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Research Article

Allelopathic Effects of Aqueous Extracts of Sorghum (*Sorghum bicolor* L. Moench) on the Early Seedling Growth of Sesame (*Sesamum indicum* L.) Varieties and Selected Weeds

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Sesame (*Sesamum indicum* L.) production is lucrative to resource poor farmers in marginalised areas of Zimbabwe, although most farmers have reportedly been failing to derive maximum economic benefits from sesame production due to poor productivity. Low productivity has been attributed to several factors including challenges of weed control due to absence of registered herbicides for use in sesame in Zimbabwe. Laboratory enzyme assays were conducted using different sorghum aqueous leaf and stem extract concentrations at 0, 2.5, 5.0, 7.5, and 10.0% wv^{-1} to determine the effect of sorghum aqueous extracts on plant defense enzymes polyphenol oxidase (PPO), peroxidase (POD), and phenylalanine ammonia lyase (PAL) in sesame and selected weeds. Greenhouse experiments were conducted to assess the effect of sorgaab or sorgaab-Agil postemergence sprays on the seedling growth and physiology of sesame and weeds. The exposure of sesame, black jack, and goose grass to sorghum aqueous extracts caused a significant ($p < 0.05$) concentration-dependent increase on the activity of antioxidant enzymes PAL, POD, and POD. Similarly, postemergence sprays of sole sorgaab, herbicide, and sorgaab-herbicide combination significantly ($p < 0.05$) increased sesame and black jack seedling growth, chlorophyll content, and fluorescence but not of goose grass. From this study, it could be concluded that the allelochemicals in sorghum aqueous extracts were not effective at inhibiting the growth and physiological processes of sesame and the weeds. Therefore, resource-poor farmers cannot rely on sorgaab to control weeds in sesame but there is a need to integrate weed control options to form an effective integrated weed management program.

1. Introduction

Sesame (*Sesamum indicum* L.) is one of the world's oldest cultivated oilseed crops, and it belongs to the *Pedaliaceae* family [1]. The place of origin of this crop is not clearly known to one place because it is thought to be either Africa or Asia which together contribute to 96% of the total global sesame production [2]. Sesame is one of the first crops to be processed for oil, and the oil extracted from the seeds is the most important product, commonly referred to as the "Queen of oils" by virtue of high-quality oil resistant to rancidity [1, 3]. In Zimbabwe, sesame is currently grown in areas that receive low to moderate rainfall (<300 to 600 mm) because of the plant's drought tolerance properties which render it suitable to be grown in low rainfall areas. In Zimbabwe, most farmers in dry land areas such as Gokwe, Guruve, Chiredzi, and Nkayi have abandoned cotton (*Gossypium hirsutum* L.) production and have since then adopted commercial sesame production for export to Mozambique [4]. In areas such as Guruve and Chiredzi, farmers are growing sesame on contract farming arrangements. In 2014/15 Sidella, a company which is promoting widespread adoption of this crop, contracted 2820 smallholder famers which resulted in total production of 1,474,860 kg [5].

As is true for any other crop production system, crop yield quality and quantity is compromised by yield reducing biotic or abiotic factors [6]. Weeds are a major yield reducing factor in sesame production as they compete with crops for photosynthetically active radiation, moisture, nutrients, and

space, ultimately causing yield quality and quantity reduction [7]. Sesame is highly sensitive to high weed infestations, and insufficient weed management will result in grain yield reduction as high as 80% [7]. Mahgoub et al. [8] reported that the critical period of weed control (CPWC) in sesame is 2–6 weeks after planting, during which the crop should be kept weed free to avoid crop yield losses. This is because sesame growth is slow during the first 3–4 weeks after emergence because a large proportion of the photo assimilates is directed towards root development [9, 10]. During this delicate growth phase, sesame seedlings are poor competitors and if the weeds and crop emerge simultaneously, the weeds have a competitive advantage [11, 12].

Most resource poor farmers growing sesame depend on manual weed-control methods, specifically hand pulling and hand-hoeing [13]. These manual weed control methods may be compromised in the case of incessant rains and unavailability of labour during the CPWC, and this pushes some farmers to adopt herbicide technology [14]. Possible herbicide options such as Fluazifop-P-butyl and Propaquizafop are used in sesame although optimum dosage requirements are unknown because there are no registered herbicides for use in sesame in Zimbabwe. Consequently, this has resulted in the adulteration of these herbicides which poses a hazard to human health and to the environment [15]. Modern agricultural practices such as manipulation of allelopathic crops which can counteract the negative effects of current weed control measures are easy to introduce as farmers are willing to accept methods that protect their crop yields. Exploitation of allelopathy as a tool for weed management can be adopted as this diversifies control options especially for resource poor farmers [16]. Previous studies have presented evidence that aqueous sorghum herbage extract (sorgaab) can be used to selectively control weeds in wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and soyabean (*Glycine max* L.) [17–19]. In this study, the weeds black jack (*Bidens pilosa* L.) and goose grass (*Eleusine indica* L. Gaertn) were selected as they represent very aggressive and difficult to control weeds of divergent morphology in Zimbabwe. This study was conducted to evaluate whether the potent allelochemicals produced in sorghum herbage have bioherbicidal effects on early seedling growth and physiological and biochemical processes of sesame and selected weeds.

2. Materials and Methods

2.1. Study Site. The study was carried out in the laboratory and greenhouse at the University of Zimbabwe's Crop Science Department in Harare, Zimbabwe, between January and May 2018. The laboratory experiment was carried out using natural light, and the average temperature was 25°C. The greenhouse experiment was conducted using natural light, and average temperature and humidity are presented in Table 1.

2.2. Sorghum Aqueous Extract Preparation. Sorghum variety SC Macia mature plants were harvested dry from SEEDCO's Rattray Arnold Research Station (RARS) in Harare, Zimbabwe, (18.3269°S, 29.9162°E) in October 2017. RARS is in Natural Region II, is situated 1363 meters above sea level, and receives an annual rainfall of above 750 mm. Stem and leaf portions were separated, chopped into 2 cm long pieces, and dried in the oven at 70°C for 48 hours. The different plant parts were ground into powder using a hammer mill grinder. The ground powder was kept in distinct well-labelled sealed envelopes in the laboratory at room temperature until use. A 10% wv^{-1} stock solution was prepared by adding 100 g of the ground powder into 1000 ml of distilled water and shaken for 48 hours at room temperature on an orbital shaker (Orbital shaker S01, Stuart Scientific Co. Ltd) at 100 rpm [20]. The resultant mixture was filtered using four layers of cheesecloth and the filtrate was centrifuged (Model Dynac II Centrifuge, Clay Adams) at 4000 rpm for 15 minutes [21]. The pH and osmotic potential of the prepared aqueous extracts was measured using a portable pH meter (Model Omega^{TM} PH222) and conductivity meter (Model SX 713 version 2.0 2013-7-30), respectively [22]. The extracts were stored in sealed plastic bottles in a refrigerator at 4°C until further use [23]. The 10% wv^{-1} stock solution was diluted with distilled water to make 2.5%, 5.0%, and 7.5% solutions prior to use [24].

2.3. Greenhouse Experiment: Effect of Sorgaab as a Postemergence Bioherbicide on the Early Seedling Growth of Six Sesame Varieties, Black Jack, and Goose Grass

2.3.1. Experimental Design. The greenhouse experiment was laid out as a Completely Randomised Design (CRD) with five treatments replicated four times. The experiment for sesame was a factorial experiment with two factors, namely, sesame variety and sorgaab concentration. The levels for sesame variety were Lindi 2002, Brown Zimbabwe, Ziada 94, IETC, Mtwara 09, and Lindi Zimbabwe, whilst the levels for sorgaab concentration are listed in Table 2. The experiment for each of the weeds was a CRD, and each treatment was replicated four times. The treatments used in this experiment are shown in Table 2.

2.3.2. Experimental Procedure. Ten sesame or 25 weed seeds were planted shallowly separately in pots measuring 20 cm diameter and 18 cm height, filled with oven sterilized sandy soil (clay 4%, silt 13%, and sand 83%), and these pots were watered daily with 450 ml of water using a perforated cup. Basal fertilizer was applied at planting at 2 g pot^{-1} using compound D (7%: 14%P_2O_5: 7% K_2O). Top dressing was done using ammonium nitrate (34.5% N) at a rate of 2 g pot^{-1} 32 days after planting. The sesame and weed seedlings were sprayed using a hand-held sprayer calibrated to discharge at a spray rate of 200 l/ha of the respective treatments when plants had reached the 3-4 fully expanded leaf stage. The experiment was terminated at 56 days after planting; by then, flowering had begun. Data collected included chlorophyll content using a chlorophyll Spadmeter (Chlorophyll meter SPAD 502Plus–Spectrum Technologies, Inc.) and chlorophyll fluorescence using a Chlorophyll Fluorometer (OS30p_+ Chlorophyll Fluorometer–OPTI-SCIENCES). Chlorophyll content was recorded on a weekly basis from a day after

Table 1: Average temperature and humidity in the greenhouse during March and April 2018.

Average temperature (°C)	Average max temperature (°C)	Average min temperature (°C)	Average max humidity (%)	Average min humidity (%)	Average humidity (%)
29.5	35.9	16.4	97.3	29.8	52.9

Table 2: Treatments.

Treatment	Treatment composition
Treatment 1	10% w/v sorgaab
Treatment 2	50 g propaquizafop (full-dose Agil)
Treatment 3	25 g propaquizafop (half-dose Agil)
Treatment 4	Half-dose Agil + 10% w/v sorgaab
Treatment 5	Control (nothing sprayed)

spraying up to 4 weeks, and chlorophyll fluorescence was recorded twice, a day after spraying and the day before terminating the experiment. Sesame and the test weed species were harvested and washed gently with water to remove any soil from the roots at 56 days after planting. The uprooted plants were separated into above-ground and below-ground portions, placed in well-labelled envelopes, and oven-dried for 72 hours at 80°C and thereafter dry weight was measured using an analytical scale (Model Analytical Balance Sartorius Research R200D).

2.4. Laboratory Experiment: Effect of Leaf and Stem Aqueous Extracts of Sorghum on the Activity of Antioxidant Enzymes PAL, POD, and PPO in Sesame Variety Lindi Zimbabwe, Black Jack, and Goose Grass

2.4.1. Experimental Procedure. The experimental design was laid in a Randomised Complete Block Design with five treatments replicated five times. The blocking factor was the distance from the window. This experiment was carried out in the Weed Science laboratory. Goose grass seeds were soaked in 16% hydrochloric acid for 20 minutes and rinsed twice in distilled water to break weed seed dormancy. Selection of black jack seeds on the basis of the length of achenes was done to eliminate dormant seeds from the experiment [25]. Sesame variety Lindi Zimbabwe was used for this experiment because it outperformed all the other varieties in the greenhouse experiment. Twenty-five seeds of either sesame or the weeds were placed separately in 9 cm diameter Petri dishes lined with Whatman No. 2 filter paper. Thereafter, the filter paper in the Petri dishes was treated with 5 ml of distilled water to allow seed germination for three days. The germinated seedlings were treated with 5 ml of the respective sorghum aqueous leaf or stem extracts at quarter, half, three-quarter, and full strength (10% wv^{-1} solution) + control (distilled water). After five days, the seedlings from the Petri dishes were harvested, pooled, and ground using a pestle and mortar in liquid nitrogen.

2.4.2. Polyphenol Oxidase Assay. Polyphenol oxidase (PPO) activity was assayed according to the method described by Ngadze et al. [26] with minor modifications. From the ground seedlings, 0.25 g of the homogenate was mixed with 0.05 M sodium phosphate buffer (pH 6.0) which contained 5% polyvinylpolypyrrolidone (w/v). The homogenate was filtered through four layers of cheesecloth, after which the resultant filtrate was centrifuged at 13000 rounds per minute for five minutes at 4°C. The solution fed into the spectrophotometer was made up of 0.5 ml of the supernatant, 1.5 ml 0.05 M sodium phosphate buffer, and 0.5 ml of 0.1 M catechol. The enzyme activity was measured at an absorbance of 546 nm at 20 second intervals for four minutes, and values are calculated per minute. The modification to this methodology was that enzyme activity readings were measured three times by making new supernatant solutions before taking readings with the same supernatant.

2.4.3. Peroxidase Assay. The activity of antioxidant enzyme peroxidase (POD) was measured according to the method described by Ngadze et al. [26]. From the ground seedlings, 0.25 g of the homogenate was mixed with 5 ml 0.05 M sodium phosphate buffer (pH 6.0) which contained 5% polyvinylpolypyrrolidone (w/v). The homogenate was filtered through four layers of cheesecloth, and the filtrate was centrifuged at 13000 rpm at 4°C for five minutes. From the supernatant, 1 ml was taken and added into a test tube containing 2.9 ml of 0.05 M sodium phosphate buffer, 1 ml of 2% H_2O_2 (v/v), and 1 ml of guaiacol. The resultant mixture was partitioned into three, and absorbance was measured at 470 nm for 4 minutes and 20 second intervals. Values were calculated per minute and are presented in U μl^{-1} min^{-1}.

2.4.4. Phenylalanine Ammonia Lyase Assay. Phenylalanine ammonia lyase (PAL) was assayed using the method described by Ngadze et al. [26]. An amount of 0.25 g of the ground seedlings was mixed in 5 ml buffer made up of 50 mM 2-mercaptoethanol and 5% polyvinylpolypyrrolidone (w/v). The homogenate was filtered through four layers of cheesecloth and centrifuged at 13000 rpm for 4 minutes at 4°C. From the supernatant, 1 ml was added to a solution containing 2 ml of 0.05 M borate buffer (pH 8.8) and 1 ml of 0.02 M L-phenylalanine, and the sample was incubated at 30°C for an hour. To stop the reaction, 0.2 ml of 6 M trichloroacetic acid was added into the test tube. This solution was aliquoted into three portions for spectrophotometer readings at 290 nm absorbance.

2.4.5. Data Analysis. The raw data were entered into Excel and subjected to analysis of variance (ANOVA) using GenStat version 14. A repeated measures ANOVA was carried out to analyse chlorophyll content and chlorophyll fluorescence data using GenStat version 14. Data were tested for normality using the Shapiro–Wilk Test. Graphs were generated using R statistical package and Sigma plot 10. Mean separation was performed using Fischer's

protected least significance difference (LSD) at 5% significance level, where there were significant differences among means.

3. Results

3.1. Greenhouse Experiment: Effect of Sorgaab as a Postemergence Bioherbicide on the Early Seedling Growth of Sesame and Weeds

3.1.1. Sesame

(1) Dry Shoot Weight, Dry Root Weight, and Number of Flowers. The interaction of sesame variety and herbicidal treatment was not significant ($p > 0.05$) for dry shoot weight, dry root weight, and number of flowers. However, the effect of variety on all the parameters was significant ($p < 0.05$) (Table 3). The variety Lindi Zimbabwe had significantly higher dry shoot weight than the other varieties which performed statistically the same. The root weight of the varieties was significantly ($p < 0.05$) different, and the variety Mtwara 09 had a significantly higher dry root weight and Ziada 94 had the lowest dry weight. The variety Lindi Zimbabwe developed the highest number of flowers, and variety Mtwara 09 had the lowest number of flowers of all the six varieties.

(2) Chlorophyll. The interaction of time × sesame variety × herbicide treatment was not significant ($p > 0.05$) on chlorophyll content. Time × sesame variety, time × herbicidal treatments effects were also not significant ($p > 0.05$) on chlorophyll content. There were no significant ($p > 0.05$) differences on the chlorophyll content of the six sesame varieties. However, these effects were nearly significant (Table 4). Herbicidal treatment effects resulted in no significant differences in chlorophyll content (Table 4). Time significantly ($p < 0.05$) influenced chlorophyll content (Table 4). The highest chlorophyll content was obtained at 3 WAS and the lowest content at 2 WAS.

(3) Chlorophyll Fluorescence. The interaction of time × sesame variety × herbicide treatment was not significant ($p < 0.05$) on chlorophyll fluorescence. Similarly, time × sesame variety and time × herbicidal treatments effects were also not significant ($p > 0.05$) on chlorophyll fluorescence. Chlorophyll fluorescence in the different sesame varieties was significantly ($p < 0.05$) different (Table 4). Lindi Zimbabwe had the highest chlorophyll fluorescence whilst the least chlorophyll fluorescence was recorded in IETC. Herbicidal treatment effects were not significant on the chlorophyll fluorescence (Table 4). Time had significant ($p < 0.05$) effects on chlorophyll fluorescence. Chlorophyll fluorescence was significantly higher at 3 WAS than at 0 WAS.

3.1.2. Black Jack

(1) Dry Shoot Weight, Dry Root Weight, and Number of Flowers. Herbicidal treatment effects were not significant ($p > 0.05$) on black jack dry shoot weight, dry root weight, and number of flowers (Table 5).

(2) Chlorophyll Content and Chlorophyll Fluorescence. Repeated measures ANOVA showed that there was no significant time ∗ herbicidal treatment interaction ($p > 0.05$) effects on black jack chlorophyll content and fluorescence.

(a) Chlorophyll Content. The herbicidal treatments were not significantly ($p > 0.05$) different on black jack chlorophyll content. Chlorophyll content of black jack significantly ($p < 0.05$) increased as time progressed. As time progressed from 0 WAS to 3 WAS, the chlorophyll content significantly increased and highest recording was observed at 3 WAS (Table 6).

(b) Chlorophyll Fluorescence. All postemergence treatments of sole sorgaab, herbicide dosages, and sorgaab-herbicide combinations were significantly ($p < 0.05$) different on black jack chlorophyll fluorescence. The highest chlorophyll fluorescence was observed in black jack seedlings treated with 10% sorgaab, and it was not statistically different from the full dose of Agil treatment (Table 6). Black jack chlorophyll fluorescence was significantly ($p < 0.05$) different as time progressed. Chlorophyll fluorescence increased as time progressed from 1 WAS to 4 WAS.

3.1.3. Goose Grass

(1) Dry Shoot Weight and Dry Root Weight. All the postemergence spray treatments of sole sorgaab, sole herbicide dosages, and sorgaab-herbicide combination were significantly ($p < 0.05$) different on the dry shoot weight and dry root weight of goose grass. All Agil treatments significantly suppressed the dry weight of goose grass shoots and roots better than the 10% sorgaab (Table 7).

(2) Chlorophyll Content. There was a significant ($p < 0.05$) time ∗ treatment interaction on the chlorophyll content of goose grass. Chlorophyll content in untreated goose grass (control) was significantly higher than the chlorophyll content in goose grass treated with Agil and sorgaab-Agil combination (Figure 1). Generally, for all the treatments which contained the herbicide Agil, as time progressed from 0 WAS to 3 WAS, chlorophyll content was significantly reduced in herbicide-treated plants as shown in Figure 1.

3.2. Laboratory Experiment: Effect of Leaf and Stem Aqueous Extracts of Sorghum on the Activity of Antioxidant Enzymes PAL, POD, and PPO in Sesame Variety Lindi Zimbabwe and Weeds

3.2.1. Sesame. There was no significant ($p > 0.05$) interaction between extract concentration and extract tissue on the activity of enzymes PAL and POD in sesame variety Lindi Zimbabwe. However, there was a significant extract concentration ∗ extract tissue interaction on enzyme PPO activity.

Table 3: Effects of sesame variety on the dry shoot weight, dry root weight, and number of flowers.

Sesame variety	Varietal effect		
	Dry shoot weight (g)/plant	Dry root weight (g)/plant	Number of flowers/plants
Lindi 2002	3.01[a]	0.644[ab]	2.62[bc]
Brown Zimbabwe	3.11[a]	0.622[ab]	1.83[b]
Ziada 94	3.40[a]	0.498[a]	2.52[bc]
IETC	3.40[a]	0.577[ab]	3.18[cd]
Mtwara 09	3.91[a]	0.992[c]	0.63[a]
Lindi Zimbabwe	5.05[b]	0.776[bc]	3.95[d]
p-value	<0.001	<0.001	<0.001
LSD	0.942	0.227	1.014
CV (%)	41.1	52.9	65.8

Means followed by the same letter in the column are not significantly different at $p < 0.05$.

Table 4: Effect of variety, treatments, and time on the chlorophyll content and chlorophyll fluorescence of six sesame varieties.

Sesame variety	Varietal effects	
	Chlorophyll content (mmol cm^{-2})	Chlorophyll fluorescence (Fv/Fm)
Lindi 2002	34.51	0.6445[b]
Brown Zimbabwe	36.05	0.5903[a]
Ziada 94	34.26	0.6429[b]
IETC	39.91	0.5598[a]
Mtwara 09	32.52	0.6473[b]
Lindi Zimbabwe	35.09	0.6586[b]
p-value	0.080	<0.001
LSD	ns	0.039
CV (%)	15.7	16.1
	Treatment effects	
10% w/v sorgaab	35.51	0.6338
Full-dose Agil	35.22	0.6331
Half-dose Agil	34.97	0.6271
Half-dose Agil + 10% sorgaab	34.55	0.6134
Control	34.53	0.6122
p-value	0.549	0.550
LSD	ns	ns
CV (%)	15.7	16.1
	Time effects	
0 WAS	33.07[a]	0.5933[a]
1 WAS	36.63[b]	*
2 WAS	32.96[a]	*
3 WAS	39.56[c]	0.6546[b]
p-value	<0.001	<0.001
LSD	1.399	0.026
CV (%)	15.7	16.1

Means followed by the same letter in the column are not significantly different at $p < 0.05$. *Chlorophyll fluorescence was not determined at 1 WAS and 2 WAS.

Table 5: Effect of postemergence sorghum aqueous extracts and Agil treatments on the dry shoot weight, dry root weight, and number of flowers of black jack.

Treatment	Dry shoot weight	Dry root weight	Number of flowers
10% ASE	9.73	3.60	8.85
100% Agil	13.02	4.58	10.02
50% Agil	14.65	4.41	10.90
50% Agil + 10% ASE	10.08	4.74	8.80
Control	11.36	4.63	9.07
p-value	0.102	0.963	0.500
LSD	ns	ns	ns
CV (%)	22.9	55.0	20.4

Table 6: Effect of different bioherbicidal treatments on the chlorophyll content and chlorophyll fluorescence of black jack.

Treatments	Treatment effects	
	Chlorophyll content (mmol cm^{-2})	Chlorophyll fluorescence (Fv/Fm)
10% w/v sorgaab	34.14	0.632[c]
Full-dose Agil	29.52	0.602[c]
Half-dose Agil	32.98	0.561[b]
Half-dose Agil + 10% sorgaab	34.17	0.546[a]
Control	30.98	0.502[a]
p-value	0.226	<0.001
LSD	ns	0.042
CV (%)	11.2	6.1
	Time effects	
1 WAS	23.12[a]	0.510[a]
2 WAS	30.89[b]	*
3 WAS	29.13[b]	*
4 WAS	47.18[c]	0.627[b]
p-value	<0.001	<0.001
LSD	3.839	0.044
CV (%)	17.3	11.6

Means followed by the same letter in the column are not significantly different at $p < 0.05$. *Chlorophyll fluorescence was not determined at 1 WAS and 2 WAS.

Table 7: Effect of postemergence herbicidal treatments on the dry shoot weight and dry root weight of goose grass.

Treatment	Dry shoot weight	Dry root weight
10% w/v sorgaab	7.00[b]	15.09[b]
Full-dose Agil	0.00[a]	0.00[a]
Half-dose Agil	0.00[a]	0.00[a]
Half-dose Agil + 10% sorgaab	0.00[a]	0.00[a]
Control	11.48[c]	15.55[b]
p-value	<0.001	<0.001
LSD	4.343	2.660
CV (%)	47.0	47.7

Means followed by the same letter in the column are not significantly different at $p < 0.05$.

(1) PAL. Increasing extract concentration from 0% to 50% increased PAL activity significantly ($p < 0.05$). A further increase in extract concentration from 5.0% to 7.5% reduced enzyme activity, and a maximal enzyme activity was recorded at sorgaab concentration of 10% (Table 8). Stem extracts significantly increased PAL activity better in sesame variety Lindi Zimbabwe as compared to leaf extracts.

(2) POD. Increasing the extract concentration from 0% to 7.5% had no significant effect on POD activity. Table 8 shows that increasing extract concentration from 2.5% to 10.0% increased POD activity and a further increase from 7.5% to 10% significantly increased enzyme activity. Stem aqueous extracts were more effective at increasing POD activity than aqueous leaf extracts.

(3) PPO. Table 8 shows that sorghum aqueous extracts significantly ($p < 0.05$) increased PPO activity in sesame variety Lindi. When the extract concentration is at 7.5%, enzyme activity was not statistically different from enzyme activity in the control. However, increasing extract concentration to 10% significantly increased enzyme activity. Leaf and stem extracts were not significantly ($p > 0.05$) different in PPO activity in sesame.

3.2.2. Black Jack. The interaction between sorghum extract concentration and extract tissue was significant ($p < 0.05$) on PAL, POD, and PPO enzymatic activity in black jack.

(1) PAL. Figure 2 shows that increasing the leaf extract concentration from 0% to 7.5% significantly decreased PAL activity. However, further increasing aqueous extract concentrations to 10.0% stimulated enzyme activity. Leaf extracts significantly reduced PAL activity at 2.5%; however, a further increment from 2.5% to 10.0% significantly increased enzyme activity in black jack seedlings.

(2) POD. There were significant ($p < 0.05$) differences in the concentrations of both leaf and stem aqueous extracts on the activity of POD. A significant increase in POD activity was observed in response to increase in leaf extract concentration from 0% to 2.5%. Further increase in leaf extract concentration to 10.0% significantly reduced POD activity (Figure 2). Aqueous stem extracts significantly ($p < 0.05$) increased POD activity in black jack as extract concentration and the highest enzyme activity was recorded at maximal activity.

(3) PPO. There were significant ($p < 0.05$) differences in the concentration of sorghum aqueous leaf and stem extracts on PPO activity in black jack. Leaf aqueous extracts at 2.5% extract concentration increased. Leaf aqueous extracts caused a hormetic effect on PPO concentration (Figure 2). However, increasing leaf extract concentration to 10.0% reduced PPO activity if compared with 2.5%. Aqueous stem extracts reduced enzyme activity when extract concentration was increased from 0% to 10.0% although there are no significant differences between the control and the maximal concentration.

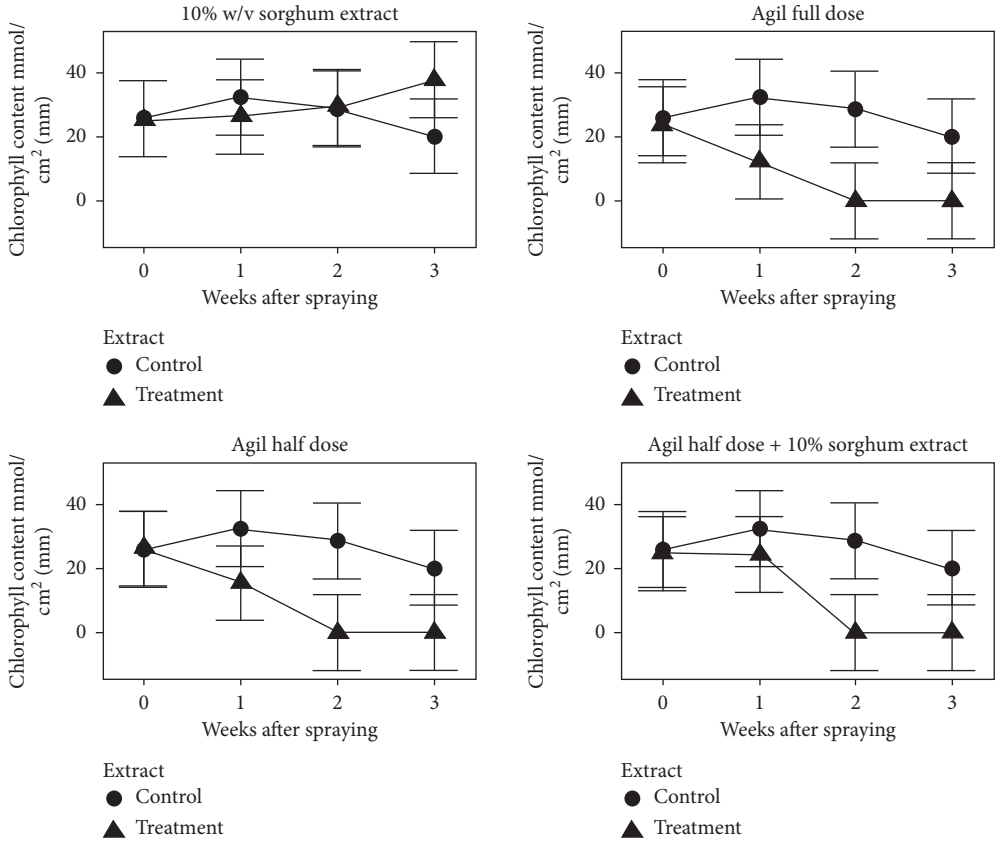

Figure 1: Effect of postemergence treatments on the chlorophyll content of goose grass. Error bars indicate least significant differences (LSD 5%).

Table 8: Effect of different concentrations of sorghum leaf and stem aqueous extracts on PAL, POD, and PPO activity in the sesame variety Lindi Zimbabwe.

Extract concentration (%)	Enzyme effects		
	PAL (μg PAL g^{-1})	POD (U μl^{-1} min^{-1})	PPO (U μl^{-1} min^{-1})
0 (control)	0.611^{a}	0.139^{a}	0.114^{a}
2.5	0.928^{ab}	0.198^{a}	0.389^{bc}
5.0	0.944^{b}	0.262^{a}	0.275^{b}
7.5	0.782^{ab}	0.288^{a}	0.130^{a}
10.0	1.348^{c}	0.558^{b}	0.504^{c}
p-value	0.002	0.015	<0.001
LSD	0.320	0.237	0.135
CV (%)	28.8	68.1	39.8
	Extract tissue effects		
Extract tissue	PAL (μg PAL g^{-1})	POD (U μl^{-1} min^{-1})	PPO (U μl^{-1} min^{-1})
Leaf	0.664^{a}	0.266	0.294
Stem	1.181^{b}	0.312	0.271
p-value	0.002	0.015	0.581
LSD	0.203	ns	ns
CV (%)	28.8	68.1	39.8

Means followed by the same letter in the column are not significantly different at $p < 0.05$.

3.2.3. Goose Grass. The interaction between sorghum extract concentration and extract tissue was not significant ($p > 0.05$) on PAL, POD, and PPO enzymatic activity in goose grass.

(1) PAL. Table 9 shows that increasing the extract concentration from 0% to 2.5% increased PAL activity and a further increase in extract concentration from 2.5% to 10.0% reduced PAL activity. Leaf and stem aqueous extracts were not statistically different on PAL activity.

(2) POD. There were no significant differences in POD activity when aqueous sorghum extract concentration increased from 0% to 10.0%. Significant differences were

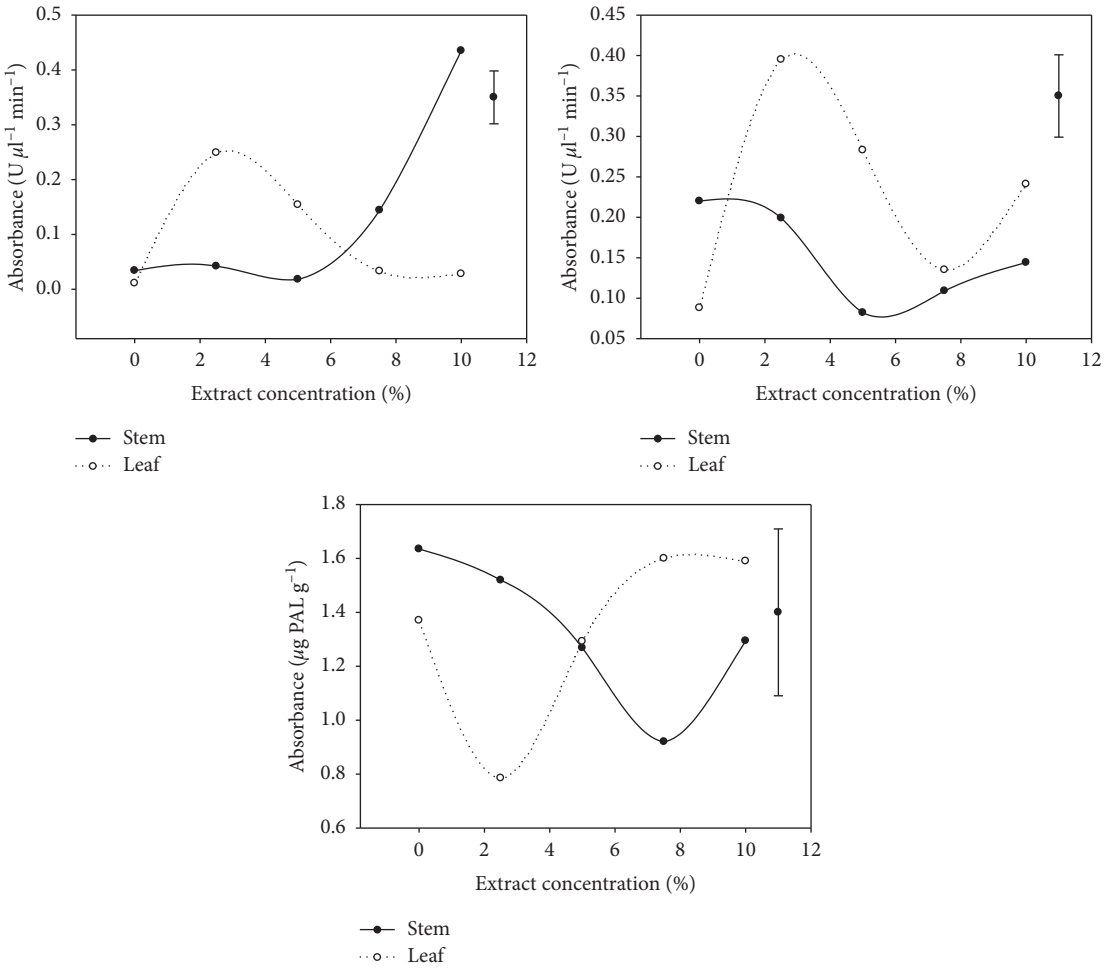

Figure 2: Effect of different concentrations of sorghum leaf and stem aqueous extracts on POD, PPO, and PAL activity in black jack. Errors bars indicate LSD at $p < 0.05$.

Table 9: Effect of different concentrations of sorghum leaf and stem aqueous extracts on PAL, POD, and PPO activity in goose grass.

Extract concentration (%)	Enzyme		
	PAL (μg PAL g^{-1})	POD (U μl^{-1} min^{-1})	PPO (U μl^{-1} min^{-1})
0 (control)	0.959[ab]	0.167	0.073
2.5	1.421[b]	0.150	0.011
5.0	1.331[b]	0.142	0.100
7.5	1.335[b]	0.173	0.134
10.0	0.726[a]	0.197	0.140
p-value	0.042	0.858	0.361
LSD	0.5056	ns	ns
CV (%)	14.1	6.8	4.9
	Extract tissue		
Extract tissue	PAL (μg PAL g^{-1})	POD (U μl^{-1} min^{-1})	PPO (U μl^{-1} min^{-1})
Leaf	1.060	0.125[a]	0.104
Stem	1.249	0.203[b]	0.119
p-value	0.233	0.032	0.526
LSD	ns	0.0705	ns
CV (%)	14.1	6.8	4.9

Means followed by the same letter in the column are not significantly different at $p < 0.05$.

recorded between stem and leaf extracts, were stems more effective in stimulating POD activity as compared to the leaves (Table 9).

(3) PPO. Stem and leaf at the different concentrations had no significant differences in the activity of PPO (Table 9).

4. Discussion

4.1. Effect of Sorgaab as a Postemergence Bioherbicide on Early Seedling Growth of Six Sesame Varieties and Weeds. In this study, it was shown that application of sole sorgaab did not inhibit the early seedling growth of sesame, black jack, and goose grass. Inhibition of seedling growth and physiological parameters was observed in goose grass seedlings treated with a sorgaab-herbicide combination. The results suggest that the sole herbicide and sorgaab-herbicide treatments effectively controlled goose grass and had no effect on sesame or black jack. This result contradicts the findings reported by Uddin et al. [27, 28] who stated that broadleaved plant species were susceptible to sorgoleone, an allelochemical produced by sorghum roots as compared to grass weeds. Physiological differences such as leaf texture and leaf orientation play an important role in capturing phytotoxins, and it is possible that broadleaved plants used in this study failed to trap and absorb the allelochemicals in the sorgaab. This result suggests that sorgaab is a selective graminicide, affects grasses and not broadleaved plants, and probably has the same mode of action as the herbicide used in this study. From the results of this study, it can be confirmed that the herbicide used in this study is a selective grass killer, and it is capable of satisfactorily suppressing goose grass even at reduced dosages. Quizalofop-p-ethyl at $50\,g\,ha^{-1}$ and $40\,g\,ha^{-1}$ were both effective, and this suggests that reduced dosages of the herbicide in combination with sorgaab can be adopted as part of an IWM programme in sesame [12, 14].

Postemergence application of sorgaab increased the dry shoot weight, dry root weight, number of flowers, chlorophyll content, and chlorophyll fluorescence of sesame and black jack. This could be a case of desirable hormesis. However, an increase of measured parameters across all the treatments indicated that the growth and development of sesame and black jack was stimulated by the allelochemicals in sorghum above ground tissues. These results suggest that sorghum variety SC Macia contains a lot of essential nutrients that can boost the growth and development of broadleaved crops. These findings corroborate with the work of Cheema et al. [18] who reported that wheat and a broadleaved weed (*Melilotus parviflora* L.) growth and development was improved by application of 10% sorgaab. Cheema et al. [19] reported that maize development and weed control was improved by applying three sprays of sorgaab. This implies that these aqueous extracts of sorghum acted as growth promoters. The results of the nutritional analysis for sorghum variety SC Macia showed that the amount of NPK that was in the extracts used exceeding the required amounts and so sesame and black jack managed to flourish when treated with sorgaab or sorgaab-herbicide treatments [29]. The sorgaab can be adopted as easily accessible foliar fertilizers to resource poor farmers but effective weed management measures must be adopted since the aqueous sprays from this study also stimulated weed growth and development.

Chlorophyll content and fluorescence of sesame and black jack increased during the course of the experiment and this suggests that allelochemicals in sorghum herbage did not damage the photosynthetic apparatus of these test plants [30]. Elisante et al. [31] reports that healthy plants will have higher quantities of chlorophyll, which was the case for sesame and black jack used in this study. Kaur and Sharma [32] reported that if allelochemicals reduce chlorophyll content or fluorescence, chlorophyll biosynthesis is inhibited or chlorophyll degradation has been enhanced. From the results from this study, photosynthetic apparatus was not affected by the presence of allelochemicals but rather photosynthesis was enhanced in plants treated with sorgaab or sorgaab-herbicide combinations. Yang et al. [33] reported similar findings when rice (*Oryza sativa* L.) seedlings were treated with three allelopathic phenolic compounds, were the chlorophyll content increased with increasing concentrations. Skrzypek et al. [34] reported that aqueous peppermint (*Mentha x piperita* L.) caused a decrease in chlorophyll content and an increase in chlorophyll fluorescence in sunflower (*Helianthus annus* L.). This increase in chlorophyll fluorescence proves that the effectiveness of electron transport in photosystem II was induced by allelochemicals in peppermint and this could be the probable reason why the physiological parameters measured in this study increased. Cheng and Cheng [35] stated that if allelochemicals interfere with photosynthetic pigment synthesis and function, other important metabolic processes are affected including enzyme activity, stomatal conductance, and transpiration. This implies that sesame and black jack are able to thrive in the presence of allelochemicals produced by sorghum because photosynthesis among other important plant processes remains uninterrupted.

4.2. Effect of Leaf and Stem Aqueous Extracts of Sorghum on the Activity of Antioxidant Enzymes PAL, POD, and PPO in Sesame Variety Lindi Zimbabwe, Black Jack, and Goose Grass. Sorghum aqueous leaf and stem extracts either increased or decreased PAL, POD, and PPO activity in sesame, black jack, and goose grass as extract concentrations increased. This suggests that exposure to allelochemicals responsible for sorghum allelopathy has a stimulatory effect on plant defense system. Ribeiro et al. [24] and Zhou et al. [36] reported that plants are capable of developing defense mechanisms in the form of reactive oxygen species (ROS) removal systems. Highly reactive superradicals such as hydroxyl (OH^*) and hydroperoxyl (H_2O^*) cause damage to the cell membrane structure, damage to DNA and proteins, lipid peroxidation, and damage to the photosynthetic apparatus [35, 37]. Cheng and Cheng [35] reported that plants are able to tolerate oxidative stress induced by allelochemicals as it is one of the proposed modes of action of allelochemicals by enhancing production and activity of antioxidant enzymes. Under oxidative stress, several enzymes such as superoxide

dismutase (SOD), catalases (CAT), POD, PPO, and PAL respond by increasing levels of activity [38]. POD, PPO, and PAL respond to oxidative stress by oxidising phenolic compounds, lignifying cell walls to reduce electrolyte leakage and synthesis of defense-related components such as lignin and phenols [39]. The pattern of changes in enzyme activity for PPO, POD, and PAL was similar in the test species, and these similarities suggest that these three enzymes cooperate in neutralising ROS in the plants. The functions of antioxidant enzymes may differ with the enzyme; for example, SOD is first in line to defend plants from oxidative stress by reducing ROS into safer compounds and POD comes to the safe disposal of the products [40].

Enzyme activity in sesame increased as extract concentration was increased; further increases would result in reduced activity, and further increases to maximal concentration would cause enhanced enzyme activity. The results from this study suggest that antioxidant enzyme activity increases as allelochemical concentration increases. Similar results were described by Singh and Sunaina [41] who reported that in *Lycopersicon esculentum* L. var, Pusa ruby antioxidant enzyme activity was enhanced when exposed to allelopathic stress induced by *Momordica charantia* L. aqueous extracts. POD and PPO activity in lettuce (*Lactuca sativa* L.) was reported by Nunes et al. [42] to increase as concentration of *Citrus sinensis* L. hexane, chloroform, and methanol fractions increased to maximal concentrations. Therefore, it can be suggested that allelochemicals in leaf and stem portions of sorghum stimulated production of reactive oxygen species (ROS) and sesame responded by enhancing antioxidant enzyme production as self-defensive. In this study, leaf and stem extracts of sorghum at 2.5% wv^{-1} increased PPO and POD activity in black jack, whilst further rises to maximal concentrations would reduce enzymatic activity. Allelochemicals in sorghum caused a hormetic effect on PAL activity, where at low concentrations, enzyme activity was enhanced but at maximal concentration, PAL activity was reduced to lower levels. These results concur with the findings by Gulzar and Siddiqui [43] who reported that PPO, POD, and PAL activity in *Brassica oleracea var. botrytis* either increased or decreased when treated with aqueous stem or leaf of *Calotropis procera* (Ait.) R. Br. Niakan and Saberi [38] reported that an increase enzyme activity indicates that enzymes are being released to mitigate the effects of allelochemicals and further increases in concentration of allelochemicals results in excess ROS generation which causes a decrease in enzyme activity. A further increase to maximal aqueous extract concentration produces an imbalance between generation of ROS caused by allelochemicals, and antioxidant enzyme activity was reduced to an extent that it cannot mitigate effects of ROS [44]. The leaf and stem aqueous extracts of sorghum reduced PAL activity and insignificantly stimulated POD and PPO activity in goose grass. Niakan and Saberi [38] reported similar findings were insignificant changes in PPO and POD activity in Phalaris weed (*Phalaris arundinacea* L.) seedlings which were treated with *Eucalyptus globus* Labill. leaf extracts. However, POD and PPO enzymatic activity increased with increasing sorghum extract concentration, and this lessened the effects of allelochemicals because these enzymes converted harmful hydrogen peroxide into water [37].

The effect of sorghum plant tissue on the activity of the three enzymes was either significant or insignificant. Generally, aqueous stem extracts of sorghum increased sesame, black jack, and goose grass PAL, POD, and PPO activity more than leaf extracts. Stem extracts induced greater oxidative stress on the test species which in turn stimulated enhanced enzyme activity in the test species. This suggests that stem extracts possess more potent allelochemicals. Moosavi et al. [45] reported that aqueous sorghum stem extracts were more allelopathic to mungbean in comparison to aqueous sorghum leaf and root extracts. Sorghum herbage contains a variety of potent allelochemicals, including dhurrin, a nonpoisonous glycoside which is hydrolysed to from hydrogen cyanide (HCN), and other phenolic compounds responsible for short-term allelopathic effects [46, 47]. Nielsen et al. [48] stated that the concentration of dhurrin which in the leaves decreases as the sorghum plant matures, and the concentration in mature plants is negligible and almost zero. Kaur and Sharma [32] stated that the differential effects of stems and leaves of the same plant are due to differences in allelochemical concentration in different plants. In response to these, allelochemicals plants increase the activity of the antioxidant enzymes as the first line of defense from enhanced ROS production and activity [49]. The results from the present study imply that differential effects of leaf and stem aqueous extracts are due to variability in the composition and concentration of allelochemicals in the different plant tissues.

In response to the allelochemicals produced by sorghum variety SC Macia, sesame, black jack, and goose grass developed a defense mechanism in the form of antioxidant enzymes as a form of protection against enhanced ROS production and activity [49]. This implies that sesame and both weed species are capable of producing defense enzymes that are capable of alleviating the effects of sorghum allelochemicals, and this results in tolerance to the allelochemicals in sorghum herbage.

5. Conclusion

From this study, it can be concluded that sorghum produces allelochemicals that are not as effective in inhibiting the early seeding growth and physiological and biochemical processes of sesame, black jack, and goose grass. These plant species have defensive mechanisms that are capable of neutralising the effects of potent allelochemicals in sorghum and therefore, sorgaab cannot be used to control weeds in sesame. This implies that early postemergence application of sorgaab in sesame is not a viable weed-control method for resource-poor farmers in marginalised areas of Zimbabwe. It also implies that sorghum can be rotated with sesame without fear of inhibiting the growth and development of the sesame crop.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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