Germination and Fresh Leaf Yield of *Amaranthus* Species Grown With or Without a Pesticide Seed Treatment

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Keywords. advanced line, apron Star, leafy amaranth, monceren, specific leaf area

Abstract. **Application of pesticides to amaranth seed can provide a mode of action to manage specific insect pests and seedborne pathogens and improve yield, depending on cultivar and a pesticide's active ingredients. The impact of two commercially available seed treatments on germination and leaf yield of eight advanced lines and a local cultivar, represented in four *Amaranthus* species (*Amaranthus blitum* L., *Amaranthus hybridus* L., *Amaranthus dubius* Mart. Ex Thell., and *Amaranthus hypochondriacus* L.) cultivated in Kenya were evaluated. Seeds of each line were treated with either a commercial formulation of Apron Star™ (thiamethoxam 20 g/kg + metalaxyl-M 20 g/kg + difenoconazole, 2 g/kg) or Monceren™ (imidacloprid 233 g/L + pencycuron 50 g/L + thiram, 107 g/L) or remained untreated as a control. The effect of these treatments was determined 1 day after application and after 3 months of storage, a storage time often used by subsistence farmers in Kenya. Seeds were stored in a seed storeroom 25 ± 1 °C, 60% to 70% relative humidity (RH), and a 12-hour light/12-hour dark photoperiod. A higher percentage of germination, 61.6% was observed for seeds of the *A. blitum* line treated with Apron Star and a lower percentage of 1.5% occurred with untreated seed of *A. dubius* line. Significant interactions of line or cultivar with seed pesticide application and line or cultivar with storage time were observed for fresh leaf weight, and pesticide application or storage time did not provide consistent increases in yield across lines or cultivar. The highest fresh leaf weights occurred with 'Terere', which was similar to lines of *A. hybridus*. Under high tunnel conditions, plants from amaranth seeds treated with either pesticide had higher leaf production than untreated seeds, and plants from seeds stored 1 day after Apron Star application and 3 months after Monceren application were higher than untreated seed stored for one day or 3 months.**

Amaranth is cultivated for its leaves in Africa, Central America, Southeast Asia, and South America, whereas in North America and some countries of Africa the seeds are consumed (Bvenura and Kambizi 2022; Gomes et al. 2024; Hancock 2022; Santra et al. 2024). Cultivation of leafy amaranth has increased for commercial and household production in Sub-Saharan Africa and it has gained momentum globally (Netshimbupfe et al. 2023). Low yields of amaranth leaves (<1.2 tons per hectare) have been attributed to variation among cultivars, poor seed germination, as well as environmental stressors including pests, inadequate growing conditions, and improper seed storage by farmers saving seed (Bokelmann et al. 2022; Nampeera et al. 2019; Shackleton et al. 2009). The application of pesticides to seeds has been considered by some to reduce the need of subsequent pesticides during crop production (Ediagbonya et al. 2025; Moumni et al. 2023; Vojvodić and Bažok 2021). For more than 30 years seed treatments have been a widely adopted practice in crop protection worldwide (Moumni et al. 2023). Increased use of treating seeds has been associated with a reduced cost of application, efficiency in the product delivery system, and benefits from protecting seed and seedlings during initial, critical stages of growth. Seed treatments are used for a wide range of crops to control damage from a wide range of pests and improve overall plant health (Kamran et al. 2021). Pesticides applied as seed treatments in wheat and soybean have helped to facilitate earlier planting, improved germination and enzymatic activity, increased antioxidants and reduced phtotoxicity, produced vigorous crops, handled environmental stresses, and increased crop yields (Catão et al.2024; Mayton et al. 2022; Sekmen Cetinel et al.2021; Vojvodić and Bažok 2021).

Neonicotinoids, including clothianidin, imidacloprid, and thiamethoxam, are the most widely used class of insecticides in the world for crop protection, with most applied as seed treatments (Klingelhöfer et al. 2022). Benefits of neonicotinoids as seed treatments include providing a mode of action to manage pests that are resistant to other insecticides, selective control of specific insect pests, and limited impacts on beneficial insects when applied in early stages of plant growth (Sehrish et al. 2024). The yield benefit of using neonicotinoids can exceed the cost of treatment (Sehrish et al. 2024; Wilson and Musgrove 2025; Wilson et al. 2022) but insect control may not always be achieved depending on growing conditions and pest populations (Kelly et al. 2020; Wilson et al. 2022).

The goal of applying fungicides as a seed treatment is to manage seedborne and soilborne pathogens that attack seeds and seedlings, manage diseases during early growth stages, and improve vigor and overall yield (Bugingo et al. 2025). Fungicides such as carbendazim, fludioxonil, and thiram, protected seeds from fungal pathogens and promoted germination of *Coffea arabica*, soybean [*Glycine max* (L.) Merr.], and onion (*Allium cepa*) seeds (Oliveira et al. 2021; Penido et al. 2021). Wheat (*Triticum aestivum* L.) cultivars treated with pyraclostrobin or combinations of difenoconazole, mefenoxam, fludioxonil, and sedaxane reduced tan spot (*Pyrenophora tritici-repentis*) and stripe rust (*Puccinia striiformis* f. sp. *tritici*) and improved yield (Bugingo et al. 2025). A combination of thiram and carboxin seed treatments reduced soilborne diseases and improved germination and yield of maize (*Zea mays* L.) and soybean (Regassa et al. 2024). To date, there are no published studies describing the effect of pesticide-treated seed on *Amaranthus* germination and fresh leaf yield.

Germination varies greatly with *Amaranthus* cultivation, in part because farmers often store seed for up to 3 months under open-air conditions

from the previous season's harvest until the next growing season (Nampeera et al. 2019; Oluoch et al. 2024). The major East African agricultural seasons are characterized by the "first rainy season," occurring in the months of March through May, and a "second rainy season," which occurs from September through November (Obubu et al. 2021). Apron Star™ and Monceren™ are registered seed pesticide treatments currently available to farmers in Kenya for protection of seeds and seedlings against early-season fungal and insect pests (Nampeera et al. 2023). Each of these seed treatments includes a mixture of a neonicotinoid (thiamethoxam or imidacloprid) and a combination of fungicides from at least two classes, such as phenylamide (metalaxyl-M), triozol (difenoconazole), dithiocarbamate (thiram), and phenylurea (pencycuron). The goal of this study was to assess seed of *Amaranthus* sp. treated with a pesticide (i.e., Apron Star™ or Monceron™) and a control and with 1 d or 3 months of storage for improved germination and yield of leafy amaranth lines or a cultivar when grown in a high tunnel. The purpose of assessing seeds after 1 day of storage was due to farmers who source seeds from the market and plant immediately or the following day (Sperling et al. 2020).

Received for publication 24 Jul 2025. Accepted for publication 4 Sep 2025.

Published online 6 Oct 2025.

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Research for this project was funded in part by Faculty for the Future, Schlumberger Foundation, Hague, The Netherlands.

We thank Dr. Hassan W. Kayondo, Department of Mathematics, Makerere University for assistance with statistical analysis.

Authors declare that there are no conflicting interests in this study.

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https://doi.org/10.21273/HORTTECH05736-25

Materials and methods

Location. The experiments were conducted at Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Juja, Kenya (Latitude 1.0891°S, Longitude 37.0105°E, Altitude 1525 m above sea level) during two growing seasons, Aug to Nov 2016 and Jan to Apr 2017. Seed germination studies investigated pesticide application and storage time and occurred Nov 2016 and Apr 2017 and leaf yield trials were conducted Aug to Nov 2016 and Jan to Apr 2017.

Advanced lines or cultivar. Four amaranth species (Table 1) were used, which included eight advanced lines from the Department of Horticulture and Food Security at JKUAT. Species of lines to be used in commercial production included *A. blitum* L. (lines 1 and 2), *A. hybridus* L. (lines 3 through 6), *A. dubius* Mart. Ex Thell. (line 7), and *A. hypochondriacus* L. (line 8). The experiments included a cultivar grown commercially for its leaves and commonly known as Terere (*A. dubius*). Advanced lines of seeds harvested from the previous season were obtained from JKUAT and 'Terere' seeds were obtained from an agricultural supplier, Nairobi, Kenya.

Seed pesticide treatments. Seeds of eight *Amaranthus* lines or Terere cultivar were treated with Apron Star™ (thiamethoxam 20 g/kg + metalaxyl-M 20 g/kg + difenoconazole, 2 g/kg) or Monceren™ (imidacloprid 233 g/L + pencycuron 50 g/L + thiram, 107 g/L) or remained untreated as a control (Table 2). Apron Star, 42WS Water Dispersible powder (Syngenta, Kenya), was purchased from an agro-chemical dealer in Nairobi, Kenya, and Monceren, GT 390 FS Flowable Concentrate, was provided by Bayer Crop Science (Bayer East Africa Ltd, Nairobi, Kenya). The components of Apron Star included one insecticide (thiamethoxam) and two fungicides (metalaxyl-m and difenoconazole) at an application rate of 1.25 mL a.i./250 g seed. Monceren included one insecticide (imidacloprid) and two fungicides (pencycuron and thiram) at an application rate of 3 mL a.i./250 g of seed. The active ingredients of the pesticides were not investigated individually because pesticide formulations for seed application are available as mixtures of insecticides and/or fungicides. Treatment application included mixing seeds of each line manually with Apron Star or Monceren solution at the recommended rates in a round-bottomed container. The seeds and the pesticides products in a solution or potable tap water for the untreated control were stirred with a spoon (teaspoon) until the pesticides or tap water were evenly distributed on the seeds. Mixing continued for 10 min before allowing the seeds to air dry on a paper towel for 24 h in the seed storage room. Each group of 250 g of seeds was sealed in brown paper envelopes until used or stored.

Seed treatment combinations. Six seed pesticide and storage treatment combinations for each advanced line and cultivar included 1) untreated seed germinated or planted 1 d after water application, 2) untreated seed germinated or planted 3 months after water application, 3) seed treated with Apron Star and germinated or planted 1 d after application, 4) seed treated with Apron Star and germinated or planted 3 months after application, 5) seed treated with Monceren and

Table 1. *Amaranthus* species and statuses of lines or a cultivar used in seed germination and leaf yield studies at Jomo Kenyatta University of Agriculture and Technology in Nairobi, Kenya.

Amaranthus line number	*Amaranthus* species	Status
1	*Amaranthus blitum*	Advanced line[i]
2	*Amaranthus blitum*	Advanced line
3	*Amaranthus hybridus*	Advanced line
4	*Amaranthus hybridus*	Advanced line
5	*Amaranthus hybridus*	Advanced line
6	*Amaranthus hybridus*	Advanced line
7	*Amaranthus dubius*	Advanced line
8	*Amaranthus hypocondriacus*	Advanced line
Terere	*Amaranthus dubius*	Local cultivar

[i]Advanced lines from Department of Horticulture and Food Security, Jomo Kenyatta University of Agriculture and Technology; local cultivar from agricultural supplier, Nairobi, Kenya.

Table 2. Details of seed pesticide treatments and posttreatment storage times of seeds for eight *Amaranthus* sp. lines or a local cultivar in studies conducted at Jomo Kenyatta University of Agriculture and Technology in Juja, Kenya.

Factor	Treatments	Details
Seed application	Untreated seed	Seeds were coated with potable tap water without pesticides
	Apron Star 42WS	Seeds were coated with thiamethoxam, metalaxyl and difenoconazole at 1.25 mL a.i./250 g of seed
	Monceren GT 390 FS	Seeds were coated with imidacloprid, pencycuron, and thiram at 3 mL a.i./250 g of seed
Post seed application storage time	1 d	Seeds were tested 24 h after seed coating
	3 mo	Seeds were tested 3 mo. after seed coating

germinated or planted 1 d after application, and 6) seed treated with Monceren and germinated or planted 3 months after application.

The number of months of seed storage was selected based on practices stated by farmers in rural and periurban Kenya (Nampeera et al. 2019). Seeds of each line or cultivar of amaranth were divided into three equal parts of 250 g. The first part was untreated and served as a control and was stored for 1 d or 3 months before planting; the second part was stored for 1 d after pesticide treatment with either Apron Star or Monceren; the third part was stored for 3 months after pesticide treatment with either Apron Star or Monceren.

Treated or untreated seeds were stored for 3 months in closed envelopes for each treatment in a seed storeroom that was 25 ± 1 °C, 60% to 70% RH, and with a 12-h light/12-h dark photoperiod.

Germination assessment. Seed germination was observed for treated or untreated seeds planted after 1 d and 3 months to establish the effects pesticide treatment and storage periods on seed germination (Yasak et al. 2024). Each combination of amaranth line or cultivar and with or without a seed treatment was replicated three times. Fifty seeds from each individual line or cultivar and pesticide application treatment combination were placed in individual plastic petri dishes (15 × 100 mm) laid with a Whatman No. 42 filter paper and sprayed with potable tap water until moist. Each petri dish with seeds was closed with a lid and then placed in a growth chamber at 25 ± 1 °C for 9 days. The petri dishes with seeds were sprayed on alternate days with water until the filter paper was moist, covered with their lids, and returned to the growth chamber to keep them moist. Seeds were observed every day following the first signs of radicle emergence until germination ceased, which was 9 days for all lines. On each day, the number of seeds with emerged radicles was counted and considered as germinated. After recording, the counted germinated seeds were removed by forceps and discarded daily. Number of germinated seeds was reported as a percentage of the seeds that germinated at the end of the test (i.e., 9 d).

Fresh leaf yield. Leaf yield was measured by growing amaranth plants in plastic pots in a high tunnel (165 m length × 9 m width and 4 m height). The average temperature in the high tunnel was 25 ± 1 °C, 60% to 70% RH, and natural photoperiod 12:12 L:D. The experimental setup used a completely randomized design with three replications of each treatment combination. Each treatment combination included one of the eight *Amaranthus* lines or a cultivar and one of six seed treatment and storage time treatment combinations (i.e., three seed treatments and two storage times). Five pots with one plant in each pot were established for each treatment and replication so that a single plant from each treatment and replication could be harvested at five different times, representing the weekly harvest time period that farmers use when producing leafy amaranth. A total of 810 potted plants (3 replication × 9 lines or cultivar × 6 seed treatment combinations × 5 weekly harvest periods) were used.

To produce these potted plants, seeds of the three different pesticide treatments and two storage times were germinated within a separate seedling tray (54 cm length × 28 cm width) containing a mix of sterilized forest soil and cow manure and sand (4:2:1 vol/vol).

Table 3. Percent seed germination of eight *Amaranthus* sp. lines and a local cultivar compared across and within two pesticide applications and an untreated control.

Amaranth line or cultivar[i]	Pesticide application[ii]			Pesticide application Means
	Apron Star	Monceren	Untreated	
Germination percentage				
Line 1	61.6 a A[iii]	30.3 b A	29.1 b A	40.3 A
Line 2	51.5 a A	24.6 b A	34.6 b AB	36.9 A
Line 3	22.0 a B	19.9 a AB	20.5 a BC	20.8 B
Line 4	2.7 a C	4.3 a BC	4.5 a DE	3.8 CD
Line 5	15.8 a BC	17.3 a AB	22.6 a ABC	18.6 B
Line 6	12.4 a BC	4.0 a BC	15.3 a CD	10.5 C
Line 7	6.5 a BC	1.1 a C	1.5 a E	3.0 D
Line 8	2.1 ab C	0 b C[iv]	3.0 a DE	1.7 D
Terere	1.5 a C	0.8 a C	1.6 a E	1.3 D
Line and cultivar means	19.6 a	11.3 b	14.7 ab	

[i] Line numbers and their species included 1, 2, *A. blitum*; 3, 4, 5, 6, *A. hybridus*; 7, *A dubius*; 8, *A. hypochondriacus*; and a local cultivar, Terere, *A. dubius*.

[ii] Seeds were coated in Apron Star or Monceren as separate solutions or untreated control.

[iii] Means followed by the same lower-case letter within a row indicate significance among pesticide applications and untreated control, Tukey's honestly significant difference test, $\alpha < 0.05$ and upper-case letter within a column indicate significance of a pesticide application and untreated control, Tukey's HSD test, $\alpha < 0.05$; data of two seasons were combined for analysis.

[iv] Seeds of line 8 with 0 value did not germinate.

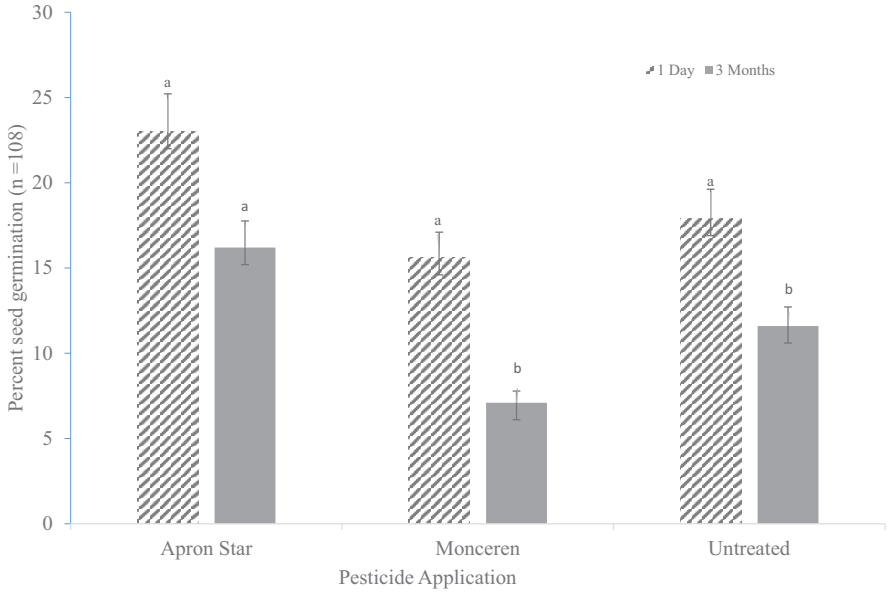

Fig. 1. Mean (± standard error) percent germination of *Amaranthus* sp. seeds based on the main effects of pesticide application treatment (Apron Star, Monceren, or untreated control) and storage time (1 d or 3 months). Means within a pesticide application treatment with the same letters were not different between two storage treatment times at $P < 0.05$ [Tukey's honestly significant difference (HSD) test]. Means within a seed storage treatment time with the same letters were not different for the pesticide application treatment at $P < 0.05$ (Tukey's HSD test).

Three weeks after germination in the nursery trays, five seedlings of the same line or cultivar and seed treatment were transplanted into individual plastic pots (17 cm diameter × 21 cm height) filled with the same soil mixture as used in the seedling tray. Pots were watered daily to saturation and placed in plastic bowls (27 cm diameter × 8.5 cm height) and filled with water to enable continuous water supply by capillarity. Three weeks after transplanting, 1.5 g of calcium ammonium nitrate (26% N) was applied to each pot's soil surface.

Harvest began 35 d after transplanting by randomly selecting one potted plant from each line or cultivar and treatment combination per replicate, once a week for 5 consecutive weeks with the final plant harvested 70 d after transplanting (Birhanu et al. 2024). Our harvested, plants were cut off at the soil level and placed into labeled brown paper bags in cool boxes packed with ice and taken to the laboratory for assessment. In the laboratory, leaves on each plant were counted, removed, and weighed. Yield data from the 5 weeks were combined at the end of each experiment for analyses.

Table 4. Fresh leaf weights (g) of eight *Amaranthus* sp. lines and a local cultivar compared within and across two seed pesticide applications and untreated control.

	Pesticide application[ii]			Pesticide application and untreated control Means
Amaranth line/LC[i]	Apron Star	Monceren	Untreated	
Fresh leaf wt (g)				
Line 1[i]	20.7 a C[iii]	20.9 a C	9.3 b CD	17.1 BC
Line 2	22.9 a BC	20.3 a C	9.6 b BCD	17.6 BC
Line 3	34.6 a A	32.3 a AB	17.0 b A	27.9 A
Line 4	27.2 a ABC	22.9 a BC	12.8 b ABC	21.0 B
Line 5	24.8 a ABC	26.7 a ABC	10.8 b ABCD	20.8 B
Line 6	32.3 a AB	32.7 a AB	13.0 b ABC	26.0 A
Line 7	18.5 a C	24.3 a BC	5.6 b D	16.1 C
Line 8	0 b D[iv]	0 b D	15.9 a AB	5.3 D
Terere	35.3 a A	36.1 a A	12.4 b ABC	27.9 A
Line means	24.0 a	24.0 a	11.9 b	

[i] Line numbers and their species included 1, 2, *A. blitum*; 3, 4, 5, 6, *A. hybridus*; 7, *A dubius*; 8, *A. hypochondriacus*; and a local cultivar, Terere, *A. dubius*.
[ii] Seeds were coated in Apron Star or Monceren as separate coating solutions or untreated control.
[iii] Means followed by the same lower-case letter within a row indicate significance among pesticide applications and untreated seeds, Tukey's honestly significant difference test, $\alpha < 0.05$ and upper-case letter within a column indicate significance of a pesticide treatment and untreated seed, Tukey's HSD test, $\alpha < 0.05$; data of two seasons were combined for analysis.
[iv] Seeds of line 8 with 0 value did not germinate.

Specific leaf area. Leaf area (cm^2) was measured with a LI-COR Li-3000 leaf area meter (LI-COR, Lincoln, NE, USA) to know how morphological leaf traits such as specific leaf area (SLA) vary across various amaranth lines, pesticide treatments, and storage periods. In response to variation in resource availability aboveground, SLA was determined (Asefa et al. 2022) and SLA ($cm^2 \cdot g^{-1}$) estimated as the amount of leaf surface per unit to dry weight of leaves (Sharmi et al. 2021).

Data analysis. Analysis of variance (ANOVA) was completed for all variables. A linear mixed model with random intercept was fitted to these data using the *lmer* function in R from the *lme4* package (Bates et al. 2015; Wang et al. 2022). The model was fitted using restricted maximum likelihood and factor effects; amaranth lines, seed treatment, storage time, and their interactions were considered fixed effects, whereas replications were treated as random effects. We used ANOVA to determine if the following parameters varied by trials when evaluating the effects of season, amaranth lines or cultivar, seed treatments, and storage times and their interactions for percent germination, fresh leaf weight (g), and SLA variables. Means were separated using Tukey's honestly significant difference (HSD) test at the 0.05 level of significance, to test the differences of amaranth lines, treatments, and storage time when averaged across trials and in each trial, and of each line across the three treatments and two storage times. Lines, treatments, and storage time that were less than the HSD test ($P \leq 0.05$) were considered significant. All analyses were performed in R version 3.4.3 from the *lme4* package (Bates et al. 2015).

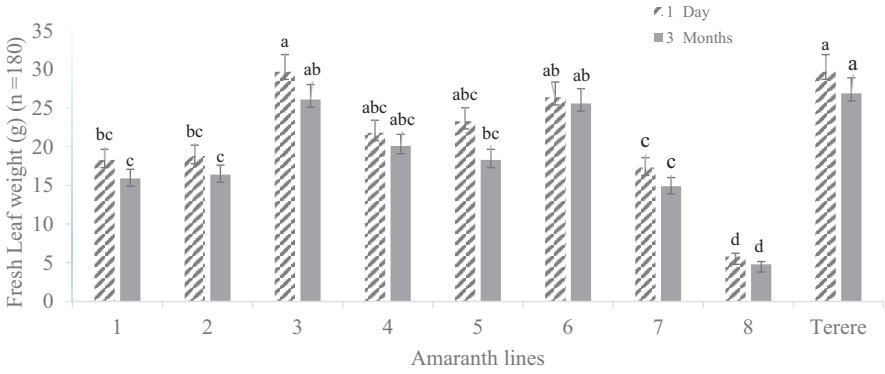

Fig. 2. Mean (± standard error) fresh leaf weight (G) for *Amaranthus* sp. line or cultivar and storage time. Means within a line or cultivar (1, 2, 3, 4, 5, 6, 7, 8, or Terere) with the same letters were not different for two storage treatment times [1 d, 3 months at $P < 0.05$, Tukey's HSD test. Means within a seed storage treatment time with the same letters were not different for lines or cultivar at $P < 0.05$ (Tukey's HSD test)].

Results

Based on ANOVA analyses, there was no significant interaction of the two growing seasons among variables and therefore seasons were combined for analysis (data not presented).

Effect of lines, pesticide application, and storage time on germinating seeds. There was a significant interaction of lines and pesticide treatments and storage time on seed germination. The greatest mean percent seed germination occurred in lines from *A. blitum* (lines 1 and 2), whereas the lowest percent germination rates were observed in *A. dubius* (line 7 and 'Terere') and *A. hypochondriacus* (Line 8) (Table 3).

Of seeds that were not treated with either pesticide, the highest percent germination occurred with *A. blitum* lines (1 and 2) (Table 3).

The interaction of lines × pesticide application × storage time was not significant for seed germination. Immediately (1 day) after being treated, seeds had similar percent germination across all pesticide treatments or untreated control (Fig. 1). After 3 months, seeds had a higher percentage of germination with an application of Apron Star compared with Monceren or the untreated control.

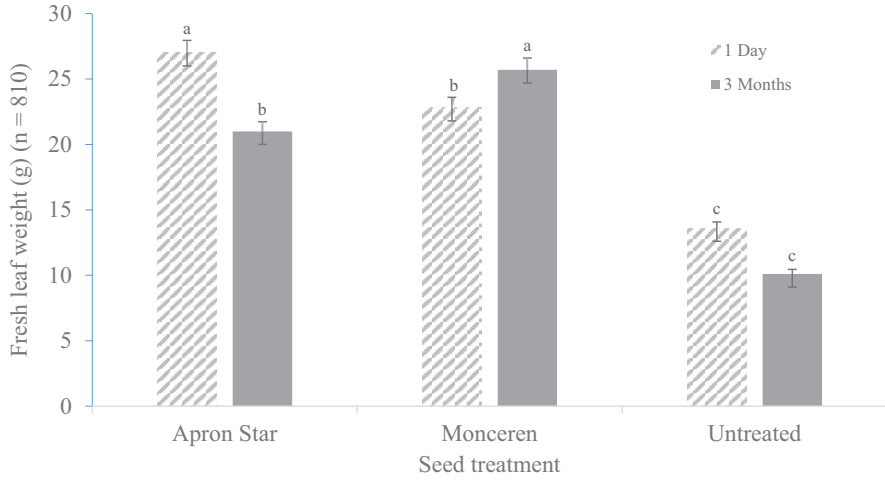

Fig. 3. Mean (± standard error) fresh leaf weight (G) of *Amaranthus* for three pesticide application treatments (Apron Star, Monceren, or untreated control) and two storage times (1 d, 3 months). Means within a pesticide application treatment with the same letters were not different for two storage treatment times at $P < 0.05$ (Tukey's HSD test). Means within a seed storage treatment time with the same letters were not different for the pesticide application treatment at $P < 0.05$ (Tukey's HSD test).

Effect of lines, pesticide application, and storage time on fresh leaf weight. A significant line × pesticide application interaction occurred for fresh weight of leaves. Seed treatment of Apron Star and Monceren resulted in a similar fresh leaf weight for all lines and a cultivar compared with the untreated control except for *A. hypcondriacus* (line 8), which had higher fresh leaf weight when untreated and *A. dubius* (line 7), which had lower fresh leaf weight (Table 4). There was 0 (g) weight of fresh leaves for line 8 of seed treatment of Monceren. Seed treatment of Monceren of line 8 did not germinate (Table 4).

There was no significant line × storage time interaction with regard to fresh leaf weight. Seed of 'Terere' and all *A. hybridus* (lines 3, 4, 5, and 6) planted 1 d or 3 months after treatment produced a higher fresh leaf weight than *A. hypocondriacus* (line 8) (Fig. 2). 'Terere' had higher fresh leaf weights compared with all lines from *A. blitum* (1 and 2), the other *A. dubius* (line 7), and *A. hypocondriacus* (line 8).

The interaction of line × pesticide application × storage time was significant. Fresh leaf weights of plants from seed planted 1 day after treatment with Apron Star were higher than plants from seed receiving Monceren application or untreated (Fig. 3). Plants grown from seed stored for 3 months and treated with Monceren had higher fresh leaf weights compared with Apron Star or untreated.

Effect of lines, treatment, and storage time on SLA. There were no significant interactions for SLA. The lowest SLA was found in *A. hypocondriacus* (line 8), when seed received Apron Star or Monceren pesticides (Table 5). Line 8 has 0 values for SLA, similar to fresh leaf weight; obviously there were no leaves so there could be no SLA. This was because line 8 seeds, which received Apron Star and Monceren pesticide treatments, did not germinate. SLA after 1 day or 3 months of seed storage showed *A. hypcondriacus* (line 8) had a lower SLA than line 1 or 'Terere' (Fig. 4). SLA means from pesticide application and storage time treatments did not differ (Fig. 5).

Table 5. Specific leaf area ($cm^2 \cdot g^{-1}$) of eight *Amaranthus* sp. lines and a local cultivar compared across and within two pesticide applications and an untreated control.

Amaranth lines/LC[i]	Pesticide applications[ii]			Pesticide application means
	Apron Star	Merceron	Untreated	
Specific leaf area ($cm^2 \cdot g^{-1}$)				
Line 1[i]	16.2 a C[iii]	17.9 a A	41.6 a A	25.2 A
Line 2	14.8 a C	21.8 a A	15.9 a A	17.5 A
Line 3	29.3 a A	26.3 a A	24.8 a A	26.8 A
Line 4	18.7 a BC	15.0 a AB	19.0 a A	17.5 A
Line 5	20.5 a ABC	20.4 a A	14.8 b A	18.6 A
Line 6	17.8 a BC	18.0 a A	14.8 a A	16.9 A
Line 7	16.1 ab C	18.0 a A	9.9 b A	14.8 AB
Line 8	0 b D[iv]	0 b B	14.2 a A	3.0 B
Terere	26.4 a AB	21.5 a A	31.0 a A	26.3 A
Line means	17.8 a	17.7 a	21.2 a	

[i] Line numbers and their species included 1, 2, *A. blitum*; 3, 4, 5, 6, *A. hybridus*; 7, *A dubius*; 8, *A. hypochondriacus*; and a local cultivar, Terere, *A. dubius*.
[ii] Seeds were coated in Apron Star or Monceren as separate coating solutions or untreated control.
[iii] Means followed by the same lower-case letter within a row indicate significance among treatments, Tukey's honestly significant difference test, $\alpha < 0.05$ and upper-case letter within a column indicate significance of a treatment Tukey's HSD test, $\alpha < 0.05$.
[iv] Seeds of line 8 with 0 value did not germinate.

Discussion

Lines and pesticide application on germinating seeds. Treating amaranth seed with Apron Star pesticide produced a higher mean germination percentage, and the response of a seed treatment varied by species with *A. blitum* having a higher mean than lines of *A. hybridus*, *A. dubius*, and *A. hypochondriacus*. Nampeera et al. (2023) also found out that *A. blitum* lines had lower aphid densities than *A. hybridus* lines with or without seed treatments. Similarly, Nampeera et al. (2020) also observed lower aphid populations in *A. blitum* lines and greater aphid populations in *A. hybridus* lines. Germination differences might be different between *Amaranthus* species and accessions (Khan et al. 2022; Ramírez-Bautista et al. 2023). Establishing traits that contributed to high germination in *A. blitum* could help in future breeding programs.

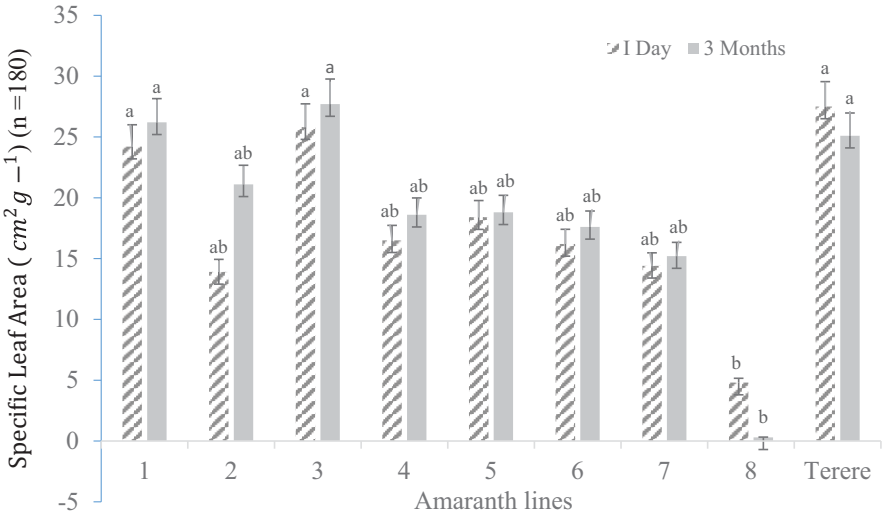

Fig. 4. Mean (± standard error) specific leaf area ($cm^2 \cdot g^{-1}$) for *Amaranthus* sp. lines and a cultivar and seed storage time. Means within a line or cultivar (1, 2, 3, 4, 5, 6, 7, 8, or Terere) with the same letters were not different for two seed storage treatment times (1 d, 3 months) at $P < 0.05$ [Tukey's honestly significant difference (HSD) test]. Means within a storage treatment time with the same letters were not different for lines or cultivar at $P < 0.05$ (Tukey's HSD test).

Lines and treatments on fresh leaf weight and SLA. Mean fresh leaf weights were higher when seeds had Apron Star or Monceren applied. Pesticide seed treatments might have protected seeds and seedlings from early-season pests and fungal infestation resulting in enhanced crop establishment and yields. Nampeera et al. (2023) also found that amaranth seeds treated with pesticide treatments provided protection against *Myzus persicae* infestations.

Pesticide-treated seed of line 8 (*A. hypochondriacus*) did not germinate, hence no fresh leaf weight and SLA were obtained compared with the untreated control. Ramírez-Bautista et al. (2023) noted that germination differences might be different between *Amaranthus* species and accessions. The influence of a species may be an important consideration for production and yield when considering advantages or disadvantages of a pesticide seed treatment.

Fresh leaf weights of plants from seed treated with Apron Star 1 day before planting were higher than Monceren-treated or -untreated seed. For seed treated and stored 3 months, Monceren application had higher fresh leaf weights than Apron Star treatment or untreated. Future research should investigate if the active ingredients of Apron Star and Monceren are influenced by seed storage time and impact fresh leaf weight of plants.

Conclusion

This is the first study to investigate horticultural impacts of pesticide application and storage time of seeds on the production of *Amaranthus* sp. as a leafy vegetable. Application of pesticides to improve amaranth seed germination and leaf yield varied by amaranth species and storage time. Any recommendation for pesticide application should consider the species of amaranth being cultivated and time requirements of storage of the seed.

A. blitum lines (1 and 2) had high percent seed germination, whereas *A. dubius* lines (7 and 'Terere') had lower percent germination. Seeds treated with any pesticide did not differ when stored for 1 day, but seeds treated with Apron Star had higher percent seed germination at 3 months than Monceren-treated or untreated seeds.

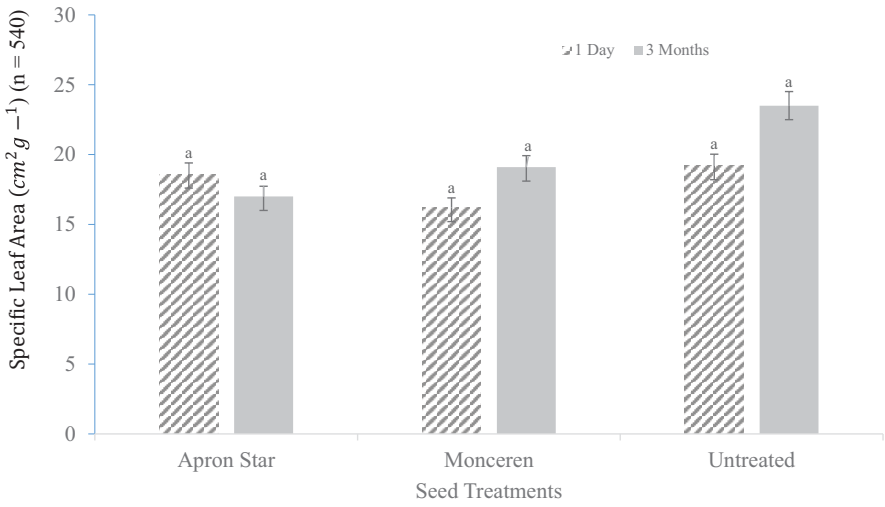

Fig. 5. Mean (± standard error) specific leaf area ($cm^2 \cdot g^{-1}$) of *Amaranthus* sp. for seed pesticide application and storage time. Means within a pesticide application treatment (Apron Star, Monceren, or untreated control) with the same letters were not different for two seed storage treatment times (1 d, 3 months) at $P < 0.05$ (Tukey's HSD test). Means within a storage treatment time with the same letters were not different for the pesticide application treatment at $P < 0.05$ (Tukey's HSD test).

'Terere' and lines of *A. hybridus* had fresh leaf weights higher than other *A. dubius* or *A. hypocondriacus* lines, supporting *A. hybridus* lines and 'Terere' for potential commercial use. The economic value of any seed treatment was not calculated, and farmers should consider the cost-benefit of using a pesticide application for subsequent benefit in seed germination and leaf yields. Further investigations of the effects of a seed treatment on other aspects of amaranth physiology, especially when the plant is challenged by insect pests and/or pathogens may provide additional recommendations for using seed treatments to enhance seed germination and leaf yield.

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