Weed Technology

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Interventions for weed seed management in cotton around the harvest time

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Research Article

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Keywords:
Integrated weed management; Palmer amaranth; waterhemp; weed seed destruction; harvest weed seed control; cotton gin trash

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Abstract

Late-season escapes of Palmer amaranth and waterhemp (both are *Amaranthus* species) pose a significant challenge in cotton production due to their high fecundity, herbicide resistance, and ability to replenish the weed seedbank at harvest. While harvest weed seed control (HWSC) has been adopted in grain systems, its feasibility in cotton remains unknown due to differences in cotton harvesting equipment design. Therefore, this study aimed to determine the fate of *Amaranthus* spp. seeds during harvest with cotton pickers and stripper harvesters, and evaluated the efficacy of an impact mill to destroy a range of weed seeds present in different types of cotton debris. Along with the seed cotton, cotton strippers removed 52% of the *Amaranthus* seeds, compared with just 7% with pickers, which are then cleaned at the cotton gin. About 85% of the seeds were retained on the plant after harvest by the pickers, and about 15% by the strippers. Seeds shattered to the ground accounted for 8% with pickers and 18% with strippers. Additionally, the cotton stripper's field cleaner mechanism removed 15% of the weed seeds. Together, seeds collected in seed cotton, retained on the plant, or separated by field cleaners (in strippers) represent points for HWSC implementation. Different types of cotton debris were then run through a stationary weed-seed impact mill with a known number of seeds for seven weed species to determine seed destruction efficacy. The stem debris had a 29% moisture content, which is too high for the impact mill and caused mill clogging; however, seed kill levels of 98% were achieved in bur debris and gin debris types, values similar to those reported in grain systems. Together, these findings provide a framework for incorporating HWSC practices into cotton, offering growers and processors a way to reduce weed seedbank inputs.

Introduction

Cotton is a slow-growing crop during its early growth stages and requires a long weed-free period to maximize yield and fiber quality (Korres and Norsworthy 2015; Tursun et al. 2015). Plants in the genus *Amaranthus*, specifically Palmer amaranth and waterhemp, are the most troublesome weeds in cotton production due to their high fecundity, environmental plasticity, extended emergence periods, rapid growth, and competitiveness (Korres and Norsworthy 2017; Morgan et al. 2001; Oliveira et al. 2022; Roberts and Florentine 2022; Ward et al. 2013). In surveys of cotton conducted in Texas in 2016–17, Palmer amaranth and waterhemp ranked as the first and third most common weed escapes, respectively, with average seed rain potential of 5.8 million seeds ha^{-1} (Werner et al. 2020). Additionally, when compared with other problematic weeds in U.S. cotton production, *Amaranthus* spp. have the highest incidence of herbicide resistance (Heap 2025; Vulchi et al. 2022).

Plants of *Amaranthus* spp. that survive in-season control interventions can develop into mature plants at harvest, commonly known as late-season weed escapes (Bagavathiannan and Norsworthy 2012). These weeds that miss early-season weed control are also more likely to contribute to the development of resistance because they may have received partial herbicide applications. These escapes typically contribute to the addition and replenishment of the weed seedbank; *Amaranthus* spp., in particular, are known to exhibit high fecundity (Sauer 1957). Restricting weed seedbank inputs is expected to reduce the number of weed plants exposed to herbicides in the following seasons, thereby minimizing the risk of resistance development and

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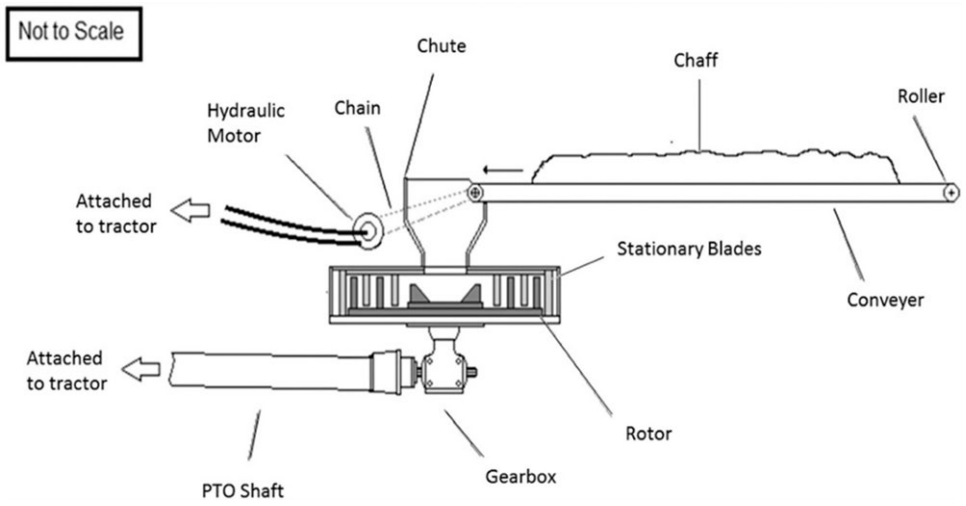


Figure 1. Schematic of the integrated Harrington Seed Destructor (iHSD) as a stationary unit. The chaff enters on the 2-m roller and feeds into the chute and exits through an opening. The entire iHSD unit is connected to the hydraulic system of a tractor (adapted from Schwartz-Lazaro et al. 2017).

improving the longevity of herbicides (Bagavathiannan and Norsworthy 2012). Understanding these factors can help in developing targeted strategies to minimize seedbank additions.

Weed seedbank contributions can be reduced through harvest weed seed control (HWSC) tactics (Walsh et al. 2013, 2018a), especially when high proportions of weed seeds are retained at a height that ensures collection during harvest (Walsh et al. 2012). Several studies have confirmed that the *Amaranthus* spp. retain high proportions (≥98%) of seed at crop maturity (Schwartz-Lazaro et al. 2016, 2017a, 2021), making it an effective target for HWSC. Current HWSC practices that target weed seeds exiting a grain combine harvester include narrow-windrow burning, chaff carts, chaff lining, chaff tramlining, bale direct systems, and impact mills (Walsh et al. 2018b; Figure 1). These systems are designed to collect and destroy or remove weed seeds that remain on the maternal plant at harvest.

HWSC tactics have been investigated in crops such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), soybean (*Glycine max* L. Merr.), canola (*Brassica napus* L.), etc. (Schwartz-Lazaro et al. 2017b; Tidemann et al. 2020; Walsh and Powles 2007; Winans et al. 2023). Previous research has demonstrated that impact mills can process wheat, rice, and soybean chaff, resulting in weed seed kill levels exceeding 95% for most weed species tested (Schwartz-Lazaro et al. 2017b; Walsh et al. 2012; Winans et al. 2023). These crops are harvested about 15 to 30 cm above the ground level, using a header designed to cut all plant material, including weeds, at the height of the combine header. For cotton, an important row crop in the southern United States, the opportunities for HWSC are unclear due to differences in harvester types. Cotton harvesters operate differently from the headers used in grain harvesters, which may affect the effectiveness of weed seed collection (Figure 2). Some researchers have suggested that the potential for HWSC is low in cotton due to the low levels of seed capture anticipated during cotton harvest (Shergill et al. 2020), although no research has specifically investigated this issue.

Two different types of harvesters are used in cotton: pickers and strippers. Cotton picker harvesters use spindles with small barbs, slightly moistened, to remove seed cotton attached to the open cotton boll (Faulkner et al. 2011; Figure 2). Cotton stripper harvesters use brushes and bats to remove seed cotton, bolls, leaves, bark, and small branches from the stem of the cotton plant (Faulkner et al. 2009, 2011; Figure 2). Unlike grain headers, neither of the two cotton harvesters cuts plants from the bottom, and only the weed seeds within the cotton rows are expected to be removed. Cotton pickers maintain fiber quality and are better suited than strippers for harvesting high-yielding cotton (Faulkner et al. 2011). The cotton-picker mechanism captures significantly less foreign material, including weed seeds (typically 5% to 8% foreign material [Faulkner et al. 2008; Hardin et al. 2011]), than a stripper harvester (up to 25% [Wanjura et al. 2011]). The stripper harvesters are fitted with a field cleaner to separate the seed cotton from the other plant materials, which minimizes the foreign material in the lint (Faulkner et al. 2008, 2011); the material collected by the field cleaner is called 'bur debris'. The extent of weed seed removed with the seed cotton (for pickers and strippers) and with the bur debris (strippers only) is unknown.

At the cotton gin, where the cotton lint and seed are separated, debris piles (i.e., gin debris, also known as gin trash) may contain leaf fragments, lint, stems, immature cotton seeds, dust, and weed seeds (Griffis and Mote 1978). Growers commonly apply gin debris to fields to enhance soil organic matter (Holt et al. 2000; Norsworthy et al. 2009; Tejada and Gonzalez 2007). In a survey of gin debris material from 23 gins in Arkansas, Mississippi, and Tennessee, Norsworthy et al. (2009) reported that grass weed seeds were present in 41.4% of the samples, whereas 8.5% of them contained broadleaf weed seeds. In that study, Palmer amaranth was found at densities of up to 4,070 germinable seeds per metric ton of cotton gin debris, underscoring the need to address this issue to prevent the spread of herbicide-resistant weeds.

The mechanical differences between stripper- and picker-type cotton harvesters (Figure 2) will influence how HWSC could be integrated into cotton systems because they may affect weed seed removal, shattering, and retention during harvest (Figure 3). Furthermore, in a cotton stripper, there is also a possibility of weed seed returning to the field through the field cleaner (Figure 3).

The overall aim of this research is to determine the fate of *Amaranthus* spp. seed during cotton harvest with the picker or stripper harvester, to offer insights into suitable avenues for intervention. The first objective of this study was to determine the

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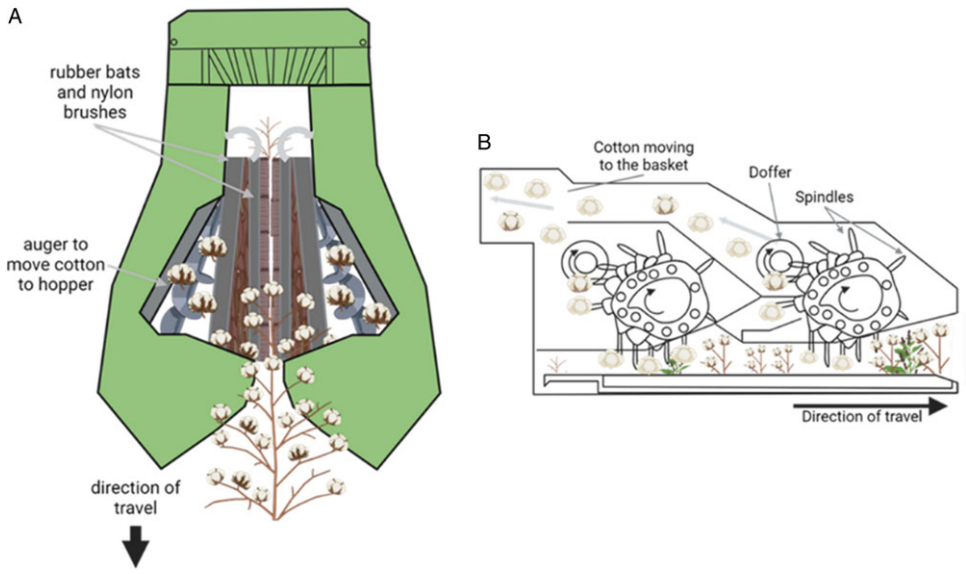


Figure 2. The designs of the two different cotton harvester types, adapted from Willcutt et al. (2010) and Wanjura et al. (2010). A: Cotton stripper from a front view: bats and nylon brushes remove cotton bolls from the plant, with augers moving the bolls to the cotton hopper. B: Cotton picker from a top view: spindles remove the cotton, which is then pneumatically moved to the basket.

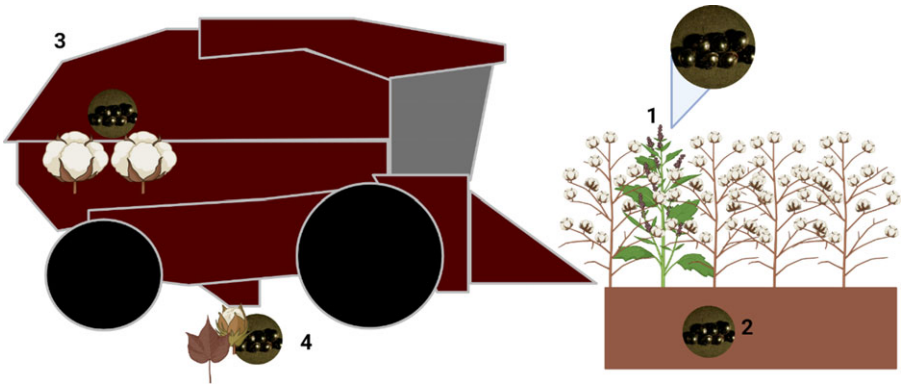


Figure 3. Possible locations where weed seeds can end up during cotton harvest: 1, seeds that are retained on the plant post-harvest; 2, seeds that shatter to the ground; 3, seeds that are removed with the seed cotton to go to the cotton gin; 4, weed seeds as part of the bur trash removed by a field cleaner, which is only present in cotton stripper harvesters.

fate of *Amaranthus* spp. seed at harvest, including shattering, collection with the harvested material, or remaining on the maternal plant. The second objective was to assess the efficacy of a weed seed impact mill in destroying *Amaranthus* spp. seeds in various types of cotton debris.

Materials and Methods

Experiment I: Seed Fate Determination

Experimental Setup. Field trials were established at four locations in Texas, two each in the fall seasons of 2022 and 2023 (Table 1). One site used a cotton picker each year, and the other used a stripper harvester. In 2022, the picker harvester site had a waterhemp infestation, whereas the other three sites had Palmer amaranth infestations (Table 1). The *Amaranthus* plants were naturally occurring populations in the experimental field and selected based on similarity in size and seed maturation. The tagged plants were within 10 cm of the crop row, ensuring they would pass through the spindles (picker) or the auger (stripper) during cotton harvest. All other weeds were removed from within the width of the harvester row unit and along a 3-m length of the cotton crop row to ensure that we were tracking the effects of harvest on a single plant. All sites received thiadiazuron (50 g ai ha^{-1}) as a defoliant within 2 wk prior to cotton harvest (Table 1).

Data Collection. To collect any seeds shattered during cotton harvest, weed mats (1.5 m × 2 m) made of Planket fabric roll (Brainchild, Dallas, TX) were placed on the ground around the base of each *Amaranthus* plant, covering a 3 m^2 area. After harvest, seeds and cotton debris were collected from the weed mat and placed in a paper bag. The weed plants were harvested by cutting them at the soil surface and separately bagging them to determine the number of seeds still retained on the plants after harvest. The collected plant samples were dried at 60 C for 72 h, then threshed, sieved, and hand-cleaned to obtain a clean seed sample. The total number of seeds per *Amaranthus* plant was determined by

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Table 1. Management details for evaluating *Amaranthus* species seed fate during cotton harvest with a picker or stripper harvester.

	Picker harvester		Stripper harvester	
	2022	2023	2022	2023
Amaranthus species	waterhemp	Palmer amaranth	Palmer amaranth	Palmer amaranth
Location	(30.55°N, 96.43°W)	(30.54°N, 96.43°W)	(30.59°N, 97.28°W)	(33.68°N, 101.82°W)
Date of collection	November 4, 2022	September 28, 2023	September 12, 2022	November 16, 2023
Harvester	International Harvester 314	John Deere 9920	John Deere 484	John Deere 7445
Cotton row spacing	101 cm	101 cm	76 cm	101 cm
Number of cotton rows harvested	1	2	4	2

counting and weighing 10 lots of 100 seeds from each sample, then using the average weight of 100 seeds to calculate the total seed number per sample (Equation 1; Jones et al. 2019):

$$T = \left(\frac{W}{S}\right) \times 100 \quad [1]$$

where W is the total seed mass per plant, S is the average mass of the ten 100-seed subsamples, and T is the total seed production per plant.

To quantify the number of weed seeds removed with the seed cotton during harvest, samples were captured just prior to the seed cotton entering the hopper of the harvester. The cotton strippers used for testing had a bag attached to the field cleaner to capture the bur debris, and any *Amaranthus* spp. seed present. In the field cleaner, the seed cotton samples were cleaned using a pneumatic fractionator (Shepherd 1972), which uses pressurized air to remove any lightweight particles (i.e., weed seeds, bur, bark, leaf, or stem particles) from the seed cotton; this bur debris was collected in a catch tray. The pneumatic fractionator operated for 40 s for each sample at 276 kPa. Bur debris samples were then cleaned to separate the weed seeds from other debris. Once the samples were processed from the pneumatic fractionator, *Amaranthus* spp. seeds were manually sorted from the other debris. Weed seed numbers in each sample were quantified using Equation 1.

Data Analysis

The data pertaining to each seed fate component (i.e., shattered to the ground, retained on the plant, part of the bur debris, or attached to the harvested seed cotton going to the gin) were converted to a percentage of total seed production per plant. To assess the homogeneity of variances of the data, a Levene test was conducted with R software (R Core Team 2025). The normality of the residuals was evaluated by inspecting the distribution of the residuals for each response variable. Once the assumptions of normality and homogeneity of variance were confirmed for all variables, an ANOVA was conducted. The data within each harvester type across the two study years were pooled due to a nonsignificant year by treatment interaction. A one-way ANOVA was conducted for each harvester type (picker and stripper) to determine the differences in the proportion of weed seeds present at each seed fate component ($\alpha = 0.05$) using the LME4 package in R (Bates et al. 2015; R Core Team 2025). If differences were detected, post hoc analyses were conducted using a Tukey HSD test ($\alpha = 0.05$), with the EMMEANS package in R (Lenth 2024; R Core Team 2025). Seeds of *Amaranthus* species in the seed cotton were compared between the two harvester types using a Student *t*-test in R (α=0.05). All data visualizations were generated using the GGPLOT2 package in R (R Core Team 2025; Wickham 2016).

Experiment II: Impact Mill Evaluation

Experimental Setup. Debris was collected from a local cotton gin (i.e., gin debris) in Brazos County, Texas, during fall 2023; from a cotton stripper field cleaner (i.e., bur debris) in Lubbock, Texas (33.69°N, 101.82°W), during fall 2023; and from shredded material using a field mower (called stem debris) in College Station, Texas (30.54°N, 96.43°W) in fall 2024. The samples collected in fall 2023 were stored in a cool, dry location until used in the study.

The cotton debris materials were fed through a single stationary integrated Harrington Seed Destructor (iHSD) impact mill (deBruin Engineering, Mount Gambier, SA, Australia; Figure 1) at a feed rate of 1 kg s^{-1}. In addition to Palmer amaranth, other regionally important weed species and those reported in cotton gin trash by Norsworthy et al. (2009) such as large crabgrass, barnyardgrass, Texas millet (*Urochloa texana* Buckley), morningglory (a mix of *Ipomoea hederacea* and *Ipomoea lacunosa*), prickly sida, and sicklepod (*Senna obtusifolia*), were included in the testing. All weed seeds were sourced from Azlin Seed Company (Loveland, MS). The study was conducted in a factorial completely randomized design with 10 replications. The debris type (three levels: gin debris, bur debris, and stem debris) and weed species (seven levels) were regarded as the two experimental factors.

The seeds (2,000/species) and cotton debris were laid out on a conveyor belt, and the weed seeds were placed in the middle 80% of the debris (as suggested by Schwartz-Lazaro et al. 2017b; Walsh et al. 2018a). Five samples of each cotton debris type were used to measure moisture content by recording the initial wet weight, drying the samples for 7 d at 60 C, and then weighing them again to determine moisture loss. Power consumption, when the samples were run through the impact mill, was recorded using a Tractor PTO Shaft Monitoring System (Datum Electronics, East Cowes, UK) that generated 90 to 100 data points per second. Once the mill reached optimal operating speed, the power draw was recorded for 5 to 10 s; then, the debris was run through the mill. The PTO monitor continued to log data throughout the processing of the debris and for another 5 to 10 s after the debris was processed. After the sample was run through the impact mill, any leftover residue within the impact mill was collected and weighed to determine whether lint clogging was present that might have affected the functionality of the mill.

The extent of seed damage caused by the impact mill was assessed using a greenhouse germination assay. Each tray (25.4 cm × 50.8 cm) was filled with 250 g of processed cotton debris containing weed seeds, representing a subsample of the 1-kg batch of processed cotton debris that had been run through the impact mill. This setup resulted in four trays (i.e., four replications) per debris sample. To improve moisture retention, the bottom 2.5 cm of each tray was filled with a potting soil mix (Jolly Gardener Pro-Line HFC/20 potting soil; Poland Spring, ME). For each debris type, an untreated control was included (four replications)

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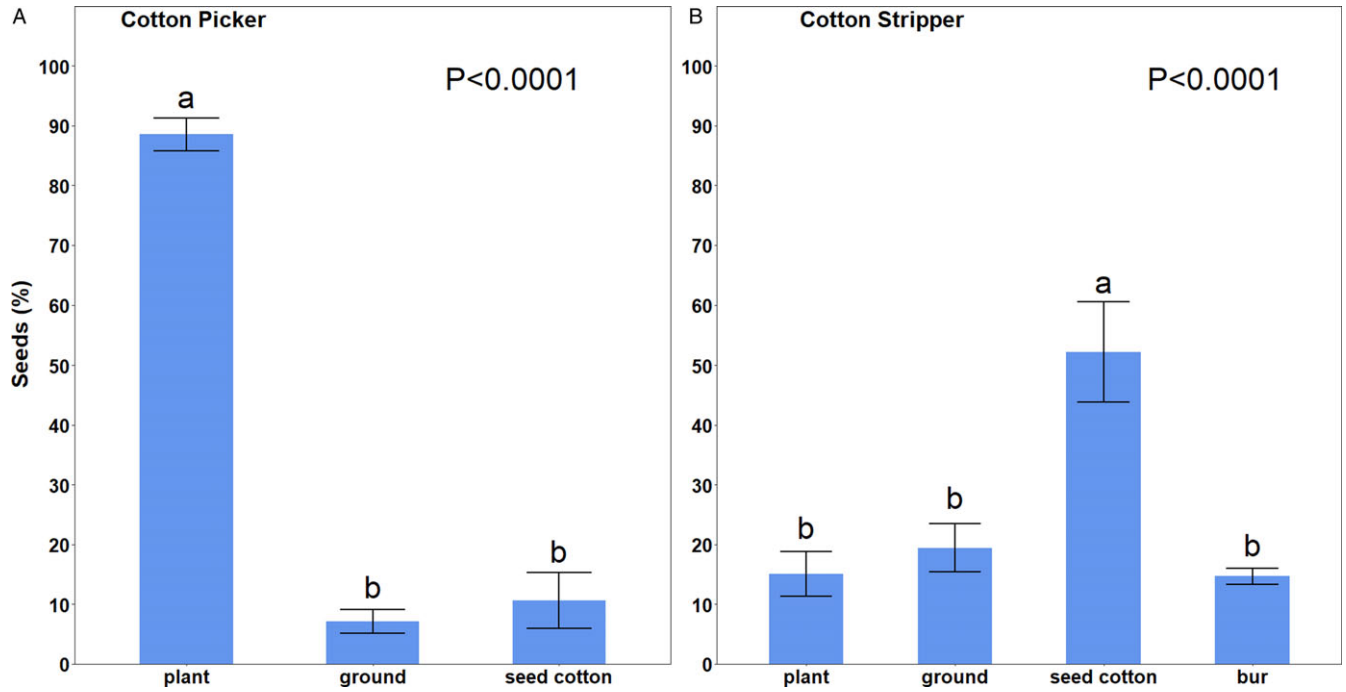


Figure 4. Mean percentage of *Amaranthus* spp. seeds retained on the plant, shattered to the ground, and removed with seed cotton in a cotton picker harvester (A), or seeds retained on the plant, shattered to the ground, removed with seed cotton, and mixed with bur debris in a cotton stripper harvester (B). Bars topped by the same letter in each graph are not significantly different ($\alpha = 0.05$). Vertical lines on each bar represent the standard error of the mean.

consisting of 100 seeds per species per tray, manually mixed into debris that had not been processed through the impact mill. To account for any background weed seed presence in the debris, a negative check (no added weed seeds and no impact mill treatment) was included. The greenhouse germination assay was conducted for 9 wk, with daily watering and manual soil mixing every 3 wk to stimulate germination. Germinated seedlings were counted and removed each week.

Data Analysis. To determine the seed kill rate in impact-mill-treated cotton debris, the germination rates were converted to percentages using Equation 2 (Walsh et al. 2018a):

$$Seed\ kill = 100 - \left\{\frac{Number\ of\ Seedlings\ in\ Processed\ Debris}{Number\ of\ Seedlings\ in\ Unprocessed\ Debris \times 100}\right\} \quad [2]$$

Data analyses were carried out using R statistical software (R Core Team 2025). To determine the homogeneity of variance of the data for seed kill rate and debris moisture content across the debris types, a Levene test was conducted. To assess the difference among the cotton debris types for the seed kill rate of each species, a one-way ANOVA ($\alpha = 0.05$) was conducted, with the study environments and replications considered as random effects within the model. Similarly, a one-way ANOVA ($\alpha = 0.05$) was conducted to test differences in moisture levels among different debris types. When ANOVA was significant, a post hoc analysis was conducted using the Tukey HSD test with the EMMEANS package in R (Lenth 2024).

The power use data from the PTO monitor were smoothened with GraphPad Prism software (Dotmatics, Boston, MA) by calculating a moving average of 20 surrounding data points. Peak power (in kilowatts, kW) was defined as the maximum power draw recorded during each replication at a flow rate of 1 kg s^{-1} for each debris type. This represents the highest energy requirement of the impact mill during operation. In contrast, the average load represents the sustained energy required when the mill is operating within its designed parameters. Average load was calculated as the total energy used to process the given quantity of cotton debris, following a method adapted from Bechere et al. (2021); Equation 3:

$$L = P \times T \quad [3]$$

where L is the average load (kilowatts per hour; kWh), P is the mean power (kW), and T is the run time (in hours) to process the debris. Data on power requirements were analyzed using a t-test in R to compare between gin debris and bur debris. All graphs were generated using GGPLOT2 in R (Wickham 2016).

Results and Discussion

Experiment I: Weed Seed Fate

Cotton Stripper Harvester. A high proportion (52.14%) of *Amaranthus* spp. seed production was collected and subsequently removed from the field during harvest with a cotton stripper unit, indicating the potential for HWSC during cotton harvest with stripper harvesters (Figure 4). The collection of *Amaranthus* seeds by stripper harvesters could substantially reduce seed bank additions and represent a potential avenue for HWSC in cotton. Of the total *Amaranthus* seed production that remained in the field after harvesting with a cotton stripper, 19.42% was found on the ground, 14.66% was in the bur debris released back onto the field during harvest, and the remaining 15.1% of the seed was retained on the plant (Figure 4). The collection of weed seeds in the bur debris provides another opportunity to target them and prevent seedbank input. This could be achieved by incorporating a HWSC

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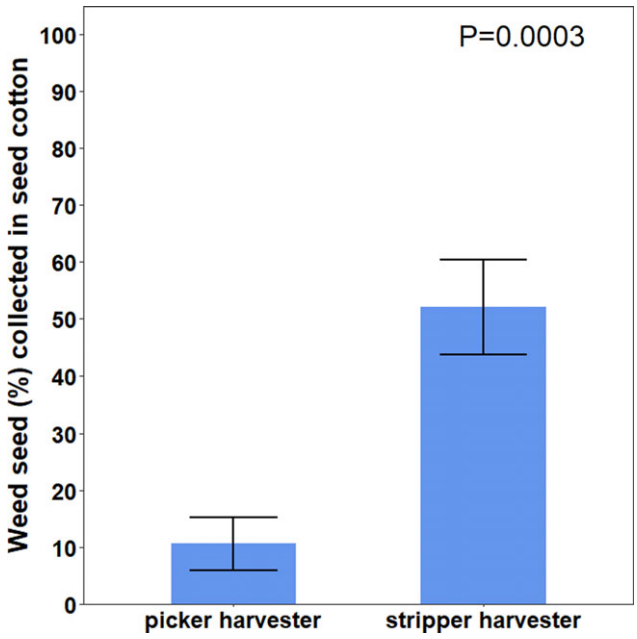


Figure 5. Mean proportion of *Amaranthus* spp. seeds collected in seed cotton (out of the total seed produced), which is removed from the field for processing at a cotton gin, after a cotton harvest operation with a cotton picker harvester or a stripper harvester. Vertical lines on each bar represent the standard error of the mean. The P-value indicates significant treatment differences based on a Student *t*-test.

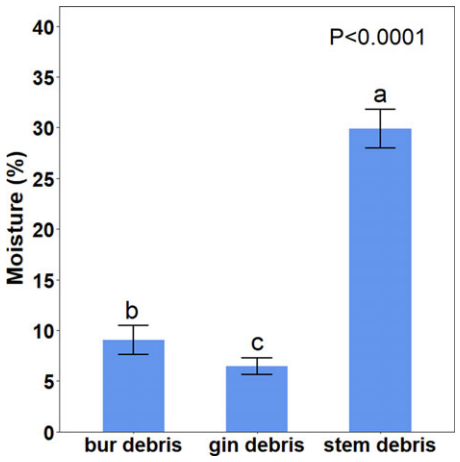


Figure 6. Moisture content (%) of bur debris (debris from a cotton stripper field cleaner), gin debris (debris from a cotton gin), or stem debris (stem shredding after cotton harvest) material prior to being treated with a seed impact mill. Bars topped by different letters indicate significant differences ($P < 0.05$). Vertical lines on each bar represent the standard error of the mean.

practice such as debris lining (akin to chaff lining), impact mill, or debris collection and removal during cotton harvest, with additional machinery (Walsh et al. 2018b). The weed seeds removed with the seed cotton typically end up in the cotton gin debris, management of which is discussed below.

The significant weed seed retention on the maternal plants after harvest with a stripper header also creates an after-harvest opportunity for targeting *Amaranthus* seeds. The retained weed seeds could be targeted during the post-harvest mowing/shredding operation of cotton stems. Further research is imperative in this regard. In southern Texas cotton production fields, there is a legal requirement to mow cotton stems after harvest to prevent overwintering of boll weevil and cotton stem weevil pests (Smith 1998). A similar approach could be applied to *Amaranthus* spp. in cotton systems, where a post-harvest treatment is used to prevent viable seedbank input.

Cotton Picker Harvester. Only a small proportion (6.14%) of *Amaranthus* seed production was collected in seed cotton during harvest with a picker unit (Figure 4). The relatively lower seed capture compared with that of the stripper harvester is likely due to the less aggressive harvesting mechanism of the picker header (Figure 2). With the picker, a large proportion of *Amaranthus* spp. seeds remained on the plant (85.97%), whereas only 7.1% and 6.14% were found on the ground and in seed cotton, respectively (Figure 4). This aligns with seed retention values prior to harvest reported by Schwartz-Lazaro et al. (2021), who found that *Amaranthus* spp. retained approximately 90% of their seeds at soybean physiological maturity.

The large proportion of seed retention on the maternal *Amaranthus* spp. plants following harvest by a picker harvester indicate the potential for reducing seedbank inputs through post-harvest interventions. This could be accomplished by developing suitable strategies, including the collection and destruction of weed seeds during the post-harvest stem shredding operation, which typically occurs as a standard field management practice in cotton. Additionally, modifying the picker header to capture more weed seeds during cotton harvest could enable targeting them at the cotton gin, facilitating their management in gin debris.

Fate of Weed Seed in Cotton Gin. A significant amount of *Amaranthus* spp. seeds can be delivered to a cotton gin through seed cotton from both the picker and stripper harvesters; however, the fate of this seed varies between cotton gins (Figure 5). The leftover material produced during the ginning process (i.e., gin debris or gin trash), which includes weed seeds, is often returned to crop land as a soil amendment (Norsworthy et al. 2009). The introduction of herbicide-resistant biotypes through gin debris should be a major concern for producers, underscoring the need to destroy weed seeds in gin debris to curtail the spread of problematic weeds. The gin debris is also used as a livestock feed (Erwin and Roubicek 1958; Hill et al. 2013); weed seeds can be disseminated through the manure or by being attached to the fur and feet of animals, potentially leading to weed reinfestations (Blackshaw and Rode 1991; Hogan and Phillips 2011).

Composting has been identified as a viable option for managing weed seeds in cotton debris. However, the necessary composting practices to ensure weed seed kill are often not properly executed, leading to the spread of viable seeds, including those of *Amaranthus* spp. (Norsworthy et al. 2009). New techniques are needed that prevent viable seeds present in cotton gin debris from re-infesting crop production fields. In this regard, the potential suitability of a novel technique of using weed seed impact mills is discussed below.

Experiment II: Impact Mill Evaluation

Moisture Content of Cotton Debris. The moisture content of the cotton debris can affect the impact mill's ability to handle it. The stem debris (material collected following stem shredding) had the highest moisture concentration at 29%, the bur debris had 9% moisture, and the gin debris had 6.5% moisture (Figure 6).

The stem debris samples clogged the impact mill, likely due to their high moisture content and/or the presence of woody stems and lint. Schwartz-Lazaro et al. (2017b) reported that soybean chaff needed to have a moisture content of ≤16% to be effectively

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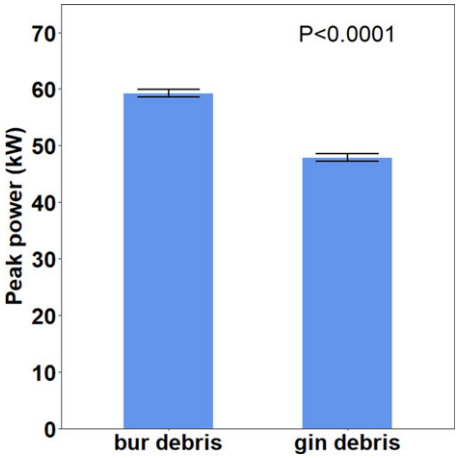


Figure 7. Peak power (kilowatts, kW) required by the integrated Harrington Seed Destructor impact mill for processing weed seeds in cotton bur debris (debris from a field cleaner of a stripper harvester) or gin debris (debris from cotton ginning mills). Vertical lines on each bar represent the standard error of the mean. The P-value indicates significant treatment differences based on a Student *t*-test.

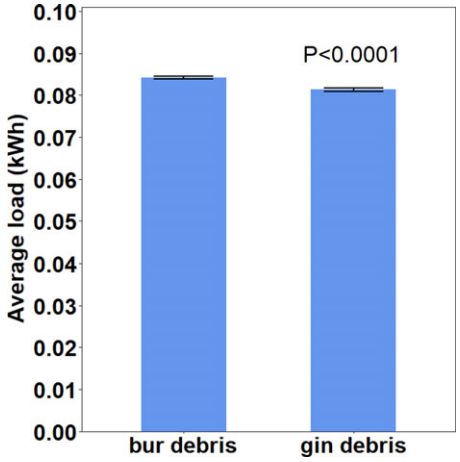


Figure 8. The average power load (kilowatt hour; kWh) required by the integrated Harrington Seed Destructor impact mill for processing weed seeds in cotton bur debris (debris from a field cleaner of a stripper harvester) or gin debris (debris from cotton ginning mills). Vertical lines on each bar represent the standard error of the mean. The P-value indicates significant treatment differences based on a Student *t*-test.

processed by the impact mill. For stem debris, no further testing was conducted due to repeated clogging. Future research aimed at enabling the processing of stem debris with the impact mill should focus on enhanced stem drying through natural frost events, alternative desiccant strategies, or modifications to the stem shredding process such as producing smaller pieces or incorporating a drying mechanism during shredding. The bur and gin debris had lower (<10%) moisture content, which allowed continual testing with the impact mill. Additionally, the amount of material that had entangled with the impact mill was <1 g for the gin and bur debris material (data not shown).

Power Requirements of the Impact Mill. The power requirements of the impact mill can inform the machine's ability to handle the debris. Two specific aspects of the power requirements can influence the feasibility of the impact mill: the peak power requirement, and the average power load. The impact mill, with no debris being run through it, had a peak power requirement of 26 kW. The peak power requirements for bur (60 kW) and gin (50 kW) debris (Figure 7) were in close alignment with the power requirements documented by Russell and Flessner (2025a, 2025b) for wheat and soybean chaff. The increase in peak power between the bur debris and the gin debris is most likely due to particle size, as the bur debris had larger particles, which would have increased power demand. The average power load requirements were 0.085 kWh for bur debris and 0.08 kWh for gin debris (Figure 8), which suggests efficient energy use during continuous operation. The average power load requirement is extremely small, suggesting that both debris types will require minimal energy to process the material.

Overall, the bur debris had a 19% greater peak power requirement and a 3% greater average power load requirement than the gin debris, suggesting that reducing the moisture or changing the composition of the bur debris to reduce the power requirement may be beneficial in decreasing the power demand. Previous research has focused on the increase in peak power requirement (Russell and Flessner 2025a, 2025b) or the increase in fuel consumption (Winans et al. 2023). The peak power increased by 92% for the gin debris and 130% for the bur debris compared to the impact mill operating empty; these observations are comparable to the increase of 136% with wheat chaff and 156% with soybean chaff (Russell and Flessner 2025a, 2025b). The lower peak power requirement for processing gin and bur debris compared to wheat and soybean chaff suggests that impact mills can effectively handle bur and gin debris.

Seed Kill Levels. Within each weed species, there were no significant differences between the two debris types in terms of seed kill level ($P > 0.05$); therefore, the analyses were combined. Kill levels for all species exceeded 98% and were not statistically different across species (Table 2). This agrees with previous research conducted in soybean, wheat, and rice systems, which reported seed kill levels of approximately 98% for the species tested (Schwartz-Lazaro et al. 2017b; Tidemann et al. 2020; Winans et al. 2023). Our findings are also consistent with previous research indicating that seed kill is not influenced by seed size or weight (Schwartz-Lazaro et al. 2017b). However, the potential influence of seed coat thickness or embryo shape, particularly in relation to their interaction with the mill blades and location within the debris, may play a role in the impact mill efficacy. Previous research examining various impact mill models suggests that other commercial impact mill units may perform similarly with cotton-based debris, achieving high seed kill rates. However, lint concentration in the cotton debris may affect the ability of some models to process the material effectively.

Practical Implications

A high proportion of the total *Amaranthus* spp. seed production was collected with seed cotton (52%) during cotton stripper harvest, thus an opportunity exists to develop or refine processing techniques at cotton gins to remove or destroy weed seeds in gin debris. Destruction of weed seeds at the cotton gin is imperative to prevent seeds of *Amaranthus* spp. and other weed species from being returned to production fields. Furthermore, given that the majority (85%) of the total *Amaranthus* spp. seed production remains on the plant after the cotton picker harvest, effective weed seed control should focus on post-harvest tactics to prevent additions to the weed seedbank. The survival of these plants to maturity suggests that they may carry herbicide resistance traits, making their elimination critical for long-term weed management. Although this experiment shows promise for weed seed

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Table 2. Seed kill rates achieved by the integrated Harrington Seed Destructor impact mill for barnyardgrass, large crabgrass, morningglory, Palmer amaranth, prickly sida, sicklepod, and Texas millet in cotton gin debris and bur debris.[a]

Species	Seed kill[b]
	% (± SE)
Barnyardgrass	99.6 ± 0.28
Large crabgrass	99.9 ± 0.14
Morningglory	98.9 ± 0.31
Palmer amaranth	99.9 ± 0.12
Prickly sida	99.8 ± 0.19
Sicklepod	99.8 ± 0.15
Texas millet	99.6 ± 0.42

[a]Bur debris is the material collected from the field cleaner of a cotton stripper harvester equipment.
[b]Significant differences were not detected (P > 0.05) between trash types or species kill levels.

management during cotton harvest, future research should examine how higher weed density may influence weed seed capture or removal during cotton harvest.

Impact mills have demonstrated potential in cotton as a new integrated weed management tool to mitigate the spread of weed seeds. The impact mill requires low plant moisture to function effectively, as evidenced by its inability to process stem debris with a moisture content of 29%. However, advancements in cotton stem management, such as enhancing desiccation during defoliation, exploiting favorable environmental conditions, or redesigning the shredding mechanism to produce finer material, could enable its future integration into harvest systems. The promising results regarding the low power requirements for gin and bur debris demonstrate high feasibility for using impact mills to manage weed seeds in different types of cotton debris. Future research should evaluate the operational lifespan of the impact mill when processing larger, more complex debris and determine the maximum lint concentration the mill can effectively handle within these samples.

The present study demonstrated high weed seed kill rates with the impact mill in both the bur debris and gin debris, showing promise for implementation on cotton strippers and cotton gins. To integrate an impact mill into a cotton stripper field cleaner, research is needed on the ability of the stripper to meet the power requirement. Additionally, research is needed on the flow rates to the impact mill and how increased debris may affect the seed destruction level. Previous research has shown that increasing the chaff flow rate can decrease seed kill levels in soybean and wheat (Schwartz-Lazaro et al. 2017b). Modifications to the impact mill design may also be necessary to enable integration with the cotton stripper harvester. Furthermore, it is important to determine the optimal point within the cotton gin's extended cleaning process for implementing an impact mill. While modifications to existing systems may increase costs, integrating a weed seed impact mill could help growers and gins mitigate future issues with herbicide-resistant weeds by curbing the spread of viable weed seeds.

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