12 mm). Such conditions are expected to constrain vegetative expansion and recovery potential, especially when combined with chemical stress [7]. In 2025, May rainfall was relatively high (113.2 mm), but June rainfall remained low (10.9 mm) while temperatures increased (mean 24.5°C), creating a scenario where early growth may start favorably but later becomes limited by moisture deficit during key developmental transitions.

Overall, these results indicate that early vegetative growth is sensitive to herbicide stress; however, moderate suppression does not necessarily translate into proportional productivity loss, suggesting activation of adaptive mechanisms through later-stage compensation [6,8].

3.2. Compensatory changes in panicle structure (panicle length)

Panicle length responded differently to herbicide stress compared to plant height. At moderate doses, panicle length remained relatively stable and approached values observed in farm control variants (Table 3), suggesting a compensatory tendency to maintain reproductive structure when vegetative growth is partially restricted.

Table 3 Panicle length of sorghum (cm)

Treatment	2023	2024	2025
A1	9.1	10.8	10.2
A2	20.3	19.0	18.7
A3	18.3	17.1	17.5
A4	17.0	16.1	16.0
A5	15.7	14.2	14.0

The interannual trends align with the recorded climate regime. In 2023, despite high maximum temperatures in July (40.9°C), rainfall during June (79 mm) and moderate rainfall in July–August (25–31 mm) likely supported partial recovery and reproductive development. In contrast, 2024 combined extreme heat with critically low rainfall in June and reduced rainfall in August, conditions that commonly limit reproductive potential and can reduce panicle development [7]. The 2025 season displayed slightly milder maximum temperatures in summer compared with 2023–2024, but limited rainfall in June and September suggests that water supply may still constrain full expression of panicle length under higher herbicide doses.

The gradual reduction at higher doses indicates that compensatory capacity diminishes when stress intensity exceeds the plant's adaptive threshold [9].

3.3. Grain mass per panicle as an indicator of compensation

Grain mass per panicle is a direct indicator of reproductive compensation and sink strength (Table 4). At the recommended herbicide dose, grain mass remained close to farm control values, while excessive doses (240–480 ml da^{-1}) reduced grain accumulation consistently across years.

Table 4 Grain mass per panicle (g)

Treatment	2023	2024	2025
A1	4.20	2.20	3.10
A2	16.27	16.09	15.80
A3	16.21	15.06	15.20
A4	14.07	12.55	12.80
A5	11.30	10.06	9.90

The markedly low values in the untreated control (A1) are consistent with the expected strong weed competition effects in early crop growth, which can irreversibly reduce reproductive potential during sensitive stages [9]. In addition, climatic stress likely contributed to the lower values in 2024: extremely low June rainfall (2 mm) and sustained heat in July–August could limit assimilate availability for grain filling [7]. In 2025, although May rainfall was comparatively favorable, the low June precipitation (10.9 mm) may have reduced water availability during canopy expansion, which can subsequently influence reproductive biomass formation.

These results support the concept that sorghum subjected to moderate herbicide stress can partially preserve grain filling through compensatory allocation, but excessive stress leads to incomplete compensation and yield component losses [6].

3.4. Vegetative biomass (stems + leaves) and stress redistribution

Vegetative biomass decreased with increasing herbicide dose (Table 5). At the same time, in years with stronger climatic constraints, biomass values reflected both the stress limitation and potential protective strategy (maintenance of vegetative tissue under chronic stress), which has been documented for stress-tolerant crops [3,7].

Table 5 Vegetative biomass (stems + leaves, g plant^{-1})

Treatment	2023	2024	2025
A1	245.0	301.8	260.4
A2	459.3	541.0	510.2
A3	355.0	532.3	480.1
A4	290.5	514.8	455.3
A5	226.3	427.3	398.0

Notably, values in 2024 are generally higher than in 2023 for several treatments, which can occur under stress regimes where plant development is slowed and a larger share of biomass remains in vegetative structures at the measurement moment, while reproductive formation is relatively constrained. The 2024 climate data show extremely limited rainfall in June (2 mm) and low rainfall in August (12 mm), combined with high temperatures, which can delay or disrupt normal growth transitions [7]. Therefore, both chemical stress (higher herbicide doses) and climatic stress may jointly shape the biomass partitioning patterns across treatments.

4. Conclusion

The study demonstrates that imazamox-tolerant sorghum exhibits pronounced adaptive and compensatory mechanisms in response to herbicide-induced stress under rainfed conditions. Moderate herbicide doses allow partial compensation through stabilization of reproductive structures (panicle length) and maintenance of grain mass per panicle, whereas excessive doses exceed the adaptive capacity of the crop and lead to reduced productivity components.

Importantly, the climatic records for April–September confirm strong interannual variability in temperature and precipitation, with 2024 characterized by extreme heat and critically low rainfall in June and August, conditions likely limiting recovery and compensation potential. Consequently, optimizing herbicide dose is essential not only for crop safety but also for ensuring yield stability under variable climatic environments.

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