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Original article

Weed community responses and maize productivity under different weed control approaches

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Abstract

Effective weed control is essential for maize productivity, but its success depends on weed community composition and intervention timing. This study evaluated how control methods and timing affected weed communities, maize growth, and grain yield. A field experiment with eight treatments and three replications was arranged in a randomized complete block design in 2024. Treatments were comprised of weedy and season-long weed-free controls, pre-emergence and post-emergence herbicides, hand weeding, and three sequential combinations. Weed density, biomass, and species composition were assessed at 20 and 55 days after sowing (DAS), together with maize growth and yield. Seventeen weed species from 11 families were recorded. The community was dominated by *Cyperus rotundus* L., *Eleusine indica* (L.) Gaertn., *Mazus pumilus* (Burm.f.) Steen., and *Alternanthera sessilis* (L.) DC., although their relative importance changed over time. Weed responses were mainly species-specific and were not consistently explained by life cycle. At 20 DAS, treatments containing pre-emergence S-metolachlor reduced weed biomass by 61.1–65.2% relative to the weedy control. At 55 DAS, pre-emergence herbicide and hand weeding alone provided 53.8 and 66.2% control, respectively, whereas sequential programs provided 87.7–99.3% control. Post-emergence atrazine + mesotrione alone reduced weed biomass by 98.2% at 55 DAS; however, because it was applied at 40 DAS, it provided no early-season control. Grain yield was significantly lower in the weedy control (3.1 $t \cdot ha^{-1}$) than in all weed-control treatments, with the highest yields in the sequential and season-long weed-free treatments. Weed biomass was more strongly negatively associated with grain yield at 55 DAS ($R^2 = 0.759$) than at 20 DAS ($R^2 = 0.324$). Overall, treatment timing and complementary interventions were important for maintaining weed suppression and maize productivity, while species-specific responses should guide control selection.

Key words: crop competition, hand weeding, herbicide application, species dominance, *Zea mays*

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, playing a crucial role in food security, livestock production, and agro-industrial development. Weed interference remains one of the major constraints to maize production. Weeds compete directly with maize for light, water, nutrients, and space, thereby reducing crop growth and productivity. Global maize yield losses attributable to weed competition have been estimated at approximately 37%, and losses may exceed 50% without effective weed control (Landau *et al.* 2021; Sharma and Rayamajhi 2022).

Herbicides are widely used for weed management because of their effectiveness, labor-saving benefits, and suitability for large-scale production (Jabran and Chauhan 2018). Pre-emergence herbicides suppress weed establishment shortly after sowing, whereas post-emergence herbicides target emerged weeds. Their performance can vary with the weed spectrum and the presence of less susceptible species (Pannacci and Bartolini 2018). Differences in morphology and physiological processes among weed species and across growth stages can influence herbicide retention, absorption, translocation, and metabolism (Zimdahl 2018), while climatic conditions, particularly temperature and atmospheric CO_2 concentration, may further modify weed growth and susceptibility to herbicides (Tursun *et al.* 2025). Consequently, weed-control outcomes should be evaluated at both the community and species levels. Nevertheless, repeated reliance on herbicides raises concerns about environmental contamination, biodiversity loss, and the evolution of herbicide-resistant weed populations (Norsworthy *et al.* 2012; Jabran and Chauhan 2018). Agronomic and non-chemical practices, including tillage, crop rotation, competitive cultivars, cover crops, mulching, fertilizer management, and adjustments to crop density and row spacing, can help reduce weed interference (Jabran and Chauhan 2018; Chauhan 2020; Riemens *et al.* 2022). However, their effectiveness may vary among weed species and production environments, while adoption may be constrained by labor, machinery, and production costs. Therefore, individual chemical or non-chemical methods may not provide season-long, broad-spectrum weed suppression. Among non-chemical methods, hand weeding can control a broad range of weed species but it is labor-intensive (Idziak *et al.* 2022). Its effectiveness depends strongly on the timing and frequency of implementation (Vu and Ha 2015; Tran *et al.* 2020), because weeds emerging after a single operation may continue to compete with the crop, while incompletely removed perennial weeds may regenerate from underground propagules. Integrating appropriately timed hand weeding with herbicide application can control surviving and later-emerging weeds, maintain low weed biomass, and improve crop productivity (Hirpha *et al.* 2024). Such integration can also reduce reliance on individual control measures and contribute to more sustainable weed management (Chauhan 2020).

The effectiveness of a weed-management strategy cannot be fully characterized by total weed density or biomass alone. Contrasting responses among species may alter weed dominance, community composition, and the competitive pressure exerted on the crop. This is particularly relevant in diverse weed communities containing both annual species that reproduce primarily by seeds and perennial species capable of regenerating from vegetative propagules. However, limited information is available on how chemical, non-chemical, and combined control approaches influence these species-specific and community-level responses throughout the maize growing season and how such responses relate to crop performance (Ngawit *et al.* 2024).

This study evaluated the effects of pre-emergence and post-emergence herbicides, hand weeding, and their combinations on weed community composition, weed suppression, maize growth, and grain yield. Specifically, it examined changes in the occurrence and relative dominance of individual weed species. It also compared the responses of annual and perennial weeds and assessed the relationships between weed biomass and maize productivity. This integrated assessment was intended to clarify how weed species composition and contrasting life cycles influence the outcomes of different weed-control approaches.

Materials and Methods

Study site and experimental conditions

The field experiment was conducted from March 11 to June 12, 2024, during the spring–summer maize-growing season at the experimental farm of the Vietnam National University of Agriculture, Hanoi, Vietnam (21°00′08.8″ N, 105°55′47.1″ E). Broccoli (*Brassica oleracea* var. *italica*) preceded maize in the crop rotation and was grown from October to December 2023. The field was then left fallow from January until land preparation and maize sowing in March 2024.

The soil contained 2.03% organic matter, 0.15% total N, 0.21% total P_2O_5, and 1.51% total K_2O. Available N, P_2O_5, and K_2O contents were 5.3, 37.1, and 23.9 mg · 100 g^{-1} soil, respectively. During the experimental period, mean daytime and nighttime temperatures ranged from 26.4 to 35.6°C and from 22.5 to 28.7°C, respectively. The early post-sowing period was characterized by frequent light drizzle and relative humidity generally above 90%.

Plant material and herbicides

The hybrid maize cultivar LTS237 (Loc Troi Seed Company, Vietnam) was used. The pre-emergence herbicide contained S-metolachlor (960 g a.i. · L^{-1}), whereas the post-emergence herbicide was a premix containing atrazine (50%, w/w) and mesotrione (5%, w/w).

Both herbicides were applied using a battery-powered backpack sprayer with an 18-L tank and a 12-V, 9-Ah battery (Taizhou Xienong Plastic Industry Co., Ltd., Taizhou, Zhejiang, China). S-metolachlor was applied at 0.75 L · ha^{-1} of formulated product in a spray volume of

400 L · ha^{-1} at 1 day after sowing (DAS). The application was performed in the afternoon at an air temperature of 21–22°C and relative humidity above 95%. The atrazine + mesotrione premix was applied at 3.2 L · ha^{-1} of formulated product in a spray volume of 500 L · ha^{-1} at 40 DAS, when maize was at the seven- to eight-leaf stage, in accordance with the product label. This application was performed in the afternoon at an air temperature of 34–36°C and relative humidity of 66–70%.

The sprayer was operated in the standard configuration supplied by the manufacturer. Because it was not fitted with a pressure gauge, operating pressure could not be documented. The nozzle identification code, nozzle-to-target height, operator walking speed, wind speed, and species-specific weed growth stages at the time of post-emergence application were not documented.

Experimental design

The experiment was arranged in a randomized complete block design with eight weed-control treatments and three replications. Each experimental plot measured 24 m². After conventional ploughing and harrowing before sowing, maize was planted at a density of 57,000 plants · ha^{-1}, with 70 cm between rows and 25 cm between plants within rows.

The treatments were: T0, weedy control without weed management; T1, S-metolachlor at 1 DAS; T2, atrazine + mesotrione at 40 DAS; T3, hand weeding at 20 DAS, when maize was at the three- to four-leaf stage; T4, S-metolachlor at 1 DAS followed by hand weeding at 20 DAS; T5, hand weeding at 20 DAS followed by atrazine + mesotrione at 40 DAS; T6, S-metolachlor at 1 DAS followed by atrazine + mesotrione at 40 DAS; and T7, a weed-free control maintained by manual weed removal throughout the growing season. In T3, T4, and T5, weeds were manually removed from the entire plot at 20 DAS using sickles and hoes as required. In T7, weeds were removed whenever they emerged.

Crop management

Fertilizers were applied at rates of 150 kg N · ha^{-1}, 90 kg P_2O_5 · ha^{-1}, and 90 kg K_2O · ha^{-1}. All phosphorous fertilizer was incorporated into the soil before sowing. Nitrogen and potassium fertilizers were each divided equally between applications at 25 DAS, when maize was at the four- to five-leaf stage, and 45 DAS, at the nine- to ten-leaf stage. Irrigation and pest and disease management practices were applied uniformly across treatments following local recommendations for maize production.

Data collection

Crop growth and phenology

Five maize plants per plot were randomly selected and permanently tagged. Plant height, leaf number, leaf length, and leaf width were recorded weekly throughout the growing season. Dates of seedling emergence and tasseling were also recorded, and crop duration was calculated as the number of days from sowing to harvest.

At 50 and 70 DAS, SPAD values were measured on five additional representative plants per plot using a SPAD-502 chlorophyll meter (Konica Minolta, Japan). These plants were then destructively sampled to determine leaf area index (LAI) and aboveground dry matter. Plant samples were oven-dried at 80°C until constant weight before dry matter determination.

Weed assessment

Weeds were assessed at 20 and 55 DAS. The first assessment was completed immediately before the hand-weeding operation scheduled at 20 DAS. At each assessment, two 0.25-m² quadrats were randomly placed within each plot to determine weed species composition, density, and aboveground dry biomass.

Weed species were identified following Koo *et al.* **(**2022), and the number of individuals of each species was recorded. Weeds were then harvested at ground level, cleaned to remove adhering soil, separated by species, and oven-dried at 80°C to constant weight to determine species-specific dry biomass. Density and dry biomass were expressed as plants · m^{-2} and g · m^{-2}, respectively.

Relative dominance index

To characterize weed dominance under untreated conditions, the relative dominance index (RDI) was calculated separately at 20 and 55 DAS using species density and dry biomass in the weedy control (T0):

where:

$$RD_i = \frac{D_i}{\sum_{j=1}^{S} D_j} \times 100$$

and

$$RB_i = \frac{B_i}{\sum_{j=1}^{S} B_j} \times 100$$

$$RDI_i = \frac{RD_i + RB_i}{2},$$

where: RD_i, RB_i, and RDI_i are the relative density, relative biomass, and relative dominance index of species *i*, respectively; D_i and B_i are the density and dry biomass of species *i*, respectively; and S is the total number of weed species recorded in T0 at the corresponding assessment time.

Weed control efficiency

Weed control efficiency based on dry biomass (WCE_B) was calculated separately at each assessment as:

$$WCE_B(\%) = \frac{B_c - B_t}{B_c} \times 100$$

where: Bc is the mean weed dry biomass in T0 and Bt is the mean weed dry biomass in the corresponding treatment.

Yield and yield components

At harvest, five representative plants per plot were sampled to determine the number of kernel rows per ear, kernels per row, and 1000-kernel weight. All plants in the remaining harvestable area were harvested to determine grain yield. Grain yield was adjusted to 14% moisture content and expressed as $t \cdot ha^{-1}$.

Statistical analysis

Data were analyzed using R version 4.6.0 (R Core Team 2026). Analysis of variance (ANOVA) was performed according to the randomized complete block design, with treatment and block included in the model. Data from different assessment times were analyzed separately. Treatment means were compared using Fisher's least significant difference test at $P \leq 0.05$.

Weed community structure was analyzed separately at 20 and 55 DAS using square-root-transformed plot-level species densities and Bray–Curtis dissimilarities. Permutational multivariate analysis of variance (PERMANOVA), with 999 permutations restricted within blocks, compared plots with and without pre-emergence herbicide at 20 DAS (before hand weeding) and treatments T0–T6 at 55 DAS. T7 was excluded because no weeds were recorded. Permutational analysis of multivariate dispersions (PERMDISP; 999 permutations) was used to test group dispersion, and non-metric multidimensional scaling (NMDS) was used to visualize community structure at 55 DAS. Analyses were conducted using the vegan and permute packages in R.

Simple linear regression based on plot-level observations (n = 24) was used to examine the relationships between weed dry biomass and maize grain yield. Separate models were fitted using weed biomass at 20 and 55 DAS.

Results

Weed community composition and dominance

A total of 17 weed species belonging to 11 plant families were identified in the experimental field (Table 1), comprising 13 annual and four perennial species. Broadleaf weeds were the most diverse group, comprising 11 species, followed by grasses with five species and sedges with one species. Poaceae was the most species-rich family, accounting for five species (29.4% of the total flora), whereas Amaranthaceae and Asteraceae each contributed two species (11.8%). The remaining species belonged to Araliaceae, Boraginaceae, Brassicaceae, Cyperaceae, Phyllanthaceae, Portulacaceae, Scrophulariaceae and Solanaceae.

The relative dominance index (RDI) was calculated from weed density and biomass in the weedy control (T0). At 20 DAS, four species dominated the weed community: the perennials *Cyperus rotundus* L. (RDI = 19.63%) and *Alternanthera sessilis* (L.) DC. (16.00%), and the annuals *Eleusine indica* (L.) Gaertn. (19.12%) and *Mazus pumilus* (Burm.f.) Steen. (17.07%). Together, these species accounted for 71.8% of total weed dominance, indicating that both annual and perennial weeds contributed substantially during the early growth stage of maize.

By 55 DAS, the relative importance of the dominant species had changed considerably. The perennial *A. sessilis* had the highest RDI, increasing from 16.00% at 20 DAS to 24.39% at 55 DAS. The annual grass *E. indica* and the perennial sedge *C. rotundus* also remained prevalent, with RDI values of 18.50% and 16.67%, respectively. Collectively, these three species accounted for 59.6% of total weed dominance at 55 DAS. In contrast, the RDI of the annual *M. pumilus* decreased from 17.07% to 4.76%.

Several other species showed intermediate contributions to the weed community at 55 DAS: the perennial grass *Cynodon dactylon* (L.) Pers. and the annual species *Echinochloa colona* (L.) Link, *Physalis angulata* L., and *Leptochloa chinensis* (L.) Nees had RDI values ranging from 4.26% to 8.76%. Most remaining species each accounted for less than 3% of total weed dominance, indicating that weed interference was largely characterized by a limited number of dominant species.

Weed control efficiency

Weed-control efficiency varied markedly between treatments and assessment times (Table 2). At 20 DAS, the treatments containing the pre-emergence herbicide (T1, T4, and T6) reduced weed biomass by 61.1–65.2% relative to T0. T2 showed only 8.4% numerical control because the post-emergence herbicide had not yet been applied. T3 and T5 had negative efficiency values (−8.7% and −2.9%, respectively), indicating slightly greater weed biomass than in T0 before their scheduled control operations.

By 55 DAS, weed-control efficiency was highest in T5 (99.3%), followed by T6 (98.9%) and T2 (98.2%). Combining the pre-emergence herbicide with hand weeding (T4) provided 87.7% control. In contrast, the single pre-emergence application (T1) and one-time hand weeding (T3) provided 53.8% and 66.2% control, respectively.

The weed-free control (T7) had 100% efficiency at both assessments by design because weeds were removed whenever they emerged. Because efficiency was calculated from treatment mean biomass rather than being subjected to a separate significance test, differences between efficiency percentages are reported descriptively.

Effects of weed control treatments on weed community structure

The PERMANOVA and PERMDISP results at 20 and 55 DAS are summarized in Supplementary Table S3. At 20 DAS, weed community structure differed between plots with and without pre-emergence herbicide application (PERMANOVA: pseudo-F = 80.293, R^2 = 0.8086, P = 0.001). However, PERMDISP also detected unequal dispersion between the groups (F = 25.923, P = 0.001); therefore, the PERMANOVA result should be interpreted cautiously.

At 55 DAS, community structure differed between treatments T0–T6 (PERMANOVA: pseudo-F = 142.033, R^2 = 0.9838, P = 0.001), whereas PERMDISP detected no difference in dispersion (F = 0.802, P = 0.495; Supplementary Table S3). NMDS showed clear separation among most treatments, with a low stress value of 0.0046 (Fig. 1). T5 and T6 overlapped closely, indicating similar weed community structures following hand weeding plus post-emergence herbicide and pre-emergence plus post-emergence herbicide, respectively.

Effects of weed management on maize growth and physiological traits

Seedling emergence ranged only from 7 to 8 DAS across treatments (Table 3). Tasseling occurred latest in T0 (65 DAS), compared with 59 and 58 DAS in T6 and T7, respectively. Crop duration ranged from 89 to 92 d and was 3 d shorter in T6 and T7 than in T0; these phenological differences are presented descriptively because no inferential test was reported for these variables.

Final plant height differed significantly between treatments ($P = 0.004$). Plants in T0 had the lowest final height (173.3 cm) and were significantly shorter than those in all weed-control treatments (186.4–195.0 cm), whereas T1–T7 did not differ significantly from one another. Final leaf number did not differ between treatments. Treatment also affected SPAD values, leaf area index (LAI), and dry matter (DM) accumulation at both assessment times ($P \leq 0.008$; Table 4). At 50 DAS, LAI in T0 (1.0) was significantly lower than in all weed-control treatments (1.4–1.6). T6 and T7 had greater LAI than T1–T4, and T7 also exceeded T5. SPAD values in T5 and T7 were greater than those in T0 and T1; T6 also exceeded T0 and T1, while the other treatments were intermediate. DM accumulation was lowest in T0 and T2 (106.5 and 127.2 $g \cdot m^{-2}$, respectively); T6 and T7 had higher DM than T0–T4, and T7 also exceeded T5.

At 70 DAS, all weed-control treatments had significantly greater LAI and DM accumulation than T0, which had the lowest LAI (2.6) and DM (312.7 $g \cdot m^{-2}$). T7 had the greatest DM accumulation (652.8 $g \cdot m^{-2}$) and exceeded all other treatments. DM accumulation in T5 and T6 (548.5 and 565.4 $g \cdot m^{-2}$, respectively) was greater than in the single-method treatments T1–T3. SPAD values in T1, T2, and T4–T7 were significantly greater than in T0 (28.8), whereas T3 did not differ from T0.

Yield components and grain yield

Kernel rows per ear did not differ between treatments and ranged from 16.0 to 17.8 (Table 5). In contrast, kernels per row, 1000-kernel weight, and grain yield were affected by weed-control treatment ($P < 0.001$). T0 had fewer kernels per row (25.3) than all weed-control treatments. T5 and T7 had the greatest numbers of kernels per row (36.7 and 37.0, respectively) and exceeded T1–T3; T4 and T6 also exceeded T1 and T3. The 1000-kernel weight was lower in T0 (134.4 g) than in all other treatments; T4–T7 (217.2–232.8 g) also exceeded T1–T3 (176.7–180.6 g). Grain yield was lowest in T0 (3.1 $t \cdot ha^{-1}$), and every weed-control treatment produced a significantly greater yield. The combined-control treatments T4–T6 yielded 6.8–7.0 $t \cdot ha^{-1}$, significantly more than the single-method treatments T1–T3 (4.7–5.6 $t \cdot ha^{-1}$) and did not differ from the weed-free control T7 (7.5 $t \cdot ha^{-1}$).

Relationship between weed biomass and maize grain yield

Linear regression indicated a negative relationship between weed biomass and maize grain yield at both assessment times (Fig. 2). At 20 DAS, weed biomass accounted for 32.42% of the variation in grain yield ($R^2 = 0.3242$). The relationship was considerably stronger at 55 DAS, when weed biomass accounted for 75.85% of the variation ($R^2 = 0.7585$). Thus, weed biomass at the later assessment was more closely associated with final grain yield than early-season weed biomass.

Discussion

Weed community composition and responses to weed control approaches

Although 17 weed species were recorded, dominance was concentrated in a few species. At 20 DAS, *C. rotundus*, *E. indica*, *M. pumilus*, and *A. sessilis* together accounted for more than 70% of total RDI. Thus, management priorities should consider the density and biomass contributions of dominant species rather than species richness alone.

C. rotundus had the highest RDI at 20 DAS. Its rhizomes and tubers allow rapid regeneration after disturbance, making control based only on the removal of aboveground shoots unlikely to provide lasting suppression (Peerzada 2017). The occurrence of *C. rotundus*, *E. indica*, *A. sessilis*, and several other species recorded in this study is also consistent with previous observations in maize fields (Tran *et al.* 2020). The changes observed between 20 and 55 DAS further indicated species-specific responses. The dominance of *A. sessilis* increased and that of *M. pumilus* declined markedly, whereas *E. indica* remained important at both assessments. The persistence of *E. indica* is consistent with its rapid tiller production and biomass accumulation and its competitive ability in maize (Takano *et al.* 2016; Souza *et al.* 2024). The contrasting responses of the annual species *E. indica* and *M. pumilus*, together with the persistence of the perennials *C. rotundus* and *A. sessilis*, showed that temporal changes could not be explained by annual or perennial status alone.

The multivariate analyses showed that weed-control approaches altered community structure as well as total weed abundance. At 20 DAS, the difference between plots with and without pre-emergence herbicide reflected its early filtering effect. However, the simultaneous difference in multivariate dispersion indicated that unequal within-group variability may have contributed to the PERMANOVA result (Anderson and Walsh 2013). At 55 DAS, significant PERMANOVA combined with homogeneous dispersion provided stronger evidence of distinct treatment-associated communities. The separation of most treatments in the NMDS ordination (Fig. 1) further supported this pattern. The overlap between T5 and T6 suggested that their shared post-emergence herbicide application largely shaped the surviving weed communities despite their different early interventions. These findings supported an integrated approach that considers shifts in the entire weed community rather than focusing only on individual species or short-term reductions in weed abundance (Riemens *et al.* 2022).

Effectiveness of different weed control approaches

The weed-control approaches differed mainly in the timing and duration of weed suppression. At 20 DAS, treatments containing the pre-emergence herbicide S-metolachlor (T1, T4, and T6) provided the greatest early suppression. These treatments markedly reduced the densities of the annual grasses *E. indica*, *E. colona*, and *L. chinensis* (Supplementary Table S1), consistent with the role of pre-emergence herbicides in limiting weed emergence and establishment in maize (Janak and Grichar 2016; Silva *et al.* 2023). By contrast, *A. sessilis*, *C. rotundus*, and *C. dactylon* were less effectively suppressed. Regeneration from underground tubers or rhizomes may partly explain the persistence of the two perennial species (Peerzada 2017); however, the response of *A. sessilis* indicated that treatment efficacy was species-specific and could not be explained by life-cycle category alone.

At 55 DAS, weed-control efficiency was 53.8% in the single pre-emergence treatment (T1) and 66.2% following one-time hand weeding (T3). The decline in the efficacy of T1 from 61.1% at 20 DAS suggested later emergence or recovery of weeds not completely suppressed by S-metolachlor. Similarly, *A. sessilis*, *C. rotundus*, and *E. indica* remained prevalent under T3 (Supplementary Table S2), showing that a single hand-weeding operation did not provide season-long control. Complete suppression in T7 was expected because weeds were removed repeatedly, but the labor requirement of this approach may limit its practical application at larger scales (Idziak *et al.* 2022).

The post-emergence treatment T2 showed a different temporal pattern. Its small numerical reduction at 20 DAS was unrelated to treatment because the herbicide had not yet been applied. Following application at 40 DAS, however, weed biomass was reduced by 98.2% at 55 DAS, with only small residual populations of *C. rotundus* and *C. dactylon* (Supplementary Table S2). This broad suppression may reflect the complementary activity of atrazine, a photosystem II inhibitor, and mesotrione, an HPPD inhibitor. Improved weed control from combining these two sites of action has also been reported in maize, although the magnitude of the interaction depends on weed species and application conditions (Fluttert *et al.* 2022).

The sequential programs T4–T6 were also highly effective at 55 DAS. Adding hand weeding to the pre-emergence treatment increased weed-control efficiency from 53.8% in T1 to 87.7% in T4 by removing surviving and later-emerging weeds. T5 and T6 achieved efficiencies exceeding 98%; however, their efficacy was similar to that of T2 (98.2%). Therefore, the present results did not show that every combined program was superior to the post-emergence treatment during this growing season. Rather, sequential interventions broadened the control period and reduced opportunities for weeds to escape or recover, particularly in T4 compared with T1. This supported integrated programs that target weeds at different stages of their life cycle (Riemens *et al.* 2022). Overall, treatment success depended jointly on application timing and species-specific susceptibility.

Weed competition as a determinant of maize growth and yield

Effective weed suppression was accompanied by improved maize growth and productivity. Treatments providing more sustained control, particularly T4, T5, T6, and T7, generally produced higher LAI, SPAD values, dry matter accumulation, and grain yield than the weedy control (T0). Reduced weed interference likely allowed greater canopy development and assimilate accumulation, thereby supporting grain production.

The yield response was expressed mainly through increased kernels per row and 1000-kernel weight, whereas the number of kernel rows per ear did not differ significantly between treatments. This suggested that weed interference affected kernel set and grain filling more strongly than kernel-row formation. Cerrudo *et al.* (2012) showed that weed competition restricted maize dry matter accumulation and subsequently reduced kernel number and kernel weight.

Regression analysis further demonstrated a negative relationship between weed biomass and maize productivity. This relationship was stronger at 55 DAS ($R^2 = 0.759$) than at 20 DAS ($R^2 = 0.324$), indicating that later weed biomass was a better indicator of final yield variation. However, this did not mean that late weed interference alone caused the observed yield reduction. Rather, weed biomass at 55 DAS integrated weed emergence, survival, and growth over a longer portion of the growing season and therefore represented cumulative weed pressure more comprehensively. Adamič Zamljen and Leskovšek (2024) found that weed dry biomass increased with the duration of weed interference, whereas weed density peaked during intermediate assessments and subsequently declined. They also reported significant maize grain-yield reductions as the period of weed interference increased. These findings demonstrated that weed density and biomass may follow different temporal patterns and supported the interpretation of later-season weed biomass as an integrative indicator of cumulative weed pressure. Nevertheless, the present experiment was not designed to determine the precise critical period of weed control. The contrasting responses of T1 and T2 also showed that weed-control efficiency at a single assessment should not be considered in isolation. T1 provided effective early suppression, but its efficacy declined later, whereas T2 achieved strong control at 55 DAS only after weeds had remained uncontrolled until 40 DAS. By contrast, T4, T5, and T6 applied control at two different times and produced grain yields comparable to the weed-free treatment. Thus, maize productivity depended on both the timing and persistence of weed suppression rather than late-season control efficiency alone. These results supported programs combining complementary control timings to protect the crop throughout sensitive growth stages (Idziak *et al.* 2022; Riemens *et al.* 2022).

These results indicated that weed-management decisions should account not only for overall control efficiency but also for the timing and persistence of weed suppression and the species that remain after control, because these factors jointly determined cumulative weed pressure and maize productivity.

Conclusions

The maize weed community was dominated by a limited number of species, particularly *C. rotundus*, *E. indica*, and *A. sessilis*, although their relative importance shifted during the growing season. Responses to the evaluated control approaches varied mainly between species and could not be explained by life-cycle category alone. Although the perennial species *C. rotundus* and *C. dactylon* tended to persist under several treatments, susceptibility differed among species within both the annual and perennial groups. Weed-control decisions should therefore consider community composition, the dominant species present, and their responses to individual control approaches.

Weed biomass at 55 DAS was more strongly associated with grain yield than biomass at 20 DAS, suggesting that the later assessment better represented cumulative weed pressure. Programs involving interventions at complementary times broadened the period of control and reduced the opportunity for surviving or later-emerging weeds to re-establish. Overall, maize growth and grain yield depended not only on the magnitude of weed suppression but also on its timing and persistence throughout the growing season.

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Table 1. Weed species composition, life cycle, and relative dominance index (RDI) at 20 and 55 days after sowing (DAS) in the weedy control (T0).

No	Weed species	Family	Weed group	Life cycle	Relative dominance index (%)	
					20 DAS	55 DAS
1	*Alternanthera sessilis* (L.) DC.	Amaranthaceae	B	P	16.00	24.39
2	*Physalis angulata* L.	Solanaceae	B	A	3.93	4.97
3	*Mazus pumilus* (Burm.f.) Steen.	Scrophulariaceae	B	A	17.07	4.76
4	*Ixeris polycephala* Cass.	Asteraceae	B	A	1.20	2.40
5	*Hydrocotyle verticillata* Thunb.	Araliaceae	B	P	1.01	1.63
6	*Amaranthus viridis* L.	Amaranthaceae	B	A	1.47	1.62
7	*Heliotropium indicum* L.	Boraginaceae	B	A	0.56	1.15
8	*Phyllanthus urinaria* L.	Phyllanthaceae	B	A	0.61	0.76
9	*Eclipta prostrata* (L.) L.	Asteraceae	B	A	0.30	0.78
10	*Rorippa benghalensis* (DC.) Hara	Brassicaceae	B	A	2.44	0.55
11	*Portulaca oleracea* L.	Portulacaceae	B	A	0.39	0.51
12	*Cyperus rotundus* L.	Cyperaceae	S	P	19.63	16.67
13	*Eleusine indica* (L.) Gaertn.	Poaceae	G	A	19.12	18.50
14	*Cynodon dactylon* (L.) Pers.	Poaceae	G	P	6.03	8.76
15	*Echinochloa colona* (L.) Link.	Poaceae	G	A	4.72	6.20
16	*Leptochloa chinensis* (L.) Nees	Poaceae	G	A	3.93	4.26
17	*Dactyloctenium aegyptium* (L.) Willd.	Poaceae	G	A	1.58	2.09

B = broadleaf weed; G = grass; S = sedge; A = annual; P = Perennial; DAS = days after sowing.

Table 2. Weed-control efficiency (%) calculated from weed biomass under different weed-control treatments at 20 and 55 days after sowing (DAS).

Treatment	Weed control efficiency (%)	
	20 DAS	55 DAS
T0	-	-
T1	61.1	53.8
T2	8.4	98.2
T3	-8.7[(i)]	66.2
T4	63.7	87.7
T5	-2.9[(i)]	99.3
T6	65.2	98.9
T7	100[(ii)]	100[(ii)]

[(i)]Negative values indicate greater weed biomass than that observed in the weedy control; [(ii)]Weed control efficiency was considered 100% in the weed-free treatment (T7), where weeds were removed manually throughout the growing season.

Table 3. Growth and phenological traits of maize under different weed-control treatments.

Treatment	Growth duration (days)			Plant height (cm)	Leaf number
	Sowing to emergence	Sowing to tasseling	Sowing to harvest		
T0	7	65	92	173.3[b]	13.7
T1	8	64	92	188.1[a]	13.8
T2	7	62	92	190.1[a]	13.7
T3	7	63	92	188.3[a]	13.7
T4	7	63	92	192.6[a]	13.7
T5	8	61	90	192.1[a]	13.6
T6	7	59	89	193.5[a]	13.8
T7	7	58	89	194.9[a]	13.8
P- value	-	-	-	*0.004*	*n.s*
LSD $_{(p = 0.05)}$	-	-	-	*8.7*	-

Values are treatment means (n = 3). P-values were obtained from ANOVA. LSD = Fisher's least significant difference at P = 0.05; n.s: not significant at p ≤ 0.05. Means followed by the same letter within a column are not significantly different according to Fisher's LSD test at P ≤ 0.05. n.s. = not significant.

Table 4. SPAD values, leaf area index (LAI), and dry matter accumulation of maize under different weed-control treatments at 50 and 70 days after sowing (DAS).

Treatment	SPAD value		LAI		Dry matter ($g \cdot m^{-2}$)	
	50 DAS	70 DAS	50 DAS	70 DAS	50 DAS	70 DAS
T0	35.9^{cd}	28.8^{c}	1.0^{f}	2.6^{e}	106.5^{d}	312.7^{e}
T1	35.7^{d}	34^{ab}	1.5^{de}	3.3^{cd}	165.5^{c}	449.0^{d}
T2	38.7^{abcd}	34.1^{ab}	1.4^{e}	3.7^{abcd}	127.2^{d}	475.4^{cd}
T3	37.6^{bcd}	32.1^{bc}	1.4^{e}	3.3^{d}	160.2^{c}	466.0^{d}
T4	38.8^{abc}	35.7^{ab}	1.5^{cd}	3.6^{bcd}	175.3^{c}	529.3^{bc}
T5	41.2^{a}	36.6^{a}	1.5^{bc}	3.7^{abc}	179.5^{bc}	548.5^{b}
T6	40^{ab}	37.9^{a}	1.6^{ab}	3.9^{ab}	208.5^{ab}	565.4^{b}
T7	41.6^{a}	37.6^{a}	1.6^{a}	4.1^{a}	222.6^{a}	652.8^{a}
P-value	*0.007*	*0.008*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*
LSD $_{(p = 0.05)}$	*3.08*	*4.38*	*0.06*	*0.42*	*30.92*	*54.43*

Values are treatment means (n = 3). P-values were obtained from ANOVA. LSD = Fisher's least significant difference at P = 0.05. Means followed by the same letter within a column are not significantly different according to Fisher's LSD test at P ≤ 0.05.

Table 5. Yield components and grain yield of maize under different weed-control treatments.

Treatment	Kernel rows per ear	Kernels per row	1000-kernel weight (g)	Grain yield ($t \cdot ha^{-1}$)	Yield increase over the weedy control (%)
T0	16.7	25.3^{e}	134.4^{c}	3.1^{d}	-
T1	16.2	29.8^{d}	180.6^{b}	4.9^{bc}	57.1
T2	16.2	33.6^{bc}	180.0^{b}	5.6^{b}	81.7
T3	16.0	30.9^{cd}	176.7^{b}	4.7^{c}	52.5
T4	17.7	35.3^{ab}	220.6^{a}	6.8^{a}	118.4
T5	16.9	36.7^{a}	228.0^{a}	6.8^{a}	119.2
T6	17.8	36.1^{ab}	217.2^{a}	7.0^{a}	126.6
T7	17.1	37.0^{a}	232.8^{a}	7.5^{a}	140.2
P-value	*n.s*	*< 0.001*	*< 0.001*	*< 0.001*	-
LSD $_{(p = 0.05)}$	-	*2.91*	*30.61*	*0.85*	-

Values are treatment means (n = 3). P-values were obtained from ANOVA. LSD = Fisher's least significant difference at P = 0.05. Yield increase (%) was calculated relative to the weedy control (T0). Means followed by the same letter within a column are not significantly different according to Fisher's LSD test at P ≤ 0.05. n.s. = not significant.

Supplementary Table S1. Weed species composition and density (plants · m^{-2}) under different weed control treatments at 20 and 55 days after sowing (DAS)

No	Weed species	Family	Weed group	Life cycle	Weed density (plant · m^{-2}) at 20 DAS								Weed density (plant · m^{-2}) at 55 DAS							
					T0	T1	T2	T3	T4	T5	T6	T7	T0	T1	T2	T3	T4	T5	T6	T7
1	*Alternanthera sessilis* (L.) DC.	Amaranthaceae	B	P	24.7	18.0	21.3	26.0	15.3	32.0	14.7	0	46.7	34.0	0	36.7	22.7	0	0	0
2	*Physalis angulata* L.	Solanaceae	B	A	6.3	1.3	7.3	5.3	1.3	9.3	2.0	0	6.7	2.0	0	1.3	0	0	0	0
3	*Mazus pumilus* (Burm.f.) Steen.	Scrophulariaceae	B	A	57.3	2.0	44.7	52.7	1.3	56.7	2.0	0	23.3	0	0	1.7	1.3	0	0	0
4	*Ixeris polycephala* Cass.	Asteraceae	B	A	5.3	1.3	3.3	1.3	0.7	4.7	1.3	0	6.0	1.3	0	2.0	0	0	0	0
5	*Hydrocotyle verticillata* Thunb.	Araliaceae	B	P	3.3	2.7	2.7	3.3	1.3	2.0	2.0	0	5.3	2.7	0	1.3	0	0	0	0
6	*Amaranthus viridis* L.	Amaranthaceae	B	A	4.7	0	5.3	4.7	1.3	6.0	0	0	4.7	1.3	0	0	0	0	0	0
7	*Heliotropium indicum* L.	Boraginaceae	B	A	2.7	0	1.3	2.7	0	1.3	0	0	2.7	1.3	0	0	0	0	0	0
8	*Phyllanthus urinaria* L.	Phyllanthaceae	B	A	2.7	0	1.3	2.0	0	3.3	0	0	3.3	0	0	0	0	0	0	0
9	*Eclipta prostrata* (L.) L.	Asteraceae	B	A	1.3	0	2.7	2.0	0	1.3	0	0	2.7	0	0	0	0	0	0	0
10	*Rorippa benghalensis* (DC.) Hara	Brassicaceae	B	A	8	1.3	8.7	4.7	0	8.7	0	0	1.3	0	0	1.3	0.7	0	0	0
11	*Portulaca oleracea* L.	Portulacaceae	B	A	1.3	0	0.7	1.3	0	1.3	0.7	0	1.3	0	0	1.3	0	0	0	0
12	*Cyperus rotundus* L.	Cyperaceae	S	P	38.7	22.7	46.0	51.3	27.3	40.0	21.3	0	54.7	42.0	14.0	24.7	25.3	7.0	8.3	0
13	*Eleusine indica* (L.) Gaertn.	Poaceae	G	A	64.0	4.7	56.7	54.3	4.0	52.0	4.0	0	58	6.0	0	15.3	8.0	0	0	0
14	*Cynodon dactylon* (L.) Pers.	Poaceae	G	P	11.3	5.3	14.0	8	10.7	16.7	6.7	0	17.3	10.7	2.0	3.3	4.0	0	0	0
15	*Echinochloa colona* (L.) Link.	Poaceae	G	A	10.7	2.7	13.3	9.3	2.7	14.7	2.0	0	12.0	2.7	0	2.7	0	0	0	0
16	*Leptochloa chinensis* (L.) Nees	Poaceae	G	A	15.3	2.0	13.3	16.7	1.3	12.7	0	0	17.3	1.3	0	2.7	0	0	0	0
17	*Dactyloctenium aegyptium* (L.) Willd.	Poaceae	G	A	4.0	0	5.3	9.3	0	6.7	2.0	0	8.0	0.7	0	1.3	0	0	0	0

Notes: B = broadleaf weed; G = grass; S = sedge; A = annual; P = Perennial; DAS = days after sowing.

Supplementary Table S2. Weed species composition and dry biomass ($g \cdot m^{-2}$) under different weed control treatments at 20 and 55 days after sowing (DAS)

No	Weed species	Family	Weed group	Life cycle	Weed dry biomass ($g \cdot m^{-2}$) at 20DAS								Weed dry biomass ($g \cdot m^{-2}$) at 55 DAS							
					T0	T1	T2	T3	T4	T5	T6	T7	T0	T1	T2	T3	T4	T5	T6	T7
1	*Alternanthera sessilis* (L.) DC.	Amaranthaceae	B	P	2.36	1.24	2.04	2.95	1.27	2.61	1.08	0	27.40	23.42	0	19.56	5.14	0	0	0
2	*Physalis angulata* L.	Solanaceae	B	A	0.57	0.06	0.66	0.72	0.08	0.58	0.12	0	6.48	2.16	0	0.82	0	0	0	0
3	*Mazus pumilus* (Burm.f.) Steen.	Scrophulariaceae	B	A	1.28	0.04	0.74	1.06	0.05	0.94	0.09	0	0.82	0	0	0.24	0.16	0	0	0
4	*Ixeris polycephala* Cass.	Asteraceae	B	A	0.04	0	0.05	0.02	0.01	0.04	0.01	0	2.24	0.48	0	0.37	0	0	0	0
5	*Hydrocotyle verticillata* Thunb.	Araliaceae	B	P	0.08	0.04	0.04	0.06	0.09	0.04	0.02	0	1.14	0.75	0	0.09	0	0	0	0
6	*Amaranthus viridis* L.	Amaranthaceae	B	A	0.12	0	0.16	0.05	0.06	0.12	0	0	1.31	0.88	0	0	0	0	0	0
7	*Heliotropium indicum* L.	Boraginaceae	B	A	0.01	0	0.01	0.04	0	0.03	0	0	1.12	0.64	0	0	0	0	0	0
8	*Phyllanthus urinaria* L.	Phyllanthaceae	B	A	0.02	0	0.03	0.05	0	0.07	0	0	0.27	0	0	0	0	0	0	0
9	*Eclipta prostrata* (L.) L.	Asteraceae	B	A	0.01	0	0.02	0.07	0	0.01	0	0	0.49	0	0	0	0	0	0	0
10	*Rorippa benghalensis* (DC.) Hara	Brassicaceae	B	A	0.19	0.03	0.14	0.09	0	0.15	0	0	0.54	0	0	0.84	0.06	0	0	0
11	*Portulaca oleracea* L.	Portulacaceae	B	A	0.03	0	0.05	0.03	0	0.05	0.02	0	0.48	0	0	0.78	0	0	0	0
12	*Cyperus rotundus* L.	Cyperaceae	S	P	2.56	1.23	2.38	2.83	1.13	2.87	1.08	0	11.44	8.27	1.04	3.11	3.59	0.65	0.93	0
13	*Eleusine indica* (L.) Gaertn.	Poaceae	G	A	1.44	0.18	1.16	1.69	0.11	1.03	0.18	0	13.56	0.72	0	0.58	1.03	0	0	0
14	*Cynodon dactylon* (L.) Pers.	Poaceae	G	P	0.81	1.08	0.84	0.71	0.78	0.98	1.01	0	9.68	2.03	0.51	0.85	0.71	0	0	0
15	*Echinochloa colona* (L.) Link.	Poaceae	G	A	0.56	0.14	0.88	0.63	0.05	0.92	0.02	0	6.92	0.58	0	0.74	0	0	0	0
16	*Leptochloa chinensis* (L.) Nees	Poaceae	G	A	0.21	0.03	0.23	0.19	0.16	0.11	0	0	1.86	0.10	0	0.84	0	0	0	0
17	*Dactyloctenium aegyptium* (L.) Willd.	Poaceae	G	A	0.17	0	0.15	0.18	0	0.22	0.01	0	1.07	0.08	0	0.56	0	0	0	0

Notes: B = broadleaf weed; G = grass; S = sedge; A = annual; P = Perennial; DAS = days after sowing.

Supplementary Table S3. Results of PERMANOVA and PERMDISP analyses of weed community structure based on Bray–Curtis dissimilarities of square-root-transformed species-density data at 20 and 55 days after sowing (DAS)

Assessment time	Comparison	pseudo-F	R^2	PERMANOVA p	PERMDISP F	PERMDISP p
20 DAS	With vs. without pre-emergence herbicide	80.293	0.8086	0.001	25.923	0.001
55 DAS	T0–T6	142.033	0.9838	0.001	0.802	0.495

At 20 DAS, treatments receiving the pre-emergence herbicide (T1, T4, and T6) were compared with treatments not receiving the pre-emergence herbicide (T0, T2, T3, and T5). At 55 DAS, treatments T0–T6 were compared. Treatment T7 was excluded because no weeds were recorded. P-values were based on 999 permutations. DAS = days after sowing.

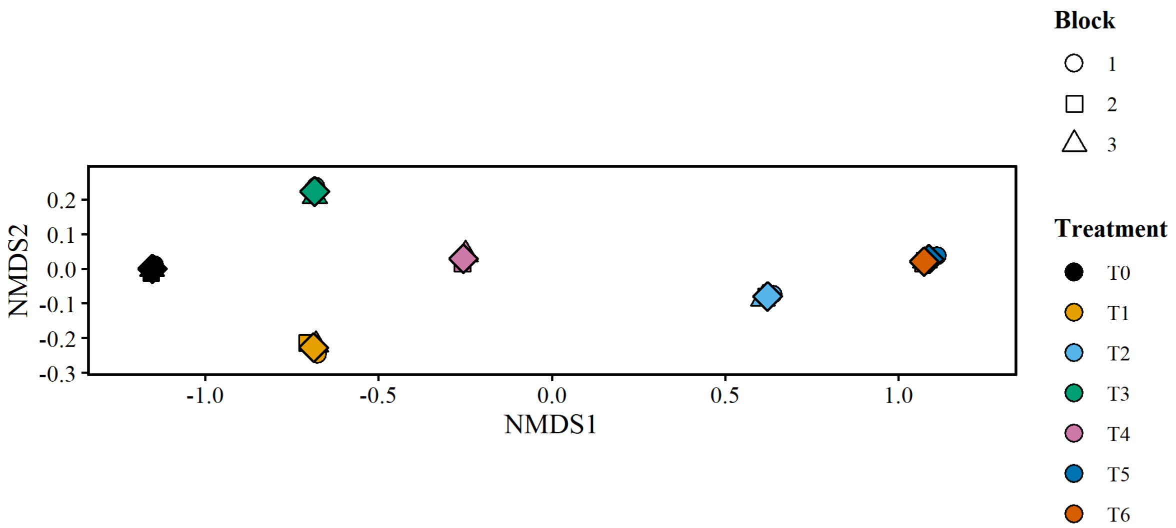

Fig. 1. Non-metric multidimensional scaling (NMDS) ordination of weed communities based on Bray–Curtis dissimilarities calculated from square-root-transformed weed density data at 55 days after sowing (DAS). Colors indicate weed-control treatments (T0–T6), and symbols indicate experimental blocks. Treatment T7 was excluded because no weeds were recorded. Stress = 0.0046.

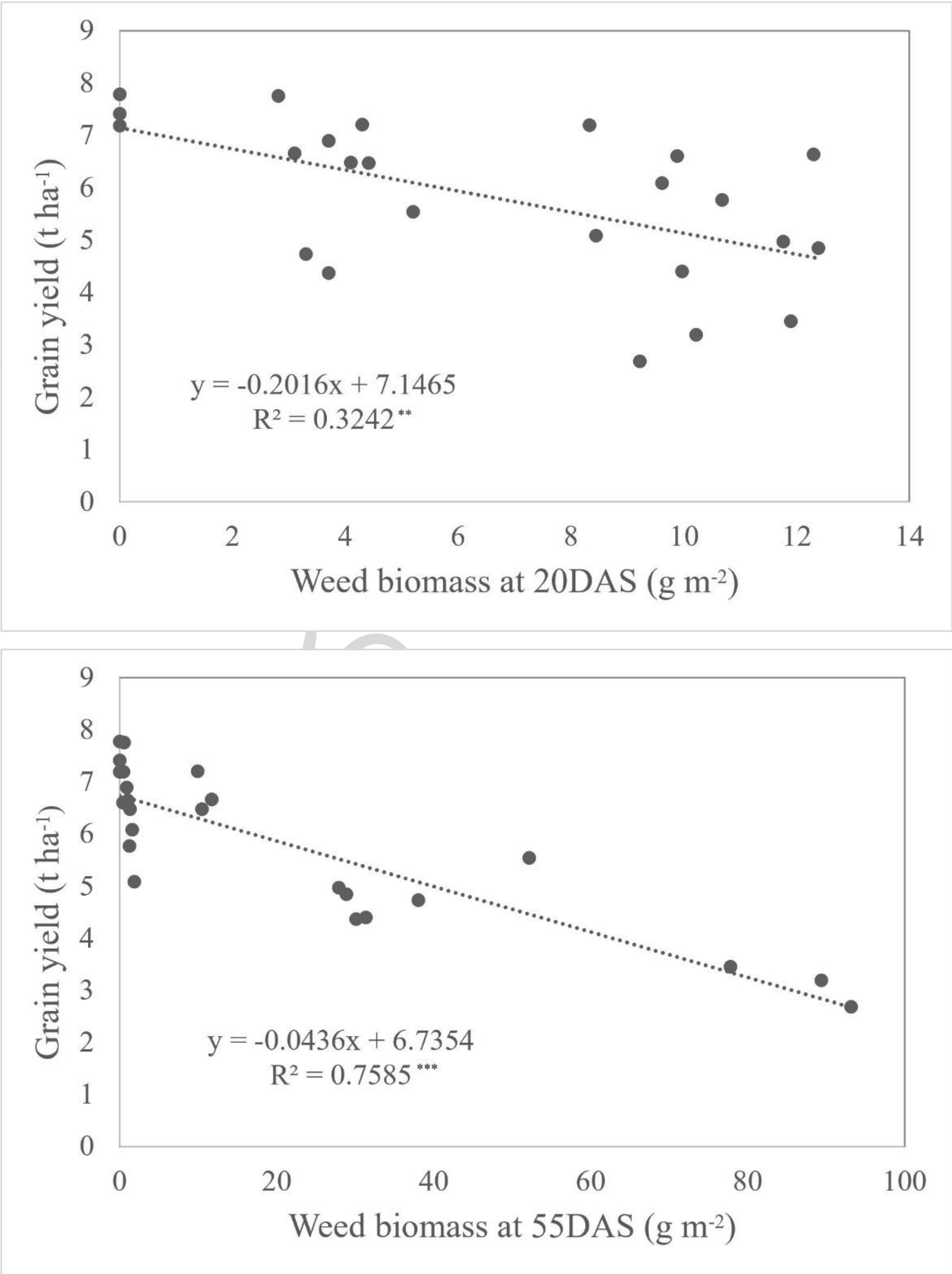

Fig. 2. Maize grain yield in relation to weed biomass at 20 and 55 days after sowing (DAS).