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Physiological response of imazamox-tolerant sorghum (*Sorghum bicolor* L.) to increasing doses of imazamox under field conditions

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Abstract

Herbicide-tolerant sorghum hybrids provide expanded opportunities for chemical weed control; however, herbicide tolerance does not necessarily imply the absence of physiological stress. The present study aimed to evaluate the physiological response of the imazamox-tolerant sorghum hybrid Sentinel IG to increasing doses of the herbicide Pulsar 40 (active ingredient: imazamox). A field experiment was conducted under rainfed conditions during the 2024 growing season in South Central Bulgaria. Net photosynthetic rate (PN), transpiration rate (E), stomatal conductance (gs), and chlorophyll concentration were measured at two time points after herbicide application. In addition, plant height was recorded at key developmental stages. The results demonstrated a clear dose-dependent reduction in chlorophyll concentration, photosynthetic activity, and transpiration intensity with increasing herbicide dose. Although partial recovery of physiological parameters was observed over time, the highest dose (480 ml da^{-1}) resulted in sustained physiological stress and growth suppression. The findings confirm that even herbicide-tolerant sorghum hybrids exhibit measurable physiological responses when exposed to elevated doses of imazamox, highlighting the importance of dose optimization to ensure crop safety under field conditions.

Keywords: Sorghum; Imazamox; Herbicide tolerance; Photosynthesis; Physiological stress

1. Introduction

Sorghum (*Sorghum bicolor* L.) is one of the most drought-tolerant cereal crops and is widely cultivated in semi-arid and sub-humid regions due to its high water-use efficiency and adaptability to environmental stress [1,2]. Despite its competitive ability, sorghum is particularly sensitive to weed competition during the early stages of development, when slow initial growth allows weeds to dominate the crop canopy and reduce yield potential [3].

The introduction of herbicide-tolerant sorghum hybrids has significantly expanded chemical weed control options, particularly through the use of acetolactate synthase (ALS)-inhibiting herbicides such as imazamox [4,5]. Imazamox inhibits ALS, a key enzyme in the biosynthesis of branched-chain amino acids, leading to growth cessation in susceptible plant species [6].

Although tolerant hybrids can survive post-emergence herbicide application, several studies indicate that herbicide tolerance does not completely eliminate physiological disturbances, especially when herbicides are applied at higher than recommended doses or under unfavorable environmental conditions [7,8]. Physiological parameters such as photosynthetic rate, chlorophyll content, transpiration, and stomatal conductance are sensitive indicators of herbicide-induced stress and are commonly used to assess sub-lethal effects of herbicides on crop plants [9,10].

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The objective of this study was to evaluate the short-term physiological response of imazamox-tolerant sorghum to increasing doses of imazamox under field conditions, focusing on gas exchange parameters, chlorophyll concentration, and plant height dynamics.

2. Materials and Methods

2.1. Experimental site and plant material

The field experiment was conducted in 2024 at the experimental field of the Agricultural University of Plovdiv, Bulgaria, under rainfed conditions. The imazamox-tolerant sorghum hybrid **Sentinel IG** was used. Standard agronomic practices for sorghum cultivation were applied throughout the growing season.

2.2. Experimental design and treatments

The experiment was arranged in a randomized block design. The following treatments were included:

- **A2** – Farm control (no herbicide application)
- **A3** – Pulsar 40 at 120 ml da^{-1} (recommended dose)
- **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 of sorghum, corresponding to the critical period for weed control [3].

2.3. Physiological measurements

Physiological measurements were conducted on fully expanded leaves at two time points after herbicide application: 24 June 2024 and 02 July 2024. Net photosynthetic rate (PN), transpiration rate (E), and stomatal conductance (gs) were measured using a portable gas-exchange system. Chlorophyll concentration was estimated using non-destructive optical measurements, a widely accepted method for assessing chlorophyll status under field conditions [11].

Plant height was measured before herbicide application (4–5 leaf stage), before heading, and at final maturity.

2.4. Statistical analysis

The data were analyzed using descriptive statistical methods. Mean values were calculated for each treatment and measurement date to assess dose-dependent trends in physiological response.

2.5. Weather conditions

The field experiment was conducted under rainfed conditions in the region of Plovdiv, South Central Bulgaria. Climatic data for the sorghum vegetation period (April–September 2024) were obtained from a local meteorological station and are summarized in Table 1. The 2024 growing season was characterized by elevated air temperatures and uneven distribution of precipitation. Particularly unfavorable conditions were observed in June, when extremely low precipitation coincided with high maximum air temperatures. These conditions created pronounced drought and heat stress during the early vegetative development of sorghum.

Table 1 Climatic conditions during the sorghum growing season (April–September 2024)

Months	**Mean air temperature (°C) 1981–2010**	**Mean air temperature (°C) 2024**	**Maximum air temperature (°C) 2024**	**Mean precipitation (mm) 1981–2010**	**Precipitation (mm) 2024**
April	12.2	16.2	31.2	39	32
May	17.2	16.9	29.5	32	83
June	20.9	26.3	37.3	36	2
July	25.0	27.6	39.2	5	24
August	25.0	26.8	37.7	5	12
September	18.3	21.1	35.2	65	17

3. Results

3.1. Physiological response to imazamox application

At the first measurement date (24 June 2024), increasing imazamox doses resulted in a gradual reduction in photosynthetic rate, transpiration intensity, and chlorophyll concentration (Table 2). Compared to the farm control, plants treated with 240 and 480 ml da^{-1} showed a noticeable decline in PN and chlorophyll content, indicating early physiological stress [9].

The observed reduction in photosynthetic activity and chlorophyll concentration was likely intensified by the unfavorable climatic conditions during the experimental period. The combination of high air temperatures and extremely low precipitation in June 2024 may have amplified the herbicide-induced stress, particularly at higher imazamox doses.

Table 2 Effect of increasing imazamox doses on physiological parameters of sorghum (24.06.2024)

Treatment	E (mmol m^{-2} s^{-1})	gs (mol m^{-2} s^{-1})	PN (µmol m^{-2} s^{-1})	Chlorophyll (mg m^{-2})
A2 – Control	1.59	0.04	31.37	487
A3 – 120 ml da^{-1}	1.54	0.03	30.15	432
A4 – 240 ml da^{-1}	1.42	0.03	25.99	418
A5 – 480 ml da^{-1}	1.32	0.03	24.04	329

At the second measurement date (02 July 2024), all treatments exhibited lower physiological values, reflecting the combined influence of herbicide application and high temperature stress. However, the highest herbicide dose consistently resulted in the lowest values of PN, gs, and E (Table 3), confirming a dose-dependent response.

Table 3 Effect of increasing imazamox doses on physiological parameters of sorghum (02.07.2024)

Treatment	E (mmol m^{-2} s^{-1})	gs (mol m^{-2} s^{-1})	PN (µmol m^{-2} s^{-1})	Chlorophyll (mg m^{-2})
A2 – Control	1.04	0.02	28.66	197
A3 – 120 ml da^{-1}	1.02	0.02	24.82	180
A4 – 240 ml da^{-1}	1.00	0.02	22.69	178
A5 – 480 ml da^{-1}	0.62	0.01	21.17	169

3.2. Plant height response

Plant height measurements supported the physiological data (Table 4). At the 4–5 leaf stage, height was recorded before herbicide application, therefore only control values are presented. Differences among herbicide treatments became evident at later developmental stages. Increasing herbicide dose led to reduced plant height before heading and at final maturity, with the strongest growth suppression observed at 480 ml da^{-1}.

Table 4 Plant height dynamics of sorghum, 2024 (cm)

<table>
<tr><th>Treatment</th><th>4–5 leaf stage</th><th>Before heading</th><th>Final height</th></tr>
<tr><td>A2 – Control</td><td rowspan="4">25.1</td><td>62.2</td><td>69.2</td></tr>
<tr><td>A3 – 120 ml da^{-1}</td><td>58.8</td><td>63.9</td></tr>
<tr><td>A4 – 240 ml da^{-1}</td><td>55.2</td><td>61.0</td></tr>
<tr><td>A5 – 480 ml da^{-1}</td><td>53.5</td><td>58.1</td></tr>
</table>

Similar growth suppression effects in ALS-tolerant crops exposed to elevated herbicide doses have been reported previously [4,7], confirming that tolerance does not fully prevent physiological stress.

4. Discussion

The results demonstrate that imazamox induces measurable physiological stress in imazamox-tolerant sorghum when applied at elevated doses. Reductions in photosynthetic rate and chlorophyll concentration are consistent with the known mode of action of ALS inhibitors and their indirect effects on plant metabolism [6,8].

The observed decrease in stomatal conductance and transpiration suggests stress-induced regulation of gas exchange, likely associated with attempts to limit water loss under combined chemical and thermal stress [1,10]. Although partial recovery was observed over time, persistent suppression at the highest dose indicates that excessive herbicide application can negatively affect crop growth potential.

5. Conclusions

- Increasing doses of imazamox cause a dose-dependent reduction in photosynthetic activity, transpiration, and chlorophyll concentration in imazamox-tolerant sorghum.
- Partial physiological recovery occurs over time; however, excessive doses result in sustained stress and growth suppression.
- Herbicide tolerance does not eliminate physiological sensitivity under elevated herbicide pressure.
- Optimized herbicide dosing is essential to maintain physiological stability and growth of sorghum under field conditions.

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