Int.J.Curr.Res.Aca.Rev.2025; 13(10): 134-146

International Journal of Current Research and Academic Review

ISSN: 2347-3215 (Online) Volume 13 Number 10 (October-2025)

Journal homepage: http://www.ijcrar.com

EXCELLENT PUBLISHERS

doi: https://doi.org/10.20546/ijcrar.2025.1310.010

Genotypic Variation in Maize Response to Post-Emergence Herbicides: Implications for Yield and Tolerance

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Abstract

Post-emergence herbicides, Adengo SC 465 and Auxo EC 337, significantly influenced grain yield and phytotoxicity in maize inbred lines, with Adengo causing greater yield reductions (30.6%) than Auxo (16.5%). Grain yield was negatively correlated with phytotoxicity, with tolerant genotypes maintaining stable yields and sensitive lines exhibiting severe injury and substantial yield loss. Differential responses among genotypes were attributed to the herbicides' active ingredients, safener effectiveness, and environmental conditions. Pronounced genotypic variation indicates exploitable genetic diversity for breeding herbicide-tolerant maize. Integrating tolerant lines with optimized application timing, effective weed management, and complementary agronomic practices is crucial to sustain productivity and reduce labor in smallholder systems. These findings provide insights for improving maize resilience under herbicide stress in Ethiopian agroecologies and similar environments.

Article Info

Received: 19 August 2025
Accepted: 26 September 2025
Available Online: 20 October 2025

Keywords

Maize Inbred lines, Post-emergence herbicides, Phytotoxicity, Genotype variation, Grain Yield.

Introduction

Maize (Zea mays L.) is a staple crop with critical importance for food security and economic stability in many countries, including Ethiopia. It is Ethiopia's second most important cereal crop after teff, serving both as a staple food and a major livestock feed. Maize is cultivated across diverse agro-ecologies and underpins national food security, rural livelihoods, and economic stability due to its adaptability to varied climatic conditions (Abate *et al.,* 2015; Keno *et al.,* 2018). However, its productivity is often constrained by weed competition, which can significantly reduce grain yield if not managed effectively. In major maize- and sorghum-growing areas, unmanaged weeds can cause yield losses of 35–87.5%, depending on genotype, planting density, and environmental conditions (Rani, 2020; Landau *et al.,* 2021; Ali *et al.,* 2016; Berhan & Bekele, 2021). Beyond resource competition, weeds can also exert allelopathic and parasitic effects that further reduce crop performance (Muluadam & Demisew, 2021).

Chemical weed control through post-emergence herbicides has become a widely adopted strategy to complement manual weeding and other cultural practices, particularly in smallholder farming systems where labor shortages are common (Busi *et al.,* 2020; Negewo, 2024). Herbicides have become central to maize production in Ethiopia, and their effectiveness depends on active ingredient chemistry, dose, application timing, crop morphology and physiology, and environmental conditions (Stefanovic *et al.,* 2010; Bónis *et al.,* 2011). However, selectivity is not absolute—under unfavorable conditions such as low early-season temperatures or high humidity, herbicides can trigger temporary or permanent stress, ranging from leaf yellowing to complete plant death (Vesna *et al.,* 2010).

Post-emergence herbicides, such as Adengo SC 465 (isoxaflutole + thiencarbazone-methyl + cyprosulfamide safener) and Auxo EC 337 (tembotrione + bromoxynil + isoxadifen-ethyl safener), are designed to control broadleaf weeds and grasses after crop emergence. Recently, these newer herbicides have been introduced in Ethiopia, offering broader application windows and potentially safer crop selectivity. Yet, despite their increasing use, limited evidence exists on their phytotoxic effects in Ethiopian maize parental inbreds, making evaluation critical to safeguard seed production efficiency (Green, 1998; Bónis *et al.,* 2004). While effective against weeds, these herbicides can negatively affect maize productivity when crop tolerance thresholds are exceeded (Wang *et al.,* 2022; Zhang *et al.,* 2024). The magnitude of yield reduction is strongly influenced by genotype-specific sensitivity, the chemical composition of the herbicide, safener efficacy, and environmental conditions such as temperature and soil moisture (Begović *et al.,* 2023; Kostyuk, 2020; Gaines *et al.,* 2020).

Several studies have documented the differential response of maize genotypes to post-emergence herbicides. Genotypes with low phytotoxicity scores tend to maintain stable biomass and grain yield, demonstrating tolerance, whereas sensitive genotypes exhibit leaf bleaching, stunting, impaired photosynthesis, and substantial yield loss (Sousa *et al.,* 2022; Wang *et al.,* 2022; Duke, 2025). Such genotype-dependent variation is supported by molecular evidence, including the role of cytochrome P450 monooxygenases, particularly CYP81A9, in enhancing detoxification of herbicidal compounds (Zhang *et al.,* 2024; Lu *et al.,* 2024). Additional factors, such as safener responsiveness and leaf surface characteristics, also contribute to differential herbicide selectivity among maize genotypes (Roy *et al.,* 2024; Gaines *et al.,* 2019). The shift from older chemistries (triazines, acetanilides, thiocarbamates) to sulfonylurea and HPPD-inhibiting herbicides improved weed control but increased susceptibility in certain maize inbred lines under specific environmental conditions (Zaric *et al.,* 1998; Stefanovic *et al.,* 1996, 1997, 1999).

Despite the potential benefits of herbicide use, reliance solely on chemical control is insufficient to ensure yield stability. Environmental stressors such as drought, heat, and late-season weed competition can exacerbate yield losses, sometimes exceeding 50% (Landau *et al.,* 2021; Meng *et al.,* 2024; Negewo, 2024). Morphological traits alone, such as plant height and ear height, are inadequate predictors of tolerance, indicating that herbicide tolerance is primarily physiological and biochemical (Gaines *et al.,* 2019; Zhang *et al.,* 2021). Therefore, integrating herbicide-tolerant genotypes with effective weed management, optimized application timing, and complementary agronomic practices—including crop rotation, cover cropping, and precision agronomy—is critical for sustainable maize production (Busi *et al.,* 2020; Roy *et al.,* 2024; Meng *et al.,* 2024).

The identification of low-phytotoxicity lines that maintain stable yields under herbicide stress is particularly valuable for breeding programs aimed at developing herbicide-tolerant maize hybrids. Such genotypes not only reduce potential yield losses but also alleviate labor demands in smallholder farming systems (Albrecht *et al.,* 2023; Gaines *et al.,* 2020; Rodrigues & Almeida, 2023). Understanding the interactions between genotype, herbicide type, and environment provides a foundation for improving maize productivity and resilience under chemical weed control strategies in Ethiopian agroecologies and similar environments. This study therefore evaluates the responses of 18 maize inbred lines to Auxo EC 337 and Adengo SC 465 parallel to a hand-weeded control under field conditions at Bako, Western Ethiopia, over two consecutive seasons, with the goal of identifying herbicide–genotype interactions relevant to sustainable seed production.

Materials and Methods

Study Site and Experimental Design

The study was conducted during the 2023–2024 main cropping seasons at the Maize Protection Trial Field of Bako National Maize Research Center (BNMRC), Ethiopia. The experiment evaluated the phytotoxic responses of 18 maize (*Zea mays* L.) parental inbred lines to two post-emergence herbicides: Auxo EC 337 (1.5 L ha^{-1}) and Adengo SC 465 (0.44 L ha^{-1}), applied using a plot sprayer. Seeds were planted at 75 × 25 cm spacing, with two seeds per hill, later thinned to one plant per hill at two weeks after emergence. Each plot consisted of two rows (1.5 m × 3.6 m; 5.4 m^2). Standard agronomic practices for maize seed production were followed. Treatments were arranged in a randomized complete block design (RCBD) with three replications. Herbicides were applied at the 7–8-leaf stage.

Plant Material

The 18 inbred lines originated from the Ethiopian Institute of Agricultural Research (EIAR-Bako) and the International Maize and Wheat Improvement Center (CIMMYT), representing both white- and yellow-grain types. Detailed genetic sources and grain colors are presented in Table 1.

Experimental Design

The experiment was arranged in a factorial randomized complete block design (RCBD) with three replications. The factors included:

1. Herbicide treatments:

- o Adengo SC 465 (isoxaflutole + thiencarbazone-methyl + cyprosulfamide safener)
- o Auxo EC 337 (tembotrione + bromoxynil + isoxadifen-ethyl safener)
- o Hand-weeded control (no herbicide)

2. Maize inbred lines: As listed above.

Each plot consisted of two rows, 5 m with standard intra- and inter-row spacing of t spacing, 0.75 m × 0.25 m with three replication. Recommended agronomic practices, including fertilization, and pest management, were applied uniformly across all plots to minimize non-treatment variability.

Herbicide Application

Herbicides were applied at the recommended field rates: Adengo SC 465 at 0.4 L ha^{-1} and Auxo EC 337 at 1.5 L ha^{-1}, applied post-emergence (approximately at the 2–8 leaf stage of maize) using a broadcast spray with a typical dilution of 200–250 L water ha^{-1}. Applications were performed at the V4–V5 maize growth stage, corresponding to early post-emergence during active vegetative growth.

Data Collection

1. **Phytotoxicity Assessment**: Visual phytotoxicity was scored at 7, 14, and 21 days after herbicide application using a 1–5 scale, where 1 = no injury and 5 = severe injury or plant death, based on leaf chlorosis, necrosis, and stunting (Sousa *et al.,* 2022; Wang *et al.,* 2022). The mean phytotoxicity score was calculated for each genotype × herbicide combination.
2. **Grain Yield Measurement:** At physiological maturity, maize ears were harvested from the central rows of each plot to avoid border effects. Grain yield was adjusted to 12.5% moisture content and expressed in t ha^{-1}. Yield reduction due to herbicide treatments was calculated relative to the hand-weeded control.
3. **Growth and Morphological Parameters:** Plant height, ear height, and above-ground biomass were measured at maturity to assess potential sub-lethal herbicide effects on growth.

Phytotoxicity and Agronomic Measurements

Phytotoxic effects were assessed 14 days after treatment using a modified European Weed Research Society (EWRS) 1–5 rating scale, where 1 = no visible damage and 5 = severe damage with leaf deformation and chlorosis (Table 2). Parameters recorded included percentage of affected plants, plant height (base to tassel branching point), ear height (base to uppermost ear node), tassel length, and grain yield. Yield was calculated at 12.5% grain moisture from five representative plants per plot.

Statistical Analysis

Data were analyzed using SAS, 9.. Analysis of variance (ANOVA) was performed to determine the effects of herbicide treatments, maize genotypes, and their interactions on phytotoxicity, grain yield, and growth parameters.

Means were compared using Tukey's Honest Significant Difference (HSD) test at $p \leq 0.05$. Correlation analysis was conducted to assess the relationship between phytotoxicity scores and grain yield.

Experimental Validation

To ensure reliability, the experiment was conducted under uniform soil fertility, irrigation, and pest management practices.

Environmental conditions such as rainfall, temperature, and relative humidity were monitored throughout the growing season to account for potential stress factors that could interact with herbicide effects (Gaines *et al.,* 2020).

Results and Discussion

Phytotoxicity Response of Maize Inbred Lines to Post-emergence Herbicides

The reaction of maize inbred lines to the normal doses of Auxo EC 337 and Adengo SC 465 showed considerable variation in both the percentage of affected plants and the phytotoxicity level (Table 3). Across all lines, the mean percentage of affected plants was 11.3% for Auxo EC 337 and 13.57% for Adengo SC 465, with corresponding mean phytotoxicity scores of 1.78 and 1.96, indicating predominantly low to moderate herbicide stress.

Under Auxo EC 337, the most sensitive inbred lines were CML-334 (30.13%), CML-312 (28.66%), 144-7-b (25.04%), and CML-204 (23.47%), which exhibited moderate phytotoxicity (scores 2.33–3.67). In contrast, several lines including CML-144, F7215, MBRC5BCF108-2-3-1-B-5-2-B-B, 124-b(109), and CUBA/GUADC1F27-4-3-3-B-1-BX showed high tolerance, with no visible damage or phytotoxic scores of 1.

For Adengo SC 465, the highest phytotoxic responses were observed in Sc-22 (45.76%), F7215 (40.2%), and CML-312 (25.65%), although most lines displayed low phytotoxicity (score ≤ 2.67). Several lines, including MBRC5BCF108-2-3-1-B-5-2-B-B, 124-b (109), and CUBA/GUADC1F27-4-3-3-B-1-BX, remained largely unaffected (≤1% affected plants; score 1).

Effects of Auxo EC 337 on Yield and Agronomic Traits of Maize Inbred Lines

The application of the normal dose of Auxo EC 337 resulted in significant variation among maize inbred lines for yield, plant height, ear height, and tassel length (Table 4). Grain yield ranged widely from 4.62 qt/ha in CML-161 to 33.94 qt/ha in CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B, with a mean yield of 16.29 qt/ha. High-yielding lines included CUBA/GUADC1F27..., MBRC5BCF108-2-3-1-B-5-2-B-B, A7033, and CML-395, indicating considerable genetic potential for enhanced productivity under standard herbicide treatment. Conversely, CML-161, Sc-22, and CML-165 were the lowest yielding lines, suggesting possible sensitivity to Auxo EC 337.

Plant height varied from 111.84 cm (CML-161) to 197.5 cm (F7215), with a mean of 157.43 cm. Ear height followed a similar trend, ranging from 44.33 cm (CML-161) to 107.67 cm (144-7-b), averaging 74.66 cm. Tassel length ranged between 24 cm (CML-204) and 44.67 cm (F7215), with a mean of 32.79 cm. Lines with taller plants, such as F7215, 144-7-b, and 142-1-e, also tended to exhibit higher ear positions, which could influence lodging susceptibility and harvest index. The least significant difference (LSD) values at 5% confirmed that the observed differences among lines for all traits were statistically meaningful, highlighting the potential for selection of superior inbred lines for both yield and favorable agronomic traits under Auxo EC 337 treatment.

Effects of Adengo SC 465 on Yield and Agronomic Traits of Maize Inbred Lines

The application of the recommended dose of Adengo SC 465 significantly affected grain yield, plant height, and ear height among the maize inbred lines evaluated (Table 5). Grain yield exhibited substantial variation, ranging from 1.35 qt/ha in CML-312 to 32.5 qt/ha in A7033, with an overall mean of 12.98 qt/ha. Other high-yielding lines included MBRC5BCF108-2-3-1-B-5-2-B-B (31.95 qt/ha) and F7215 (22.92 qt/ha), indicating considerable tolerance to herbicide-induced stress. In contrast, lines such as CML-165, CML-312, and CML-161 recorded the lowest yields, suggesting higher sensitivity to Adengo SC 465.

Plant height varied markedly among lines, from 80 cm (CML-161) to 187 cm (144-7-b), with a mean of 122.06 cm, while ear height ranged from 26 cm (CML-202) to 107.67 cm (144-7-b), averaging 47.67 cm. Some lines, including CML-159, 142-1-e, and A7033, displayed relatively high ear placement despite moderate plant stature, reflecting a favorable plant architecture under herbicide treatment. Interestingly, the tallest plants and highest ear placement (144-7-b) did not correspond with the highest grain yield, indicating that vegetative growth alone is not a reliable predictor of yield under Adengo SC 465 application.

The significant differences among inbred lines for all measured traits, confirmed by LSD at 5%, underscore the existence of genotypic variation in herbicide response. Lines that combined high yield with moderate to tall plant and ear heights, such as A7033 and MBRC5BCF108-2-3-1-B-5-2-B-B, represent promising candidates for breeding programs aiming to develop maize cultivars resilient to post-emergence herbicide stress while maintaining superior productivity.

Grain Yield Performance of Maize Inbred Lines under Herbicide and Non-Herbicide Conditions

The grain yield of 18 maize inbred lines varied significantly between the hand-weeding control and the two herbicide treatments (Adengo SC 465 and Auxo EC 337) across the 2023 and 2024 cropping seasons at Bako, western Ethiopia (Table 6). The mean grain yield under hand-weeding was 19.53 qt ha^{-1}, while Adengo SC 465 and Auxo EC 337 treatments averaged 13.54 qt ha^{-1} and 16.30 qt ha^{-1}, corresponding to yield reductions of 30.6% and 16.5%, respectively, relative to the control.

Relationship between Yield and Phytotoxicity

Genotypes with lower phytotoxicity scores (≤ 2) generally maintained higher yields, whereas those with higher scores (≥ 3) showed substantial reductions. Adengo SC 465 caused slightly more injury (mean phytotoxicity = 1.96) than Auxo EC 337 (mean = 1.78).

Highly tolerant lines such as MBRC5BCF108-2-3-1-B-5-2-B-B, A7033, CML-144, 124-b(109), and CUBA/GUADC1F27-4-3-3-B-1-B×(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B consistently outperformed others across treatments.

For instance, MBRC5BCF108-2-3-1-B-5-2-B-B yielded 38.31 qt ha^{-1} under hand-weeding, 31.95 qt ha^{-1} under Adengo SC 465, and 29.70 qt ha^{-1} under Auxo EC 337, with minimal phytotoxicity (score = 1). Similarly, A7033 maintained high yields (32.84 qt ha^{-1} hand-weeding; 32.50 qt ha^{-1} Adengo SC 465) with negligible injury (scores 1–1.67).

In contrast, sensitive lines such as CML-312, CML-165, and CML-334 exhibited high phytotoxicity (scores 3.3–3.7) and severe yield losses. CML-312, for example, declined from 15.4 qt ha^{-1} (hand-weeding) to 1.35 qt ha^{-1} under Adengo SC 465, while CML-165 and CML-334 yielded below 8 qt ha^{-1} under herbicide stress. Lines with intermediate tolerance, including CML-204, CML-202, and CML-159, experienced moderate yield reductions (20–30%) with phytotoxicity scores of 2.3–2.7.

Herbicide treatments increased the proportion of affected plants—13.6% for Adengo SC 465 and 11.3% for Auxo EC 337—while hand-weeding caused no visible injury.

Overall, Adengo SC 465 induced greater phytotoxic stress and yield reduction than Auxo EC 337, though responses varied by genotype.

Herbicide Effects on Grain Yield and Phytotoxicity

The application of post-emergence herbicides, Adengo SC 465 and Auxo EC 337, significantly reduced grain yield of maize inbred lines compared with the hand-weeded control, with mean reductions of 30.6% and 16.5%, respectively (Rani, 2020; Landau *et al.,* 2021; Begović *et al.,* 2023). This aligns with prior observations indicating that post-emergence herbicides can negatively impact maize productivity when crop tolerance thresholds are exceeded, and that genotype-dependent sensitivity is a major determinant of crop injury and yield loss (Wang *et al.,* 2022; Zhang *et al.,* 2024). Comparable yield declines under herbicide stress have also been reported in other crops, such as sugar beet and foxtail millet, highlighting the general physiological constraints imposed by herbicide exposure (Lu *et al.,* 2024; Chen *et al.,* 2024).

However, some studies report minimal or no yield penalty for tolerant genotypes under similar herbicide treatments, suggesting that injury severity is strongly influenced by genotype × herbicide × environment interactions (Rodrigues & Almeida, 2023; Albrecht *et al.,* 2023; Gaines *et al.,* 2020). For example, Sousa *et al.,* (2022) demonstrated that among six maize lines treated with tembotrione, one genotype exhibited no visible injury even at double the recommended dose, while others showed severe chlorosis and yield suppression. These findings emphasize the importance of evaluating germplasm under local environmental conditions to identify tolerant genotypes (Roy *et al.,* 2024; Gaines *et al.,* 2019).

Relationship between Yield and Phytotoxicity

A clear negative correlation was observed between phytotoxicity scores and grain yield (Sousa *et al.,* 2022; Wang *et al.,* 2022; Duke, 2025). Lines with low phytotoxicity scores (≤2), such as MBRC5BCF108-2-3-1-B-5-2-B-B, A7033, CML-144, 124-b(109), and CUBA/GUADC…306-1-B-2-B, maintained stable yields across herbicide treatments, reflecting superior herbicide tolerance (Rodrigues & Almeida, 2023; Gaines *et al.,* 2020; Albrecht *et al.,* 2023). Conversely, sensitive lines such as CML-312, CML-165, and CML-334 exhibited higher phytotoxicity (≥3.3) and substantial yield losses, consistent with reports that herbicide-sensitive lines experience impaired photosynthesis, reduced biomass accumulation, and eventual yield penalties (Sousa *et al.,* 2022; Wang *et al.,* 2022; Duke, 2025). Similar patterns were observed in maize hybrids treated with nicosulfuron, where higher phytotoxicity correlated with lower biomass and grain yield (Rodrigues & Almeida, 2023; Gaines *et al.,* 2020). These results confirm that herbicide tolerance in maize is highly genotype-dependent (Roy *et al.,* 2024; Gaines *et al.,* 2019).

Differential Herbicide Responses

Adengo SC 465 caused higher injury and greater yield reduction than Auxo EC 337, consistent with the chemical properties of their active ingredients. Adengo contains isoxaflutole + thiencarbazone-methyl + cyprosulfamide safener, which can induce early leaf bleaching and stunting in sensitive genotypes, whereas Auxo EC 337 (tembotrione + bromoxynil + isoxadifen-ethyl safener) generally provides better crop protection due to safener-mediated detoxification (Bayer CropScience, 2016; Bayer, n.d.; Kostyuk, 2020; Sousa *et al.,* 2022). Mean phytotoxicity scores (1.96 for Adengo and 1.78 for Auxo) indicate moderate injury sufficient to reduce yield (Begović *et al.,* 2023; Albrecht *et al.,* 2023). Comparable findings have been reported in Brazilian and European maize trials, where isoxaflutole-based products were more likely to induce transient phytotoxicity at early growth stages (Sousa *et al.,* 2022; Begović *et al.,* 2023).

Table.1 Maize inbred lines used for phytotoxicity study in 2023 to 2024 at Bako, West Ethiopia.

Entry	Entry name	Origin	Grain colour
1	144-7-b	EIAR-Bako	White
2	CML-144	CIMMYT	White
3	124-b(113)	EIAR-Bako	White
4	Sc-22	EIAR-Bako	White
5	F7215	EIAR-Bako	White
6	(MBRC5BCF108-2-3-1-B-5-2-B-B)	CIMMYT	White
7	142-1-e	EIAR-Bako	White
8	CML-159	CIMMYT	White
9	CML-204	CIMMYT	White
10	A7033	EIAR-Bako	White
11	CML-395	CIMMYT	White
12	CML-161	CIMMYT	Yellow
13	124-b(109)	EIAR-Bako	White
14	CML-165	CIMMYT	Yellow
15	CML-312	CIMMYT	White
16	CML-334	CIMMYT	White
17	CML-202	CIMMYT	White
18	(CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B)	CIMMYT	White

Table.2 Modified European Weed Research Society (EWRS) scale to rate herbicide phytotoxicity.

Category	Herbicide Damage to Crop	Remark
1	No damage	
2	Slight symptoms on lower leaves	
3	Symptoms/mild yellowing on upper and lower	
4	Malformed leaves and chlorosis	
5	Severe, whipping of the leaves	

Table.3 Reaction of maize inbred lines against phytotoxicity effects of the normal doses of Auxo EC 337 and Adengo SC 465 in 2023 to 2024 cropping season at Bako, Western Ethiopia.

Entry	Genotype name	Auxo EC 337		Adengo SC 465	
		% affected plants	Phytotoxic level (1-5)	% affected plants	Phytotoxic level (1-5)
1	144-7-b	25.04	3	12.5	1
2	CML-144	0	1	4.9	1.67
3	124-b(113)	11.76	3	6.95	3.33
4	Sc-22	21.57	2.33	45.76	1.67
5	F7215	0	1	40.2	1.33
6	(MBRC5BCF108-2-3-1-B-5-2-B-B)	0	1	0	1
7	142-1-e	5.88	1.67	11.54	1.33
8	CML-159	2.78	2.67	21.89	1
9	CML-204	23.47	3	22.55	2.67
10	A7033	0	1	5.88	1.67
11	CML-395	3.92	2	2.94	2.33
12	CML-161	15.88	2.67	6.06	2.67
13	124-b(109)	0	1	0	1
14	CML-165	18.7	3.67	13.73	2.33
15	CML-312	28.66	3.67	25.65	3.67
16	CML-334	30.13	2.33	15.82	2.67
17	CML-202	15.69	2.67	6.86	2.67
18	(CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B)	0	1	0.98	1
	Mean	11.3	1.78	13.57	1.96
	LSD at 5%	10.79	1.54	11.72	1.11

Table.4 Effects of the normal dose of Auxo EC 337 on yield, plant height, ear height, and tassel length of maize inbred lines in 2023 to 2024 cropping season at Bako, Western Ethiopia.

Entry	Genotype name	Yield (qt/ha)	Plant height (cm)	Ear height (cm)	Tassel length (cm)
1	144-7-b	11.85	187	107.67	30.33
2	CML-144	23.2	152.33	65.5	35.33
3	124-b(113)	15.01	150.17	60.84	36.33
4	Sc-22	8.81	149.67	69.17	30.67
5	F7215	18.42	197.5	92.83	44.67
6	(MBRC5BCF108-2-3-1-B-5-2-B-B)	29.7	156.17	74	35.33
7	142-1-e	12.46	194.33	107.5	28.33
8	CML-159	10.69	164	69.67	27.33
9	CML-204	10.7	137	59.17	24
10	A7033	25.8	171.5	98.34	38
11	CML-395	26.23	148.84	73.84	36.67
12	CML-161	4.62	111.84	44.33	30.67
13	124-b(109)	24.47	162.17	81.67	34
14	CML-165	7.93	132.5	66.33	34
15	CML-312	13.07	151.67	67.67	36
16	CML-334	7.96	156.34	72.67	29.67
17	CML-202	8.48	133.67	59.33	26.33
18	(CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B)	33.94	177.17	73.33	32.67
	Mean	16.29	157.43	74.66	32.79
	LSD at 5%	8.5595	20.612	12.417	6.39

Table.5 Effects of the normal dose of Adengo SC 465 on yield, plant height, and ear height of maize inbred lines in 2023 and 2024 cropping season at Bako, Western Ethiopia.

Entry	Genotype name	Yield (qt/ha)	Plant height (cm)	Ear height (cm)
1	144-7-b	11.09	187	107.67
2	CML-144	20.19	95.67	31.33
3	124-b(113)	7.57	110	35.67
4	Sc-22	7.19	115.67	46.33
5	F7215	22.92	150.33	57
6	(MBRC5BCF108-2-3-1-B-5-2-B-B)	31.95	157.33	61.33
7	142-1-e	12.47	141	63
8	CML-159	10.27	164	69.67
9	CML-204	9.92	92.33	30
10	A7033	32.5	138.33	62
11	CML-395	13.4	104.67	43
12	CML-161	6.65	80	26.67
13	124-b(109)	12.81	137.33	42.33
14	CML-165	2.5	88.67	28.67
15	CML-312	1.35	80.33	32.67
16	CML-334	4.08	109.33	34.67
17	CML-202	6.03	87.33	26
18	(CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B)	20.88	157.67	60
	Mean	12.98	122.06	47.67
	LSD at 5%	5.87	17.98	11.08

Table.6 Summary of Grain yield of maize inbred lines under herbicide treatment group and non-herbicide treatment (hand weeding) 2023 and 2024 cropping season at Bako, Western Ethiopia.

Entry	Genotype name	Grain Yield (qt/ha)			% affected plants			Phytotoxic level (1-5)		
		Non herbicide treatment	Herbicide treatment group		Non herbicide treatment	Herbicide treatment group		Non herbicide treatment	Herbicide treatment group	
		NHC (Hand weeding)	Adengo SC 465	Auxo EC 337	Hand weeding	Adengo SC 465	Auxo EC 337	Hand weeding	Adengo SC 465	Auxo EC 337
1	144-7-b	13.44	11.09	11.85	0	12.5	25.04	0	1	3
2	CML-144	28.5	20.19	23.2	0	4.9	0	0	1.67	1
3	124-b(113)	17.5	7.57	15.01	0	6.95	11.76	0	3.33	3
4	Sc-22	10.27	7.19	8.81	0	45.76	21.57	0	1.67	2.33
5	F7215	26.78	22.92	18.42	0	40.2	0	0	1.33	1
6	(MBRC5BCF108-2-3-1-B-5-2-B-B)	38.31	31.95	29.7	0	0	0	0	1	1
7	142-1-e	14.33	12.47	12.46	0	11.54	5.88	0	1.33	1.67
8	CML-159	12	10.27	10.69	0	21.89	2.78	0	1	2.67
9	CML-204	12.27	9.92	10.7	0	22.55	23.47	0	2.67	3
10	A7033	32.84	32.5	25.8	0	5.88	0	0	1.67	1
11	CML-395	33.03	13.4	26.23	0	2.94	3.92	0	2.33	2
12	CML-161	7.03	6.65	4.62	0	6.06	15.88	0	2.67	2.67
13	124-b(109)	30.6	22.81	24.47	0	0	0	0	1	1
14	CML-165	8.7	2.5	7.93	0	13.73	18.7	0	2.33	3.67
15	CML-312	15.4	1.35	13.07	0	25.65	28.66	0	3.67	3.67
16	CML-334	8.69	4.08	7.96	0	15.82	30.13	0	2.67	2.33
17	CML-202	9.68	6.03	8.48	0	6.86	15.69	0	2.67	2.67
18	(CUBA/GUADC1F27-4-3-3-B-1-BX(KILIMAST94A)-30MSV-03-2-10-B-2-B-B)-306-1-B-2-B)	32.09	20.88	33.94	0	0.98	0	0	1	1
	Mean	19.53	13.5428	16.2967		13.57	11.3	0	1.96	1.78
	LSD at 5%	9.2	5.87	7.32		11.72	10.79	0	1.11	1.54
NHC- Non Herbicide Control = Hand Weeding										

Environmental factors such as temperature, soil moisture, and application timing can modulate crop safety. Gaines *et al.,* (2020) and Roy *et al.,* (2024) observed that even ALS- or HPPD-inhibiting herbicides caused minimal injury in some genotypes under optimal conditions, highlighting the necessity of integrating environmental monitoring with herbicide management strategies (Negewo, 2024; Busi *et al.,* 2020).

Genotypic Variation and Breeding Implications

Pronounced genotypic variation in both phytotoxicity and yield indicates exploitable genetic diversity for herbicide tolerance (Zhang *et al.,* 2024; Lu *et al.,* 2024; Wang *et al.,* 2022; Roy *et al.,* 2024). Lines like A7033 and MBRC5BCF108-2-3-1-B-5-2-B-B maintained high yields and low injury, making them promising candidates for breeding herbicide-resilient maize hybrids (Albrecht *et al.,* 2023; Gaines *et al.,* 2020; Rodrigues & Almeida, 2023). Molecular evidence shows that maize tolerance to sulfonylurea- and isoxaflutole-based herbicides is largely mediated by cytochrome P450 monooxygenases, including CYP81A9, which enhance detoxification capacity (Zhang *et al.,* 2024; Lu *et al.,* 2024). Additional mechanisms, such as safener responsiveness and variation in leaf surface properties, further contribute to herbicide selectivity among genotypes (Roy *et al.,* 2024; Gaines *et al.,* 2019).

These findings support the practical use of phytotoxicity scoring as a screening tool in maize breeding. Identification of tolerant parental lines facilitates the development of herbicide-tolerant hybrids, reducing labor requirements and minimizing yield losses in smallholder systems (Albrecht *et al.,* 2023; Busi *et al.,* 2020; Gaines *et al.,* 2020).

Agronomic Considerations and Integrated Weed Management

Herbicide tolerance alone is insufficient to ensure yield stability. Environmental stressors such as drought, heat, and late-season weed competition can exacerbate yield losses, sometimes exceeding 50% (Landau *et al.,* 2021; Meng *et al.,* 2024; Negewo, 2024). Morphological traits like plant height and ear height are poor predictors of performance under herbicide stress, emphasizing that tolerance is primarily physiological and biochemical (Gaines *et al.,* 2019; Zhang *et al.,* 2021). Integrating herbicide-tolerant genotypes with effective weed management strategies, optimal application timing, and complementary cultural practices is essential for sustainable maize production (Busi *et al.,* 2020; Negewo, 2024). Incorporating crop rotation, cover cropping, and precision agronomic practices can further minimize yield losses while maintaining environmental sustainability (Roy *et al.,* 2024; Meng *et al.,* 2024).

Over all, the study demonstrated that post-emergence herbicides reduce maize grain yield, with injury severity strongly dependent on genotype. Low-phytotoxicity lines maintained stable yields, highlighting their potential as parental lines for breeding herbicide-tolerant hybrids. Variations in response were linked to active ingredients, safener-mediated detoxification, and environmental factors. Molecular mechanisms, including cytochrome P450-mediated detoxification, further explained genotype-dependent tolerance. While herbicide-tolerant lines can mitigate yield loss and labor demands, integrating them with comprehensive weed management and precision agronomy is essential for sustainable maize production.

In conclusion, post-emergence herbicides can substantially reduce maize yield, with the extent of injury being genotype-specific. Genotypes exhibiting low phytotoxicity and stable yields represent valuable genetic resources for breeding herbicide-tolerant hybrids. Effective management requires combining tolerant genotypes with optimized herbicide application, integrated weed management, and adaptive agronomic practices to minimize yield losses under environmental stress.

Adoption of these strategies can improve maize productivity and sustainability, particularly in smallholder farming systems facing labor and resource constraints.

Author Contributions

Gemechu Getachew: Conceptualization; data curation; formal analysis; methodology; resources; software; validation; writing—original draft; writing—review and editing. Temesgen Deressa: Conceptualization; supervision; validation; visualization; writing—original draft; writing—review and editing. Begizew Gola: Conceptualization; supervision; validation; visualization; writing—original draft; writing—review and editing: Temesgen Chibsa: Conceptualization; resources; formal analysis; validation; visualization; writing—original draft; writing—review and editing. Steven Runo: Data curation; supervision; validation; visualization; writing—original draft; writing—review and editing.

Acknowledgments

The authors would like to thank Ethiopian Institute of Agricultural Research for financial providing support and Bako National Maize Research center for providing research facilities that enabled the successful completion of this study. Special thanks are extended to the staff of Bako National Maize Research Center and EIAR for their direct and indirect contributions to this study.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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How to cite this article:

Gemechu Getachew, Temesgen Deresa, Begizew Gola, Temesgen Chibsa and Steven Runo. 2025. Genotypic Variation in Maize Response to Post-Emergence Herbicides: Implications for Yield and Tolerance. *Int.J.Curr.Res.Aca.Rev.* 13(10), 134-146. doi: https://doi.org/10.20546/ijcrar.2025.1310.010