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CROP PROTECTION

Growth and development of smooth pigweed (*Amaranthus hybridus*) emerged at different times of the year

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ABSTRACT: Successful chemical weed control requires applying the herbicide when the weed is still small. However, the rapid growth of *Amaranthus* species makes the time window between emergence and maximum controllable size shorter, making their management difficult. Little is known about the *Amaranthus hybridus* growth rate under the edaphoclimatic conditions of South America. Therefore, this study defined the daily growth of *A. hybridus* in different emergence times. Smooth pigweed plants were established in November 2020, December 2020, and January 2021. Plants were measured every two days, and the entire development cycle was monitored. *A. hybridus* plants that emerged in November had higher plant height, on average, 227 cm, and higher dry mass, around 909.5 g plant^{-1}. Plants that emerged in January were shorter, reaching around 197 cm, and had a lower dry mass, that is, on average 296.5 g plant^{-1}. However, plants that emerged in January had a higher daily growth rate. Flowering occurred between 30 and 56 days after sowing, with an accumulated thermal sum of 468 to 926 degree-days. The *A. hybridus* growth rates were 2.47, 2.5, and 2.98 cm day^{-1} for emergence in November, December, and January, respectively.
Key words: phenology, sustainable agriculture, integrated management, soil and climate conditions.

Crescimento e desenvolvimento de caruru-roxo (*Amaranthus hybridus*) emergido em diferentes períodos do ano

RESUMO: Para que o controle químico de plantas daninhas seja bem sucedido, o herbicida deve ser aplicado quando a planta daninha ainda é pequena. Devido ao rápido crescimento das espécies de *Amaranthus*, a janela de tempo entre a emergência e o tamanho máximo controlável é mais curta, dificultando seu manejo. Entretanto, pouco se sabe sobre a taxa de crescimento de *Amaranthus hybridus* nas condições edafoclimáticas da América do Sul. Desta forma, o presente estudo visa definir o crescimento diário de *Amaranthus hybridus* em diferentes épocas de emergência. Um experimento foi implantado com estabelecimento de plantas de caruru-roxo em novembro de 2020, dezembro de 2020 e janeiro de 2021. As plantas foram medidas a cada dois dias, e todo o ciclo de desenvolvimento foi monitorado. Plantas de *A. hybridus* que emergem em novembro apresentam maior estatura de plantas, em média 227 cm, e maior massa seca, em torno de 909,5 g planta^{-1}. Já as plantas que emergem em janeiro são mais baixas, cerca de 197 cm, e têm menor massa seca, em média 296,5 g planta^{-1}. Entretanto, plantas emergidas em janeiro apresentam maior taxa de crescimento diário. O florescimento ocorreu entre 30 e 56 dias após a semeadura, com soma térmica acumulada de 468 a 926 graus-dia. A taxa de crescimento de *A. hybridus* foi de 2,47; 2,5; 2,98 cm dia^{-1} para a emergência em novembro, dezembro e janeiro, respectivamente.
Palavras-chave: fenologia, agricultura sustentável, manejo integrado, condições edafoclimáticas.

INTRODUCTION

The genus *Amaranthus* includes species considered weeds in agricultural systems. Smooth pigweed (*Amaranthus hybridus* L.) is a dicotyledonous plant, with an annual cycle, recognized as one of the main weeds in agricultural areas (LARRAN et al., 2018). This species has highly competitive capacity, production rate, and seed viability (BARROSO et al., 2012), and uneven germination, which results in emergence flows throughout the growth of crops (NETTO et al., 2016). Furthermore, there are reports of biotypes resistant to herbicides that inhibit ALS and EPSP enzymes in Brazil, which places it among the most important agronomic weeds (ZANDONÁ et al., 2022).

Weeds of the genus *Amaranthus* show high phenotypic plasticity, which is the ability to change their phenotype in response to environmental changes (MARTÍNEZ-NUÑEZ et al., 2019). The discontinued germination pattern lasts throughout the growing season, which allows smooth pigweed to grow after all management practices have been completed, contributing to the increase in specimens in the soil seed bank (HENEGHAN & JOHNSON, 2017). Understanding weed biology and ecology, such as the duration of the development cycle and

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growth rate in response to environmental conditions, enables preventive control and is critical to mitigating and managing herbicide-resistant populations. This information should be used to select, integrate, and implement various control tools to eliminate the weed population over time rather than continuing with the reactive use of exclusively chemical solutions (WESTERMAN et al., 2005).

Studies have shown that *Amaranthus palmeri* grows 1.6 times faster than *Amaranthus rudis* and produces twice the leaf area of other *Amaranthus* species. SELLERS et al. (2003) reported that the height of *A. palmeri* is 3.7 cm larger than *Amaranthus retroflexus*, the second tallest species among the evaluated *Amaranthus*. Successful chemical control with adequate target coverage requires applying herbicide when the weed is still small, as described on most product labels (BERGER et al., 2015). Even control methods other than chemical ones need to be conducted early for effective control (PISKACKOVA et al., 2020). The rapid growth of *Amaranthus* species makes the time window between emergence and maximum controllable size shorter, making their management difficult (PISKACKOVA et al., 2020).

However, little is known about the *A. hybridus* growth rate under the edaphoclimatic conditions of South America. Considering the need for knowledge of the biology of weeds and the importance of this knowledge for integrated weed management and a consequent more sustainable agriculture, this study defined the daily growth of *A. hybridus* at different emergence times.

MATERIALS AND METHODS

The experiments were conducted on planting beds at the School of Agricultural Sciences, Innovation, and Business at the Universidade de Passo Fundo (ESAN/UPF) (28°13'17"S, 52°23'04"W, 672 m altitude). The seeds were collected from an agricultural area infested with smooth pigweed in the municipality of Pontão, in the state of Rio Grande do Sul (28°2'31"S, 52°34'49"W, 695 m altitude), during the 2019/2020 harvest. The experimental design was completely randomized with 10 replications for each emergence time, that is, the months of November and December 2020 and January 2021. Smooth pigweed seeds were sown in polystyrene trays filled with substrate and soil in a 1:1 ratio to obtain plants at those times. The seedlings at the two-leaf stage were transplanted into the planting bed with a spacing of 0.5 m between plants. The seedlings were watered at the transplanting time, and soil moisture was maintained close to field capacity throughout the experiment, with watering whenever necessary. Figure 1 shows the mean air temperature and rainfall conditions extracted from the Embrapa Wheat meteorological station in Passo Fundo (RS). The planting bed was maintained free from infestation of other weeds through manual control. Insecticide was applied when necessary to control aphids that attacked smooth pigweed plants.

Plant height data was collected every two days, measuring all plants from the soil surface to the apex of the shoot or highest point of the reproductive structure, when it was present. Plant phenology was evaluated every two days according to the BBCH scale, a system for uniform coding of phenological growth stages of all species of mono- and dicotyledonous plants (MEIER et al., 2009). The beginning of flowering was determined when the inflorescence emerged 0.6 cm above the shoot apex. The plants with the emerged inflorescence were counted and divided by the total number of plants at each time to obtain the percentage. These data were collected from transplanting until one week after full flowering.

Dry mass was evaluated in plants from each time harvested four weeks after the collective flowering average exceeded 90%, allowing maturation and retention of seeds. At the same time, the roots were collected using a cutting shovel. After extraction, the roots were washed to remove the soil. Then, plants and roots were dried in an oven at 65 °C for 72 hours and, subsequently, weighed on a precision scale.

The daily thermal sum, in degree-days (DD), was obtained using equation 1:

$$DD = \{[(T_{max} + T_{min})/2] - T_b \quad (1)$$

where DD is the degree-days for a given day, T_{max} and T_{min} are the maximum and minimum daily air temperatures, respectively, with a lower limit of 10 °C, and T_b is the base temperature below which little or no growth occurs. The T_b of 10 °C was chosen based on the minimum germination temperatures for *Amaranthus* species (MARTÍNEZ-NÚÑEZ et al., 2019).

Plant height data relative to accumulated degree-days were fitted to a four-parameter non-linear regression model, according to equation 2:

$$y = c + \frac{(d-c)}{[1+\left(\frac{x}{i50}\right)^{(-b)}]} \quad (2)$$

where y is the height (cm) at time x, c is the maximum height (cm), d is the minimum height (cm), $i50$ is the inflection point or time to reach 50% of the final

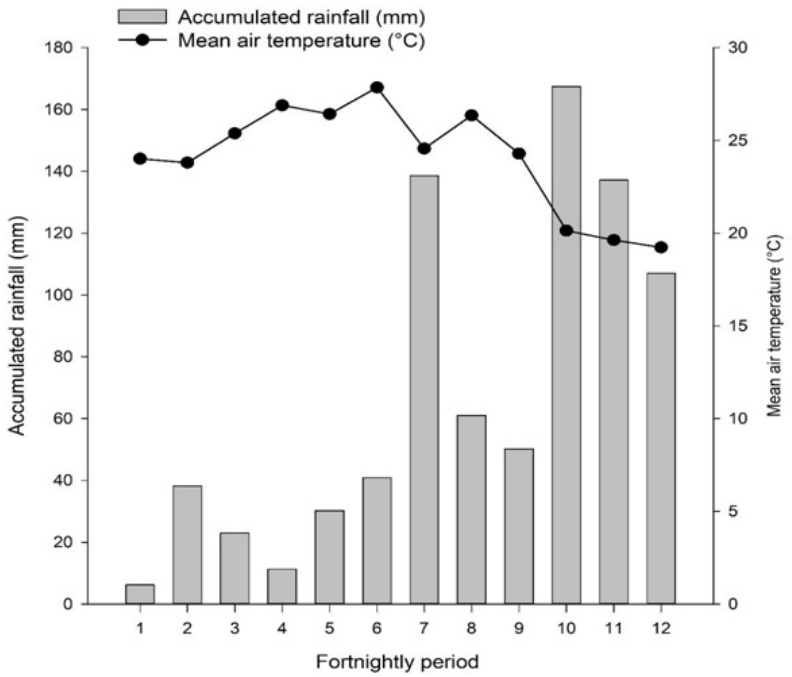


Figure 1 - Accumulated rainfall (mm) and daily mean air temperature (°C) during the experiment period. Passo Fundo, RS, Brazil, 2022. *Accumulated rainfall and mean air temperature data were grouped by fortnight. The period covered begins on 11/01/2021 and ends on 04/30/2022. The fortnights are represented by the numbers 1 to 12 in the figure, where "1" corresponds to the period from 11/01/2021 to 11/15/2021, "2" to the period from 11/16/2021 to 30/11/2021, and so on.

Source: Adapted from INMET (2022).

height (accumulated degree-days), and *b* is the rate of change around *i50*.

Plant height relative to the days of duration of the experiment was adjusted to a three-parameter non-linear logistic regression, as described in equation 3:

$$y = \frac{a}{1+\left(\frac{x}{b}\right)^{c}} \quad (3)$$

in which *y* is the plant height (cm), *x* is the time in days after transplanting, *a* is the range between maximum and minimum height (cm), *b* is the time to reach 50% of final height (days after emergence), and *c* is the slope of the curve around *b*.

The mass data was subjected to analysis of variance using the F-test at a 5% probability. The normality of residuals was verified by the Shapiro-Wilk test and the homogeneity of variances was verified by the Bartlett test. Subsequently, the data were subjected to the Tukey test at a 5% probability of error, in the RStudio software (R CORE TEAM, 2019).

RESULTS AND DISCUSSION

The height of *A. hybridus* plants varied between emergence times, showing a tendency to be higher in the first emergence period (227 cm) and shorter when it emerged in January (197 cm) (Figure 2). The faster accumulation of thermal sum and exposure to decreasing photoperiods, starting from the summer solstice, may have accelerated the development cycle and reduced the growth of smooth pigweed plants emerging in January. Populations of *A. palmeri* from different locations in the United States showed differences in plant height, with late-established populations being on average 30% taller than those established at the beginning of the growing season (SPAUNHORST et al., 2018).

The regressions generated for plant height as a function of the degree-days accumulated in the evaluated emergence periods showed that 684.88 and 611.91 degree-days are required for emergences

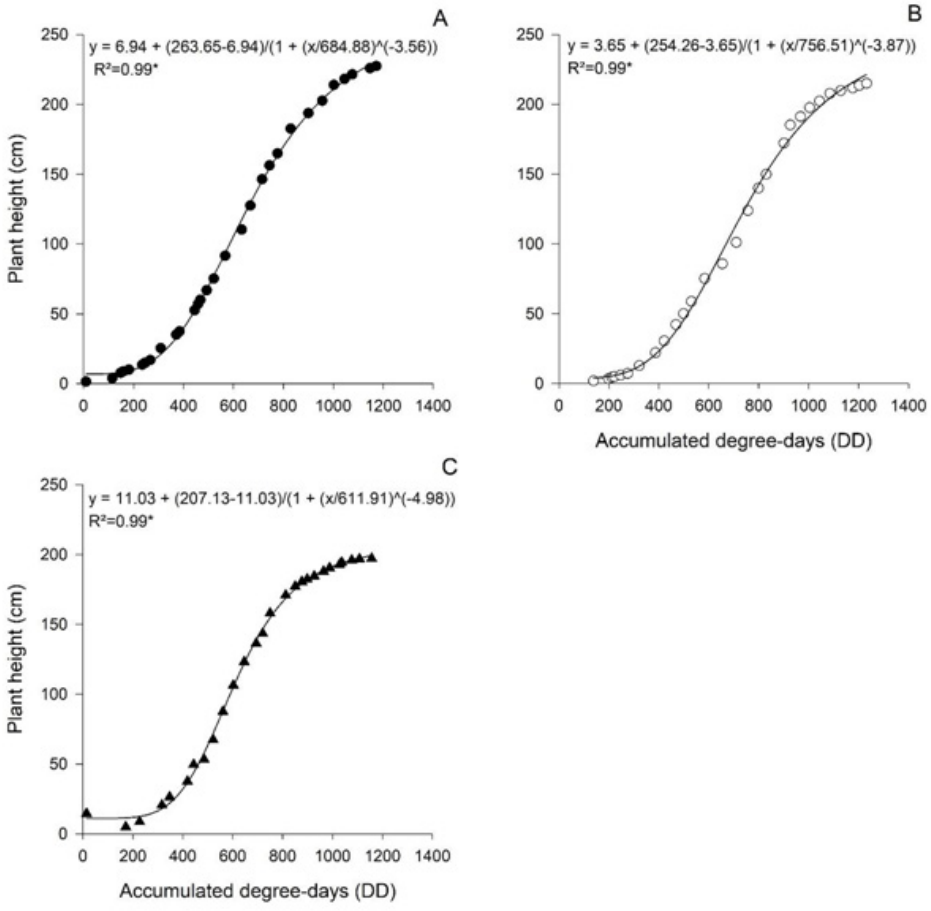


Figure 2 - Plant height (cm) of *Amaranthus hybridus* as a function of accumulated degree-days (DD) for emergences in November 2020 (A), December 2020 (B), and January 2021 (C). Passo Fundo, RS, Brazil, 2023. *Significant regression at the 0.01 probability level.

in November and January, respectively, for *A. hybridus* to reach 50% of its maximum height. These values are lower than those found for emergence in December, which requires 756.51 accumulated degree-days to reach 50% of maximum plant height (Figure 2). *A. palmeri* required fewer degree-days accumulation when established later in the season compared to populations established at the beginning of the growing season. Nevertheless, some species, such as *A. palmeri*, are sensitive to photoperiod (SPAUNHORST et al., 2018). *A. retroflexus* requires 51 days from seedling emergence to seed maturation when exposed to an 8-hour photoperiod and 105 days to complete the same development phases with a 16-hour photoperiod (HUANG et al., 2000).

Regarding plant height as a function of days after sowing, *A. hybridus* that emerged in November and December required 46 and 43 days after sowing to reach 50% of the maximum height. Conversely, the species required only 33 days when it emerged in January (Figure 3). This is due to the range of temperatures occurring during plant development at each time of the year, with means of accumulation of 11, 13, and 15 degree-days in November, December, and January, respectively.

The regressions generated for plant height as a function of days after sowing and the maximum height of *A. hybridus* during emergence times (Figure 3) showed that, on average, the daily growth of *A. hybridus* reached 2.47, 2.5, and 2.98 cm for plants that emerged in November, December, and January, respectively. Therefore, plants that appear later in the crop field tend to develop more quickly, reducing the weed control window.

The accumulated dry mass per plant was higher for *A. hybridus* plants emerging

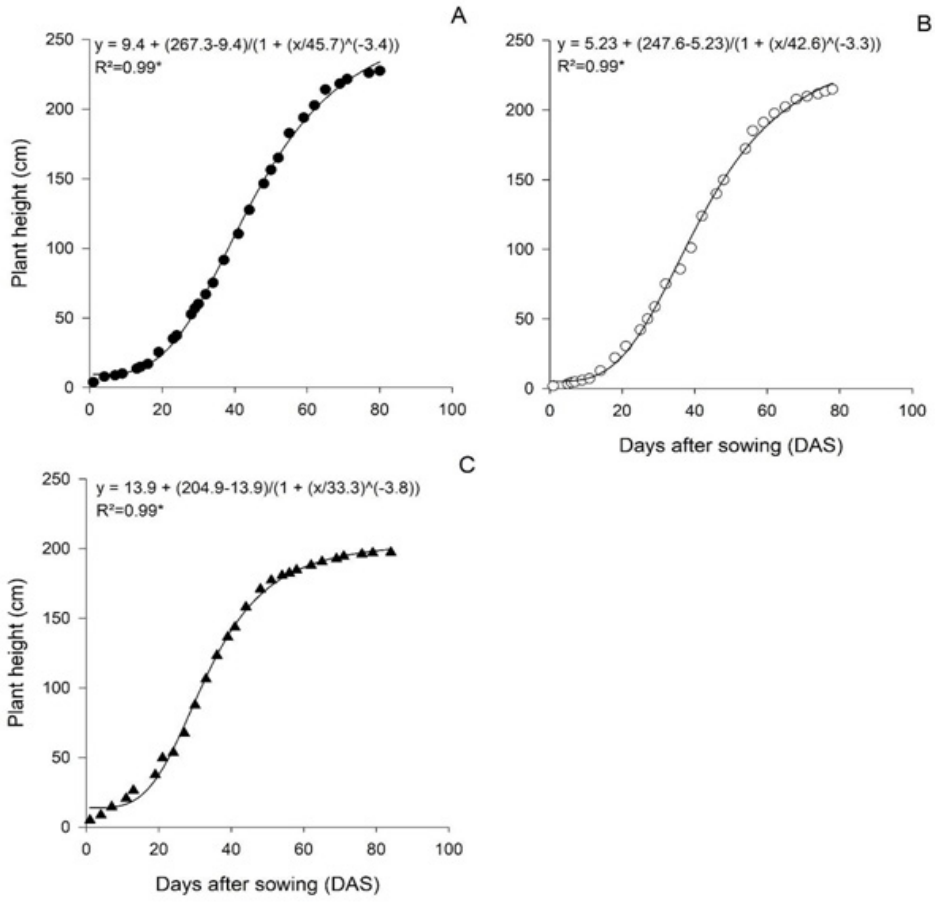


Figure 3 - Plant height (cm) of *Amaranthus hybridus* as a function of days after sowing (DAS) for emergences in November 2020 (A), December 2020 (B), and January 2021 (C). Passo Fundo, RS, Brazil, 2023. *Significant regression at the 0.01 probability level.

in November compared to those emerging in December and January (Figure 4). This is intrinsically related to the higher growth of plants that emerged in the first emergence period (Figures 2 and 3). Therefore, the later the emergence of *A. hybridus*, the smaller its height and, consequently, the smaller its accumulated dry mass. A similar pattern was reported for *A. palmeri*, in which plants established at the beginning of the growing season produced 164% more mass than those established late (SPAUNHORST et al., 2018).

The development of the root system in *A. hybridus* that emerged in November was 78% higher than that of plants that emerged in January (113.9 and 25.0 g plant^{-1}, respectively). Similarly, the shoot mass of plants that emerged in November was 69.26% higher than when the emergence occurred in January (795.5 and 244.5 g plant^{-1}, respectively) (Figure 4). A positive correlation is found between dry mass above ground and seed production in *A. palmeri* and *A. tuberculatus*, that is, plants with higher mass produce more seeds (SCHWARTZ et al., 2016; SPAUNHORST et al., 2018).

MARTÍNEZ-NÚÑEZ et al. (2019) used the BBCH scale as a base and described the phenological stages of *Amaranthus cruentus*, *A. hybridus*, and *Amaranthus hypochondriacus* grown in restricted spaces. Similarly, table 1 shows the phenological stages of *A. hybridus*, as well as their duration in degree-days and days after sowing observed in the present study.

In general, the duration of the phenological stages was higher in days after sowing and accumulation of degree-days at all emergence times compared to the results observed by MARTÍNEZ-NÚÑEZ et al. (2019). These authors observed three

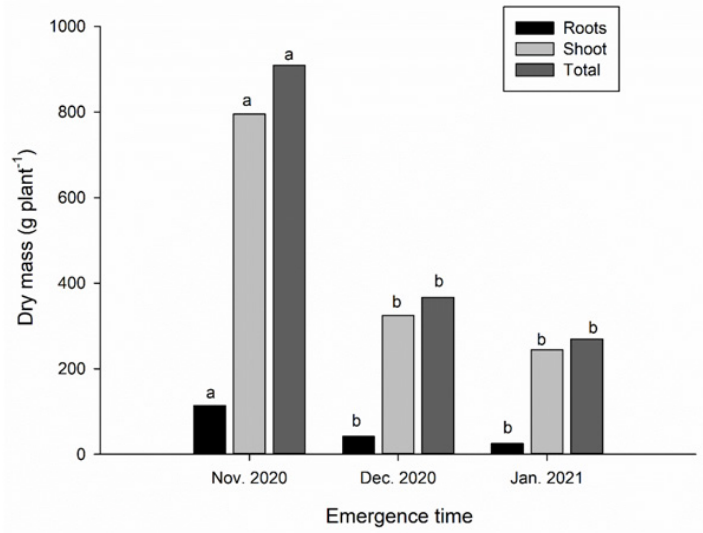


Figure 4 - Root, shoot, and total dry mass (g plant $^{-1}$) of *Amaranthus hybridus* as a function of emergence times in November 2020, December 2020, and January 2021. Passo Fundo, RS, Brazil, 2023.

Amaranthus species grown in a restricted space, with plant height ranging from 15 to 22 cm. In contrast, the plants in the present experiment were grown in an open space, where they could develop freely, reaching 227, 215, and 197 cm in height for emergences in November, December, and January, respectively. Moreover, only the species *A. hybridus* was used, factors that may have influenced the distinction in results between the studies.

Some phenological stages occur concomitantly in the development of *A. hybridus*, such as anthesis and axial inflorescence, as well as maturation and senescence, thus being described together. The comparison of the emergence times from germination to the two-leaf stage (when transplanting occurred) showed that the duration and accumulation of degree-days were similar between populations (Table 1). The development stages

Table 1 - Phenological stages of *Amaranthus hybridus* as a function of emergence times in November 2020, December 2020, and January 2021 based on the BBCH scale. Passo Fundo, RS, Brazil, 2023.

Phenological stages	---------Nov.---------		---------Dec.---------		----------Jan.---------		-------Reference*------		BBCH
	DD	DAS	DD	DAS	DD	DAS	DD	DAS	
Germination	18	5	21	4	24	4	13-16	3-4	0
Opening of the cotyledons	22	6	25	5	30	5	16-20	4-5	
Two leaves	56	10	60	9	65	8	26-28	8-10	1
Five to six leaves	114	14	138	16	171	13	63-115	21-32	
Apical inflorescence	468	30	926	56	645	39	130-218	40-57	5
Axial inflorescence	667	44	1085	68	811	48	299-377	69-79	6
Seed development	1002	65	1177	74	1027	69	410-644	85-113	7
Maturation and senescence*	1172	-	1232	-	1156	-	709-731	120-153	8-9

*Reference: thermal sum, in degree-days (DD) and days after sowing (DAS) of the *Amaranthus* development stages based on the BBCH scale observed in the study by MARTÍNEZ-NÚÑEZ et al. (2019).
*Maturation and senescence: the plants were collected 80 days after sowing. Therefore, maturation and senescence are presented with a duration of 80 DAS and degree-days accumulated during the period.

up to two leaves would be the ideal period for the application of the recommended herbicides to obtain satisfactory control.

The thermal sum from the 5 to 6 leaf stage was higher for emergence in January, and the duration in days after sowing was higher for emergence in December (Table 1). The beginning of flowering marks another important stage in the management of this weed. The emergence of the apical inflorescence varied from 30 to 56 DAS, with thermal accumulation between 468 and 926 degree-days for emergence in November and December, respectively. *A. hybridus* required 30 days and a thermal sum of 420 degree-days from the emergence of the first true leaf to flowering, with a precipitation of 77 mm in this period (MOSKOVA, 2013). MARTÍNEZ-NÚÑEZ et al. (2019) observed that *A. hybridus* required approximately 79 days after sowing to begin flowering.

A. hybridus plants were collected to determine dry mass at 80 DAS. Therefore, maturation and senescence are not presented. However, the accumulated thermal sum up to 80 DAS reached 1172, 1232, and 1156 degree-days for *A. hybridus* emergence in November, December, and January, respectively. According to MOSKOVA (2013), *A. hybridus* requires 1308 accumulated degree-days and 120 days to complete its life cycle. In contrast, MARTÍNEZ-NÚÑEZ et al. (2019) stated that *A. hybridus* requires 153 days after sowing to complete its development, with an accumulation of 731 degree-days in this period. A discrepancy could be observed between the accumulated degree-days and the days of *A. hybridus* life cycle duration in the studies. However, it is due to the intrinsic characteristics of the tested *A. hybridus* populations and the soil and climate conditions specific to the location where the experiment was conducted.

The fundamental principles of integrated weed management include suppressing weed growth, preventing seed production, and reducing the soil seed bank (ALBRECHT et al., 2021). The results presented here can help in decision-making regarding the control of this weed and mainly warn about the need for continuous monitoring during the growing season in areas known to be infested. These procedures could allow farmers to make timely herbicide applications, as *A. hybridus* grows rapidly in a short period and can easily surpass the optimal control window. Plants that emerge early in the growing season tend to be taller and exhibit greater biomass, leading to higher seed production. Management of late-season emergent plants should not be neglected, as these plants as develop and grow more rapidly, flower and produce seeds that replenish the soil seed bank. Successful control of *A. hybridus* requires an integrated weed management approach, and preventing seed introduction is the first step to successful weed management.

CONCLUSION

A. hybridus with emergence in November presented higher plant height, reaching, on average, 227 cm, and dry mass accumulation of around 909.5 g plant^{-1}. Plants that emerged in January were shorter, around 197 cm, and had reduced dry mass, on average 269.5 g plant^{-1}.

The daily growth rate of *A. hybridus* reached 2.47, 2.5, and 2.98 cm day^{-1} for plants that emerged in November, December, and January, respectively.

The beginning of flowering ranged from 30 to 56 days after sowing, with an accumulation of 468 to 926 degree-days.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript. All authors critically reviewed the manuscript and approved the final version.

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Opening of the cotyledons	22	6	25	5	30	5	16-20	4-5	
Two leaves	56	10	60	9	65	8	26-28	8-10	1
Five to six leaves	114	14	138	16	171	13	63-115	21-32	
Apical inflorescence	468	30	926	56	645	39	130-218	40-57	5
Axial inflorescence	667	44	1085	68	811	48	299-377	69-79	6
Seed development	1002	65	1177	74	1027	69	410-644	85-113	7
Maturation and senescence*	1172	-	1232	-	1156	-	709-731	120-153	8-9

*Reference: thermal sum, in degree-days (DD) and days after sowing (DAS) of the *Amaranthus* development stages based on the BBCH scale observed in the study by MARTÍNEZ-NÚÑEZ et al. (2019).

*Maturation and senescence: the plants were collected 80 days after sowing. Therefore, maturation and senescence are presented with a duration of 80 DAS and degree-days accumulated during the period.