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Research Article

Allelopathic Potential of Green Manure Cover Crops on Germination and Early Seedling Development of Goose Grass [*Eleusine indica* (L.) Gaertn] and Blackjack (*Bidens pilosa* L.)

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Green manure cover crops (GMCCs), which are recommended for improving soil fertility, also have the potential of reducing weed populations in cropping systems through allelopathy. The objective of this study was to evaluate the effect of eight GMCCs on the germination and seedling development of two weeds of divergent morphology, namely, goose grass [*Eleusine indica* (L.) Gaertn] and blackjack (*Bidens pilosa* L.). Aqueous leaf, stem, and root extracts of hyacinth bean (*Lablab purpureus* L), red sunnhemp [*Crotalaria ochroleuca* (G.) Don], showy rattlebox (*Crotalaria grahamiana* Wight & Arn.), common bean (*Phaseolus vulgaris* L.), common rattlepod (*Crotalaria spectabilis* Roth.), radish (*Raphanus sativus* L.), tephrosia (*Tephrosia vogelii* L.), and black sunnhemp (*Crotalaria juncea* L.) at 0, 1.25, 2.5, 3.75, and 5% wv^{-1} were applied to weed seeds in Petri dishes to determine their effect on germination, radicle and plumule growth, and germination vigor index. The experimental design was 3(tissue types) $*$ 5(concentrations) treatment combinations replicated four times in a completely randomized design. In the pot study, 25 seeds of either goose grass or blackjack were planted separately in approximately 400 g of soil mixed with cover crop tissue powder at 1% concentration per pot. The experimental design was cover crop residues + control replicated four times in randomized complete blocks. There was a significant ($p < 0.05$) extract $*$ concentration interaction on all germination parameters across all GMCCs. The different cover crop aqueous extracts differentially reduced all germination parameters of both weeds in the order leaf > stem > root extract except for radish root extracts being most inhibitory to all germination parameters of goose grass. The leaf, stem, and root soil-incorporated residues of GMCCs significantly ($p < 0.05$) affected seedling emergence, dry weight, and vigor indices of both weeds. Based on the results of this study, it was concluded that the different GMCC tissues contain allelochemicals that inhibit the emergence of both monocotyledonous and dicotyledonous weeds.

1. Introduction

The widespread and improper use of synthetic herbicides leads to environmental damage and a surge in the development of herbicide-resistant weed biotypes [1]. This has created the need for alternative sustainable weed control methods. Crop rotations with GMCCs, mainly practiced in conservation agriculture (CA) and organic farming, are arguably the most efficacious, environmentally friendly, and economically feasible alternative or complement to herbicides [2]. Cover crops play an important role in integrated weed management (IWM) either as smother crops, mulches, or allelopathic crops [3].

Most of the cover crops that are being promoted in the smallholder sector of Zimbabwe are fast growing and produce a lot of biomass, resulting in rapid canopy closure, which smothers weeds when they are used as live mulches [4]. Alternatively, their dead residues may be used as surface mulches or be incorporated into the soil. Weed suppression when cover crop residues are incorporated into the soil may occur via altered nutrient dynamics depending on several other factors including type of tillage used, carbon to

nitrogen ratio (C : N) of the decomposing cover crop material, soil type, and the environment [5]. In addition, cover crops can suppress weeds by competing for resources [6], disruption of life cycles of crop bound and crop associated weeds [7], through resource and light competition [8, 9], creation of soil conditions that promote seed decay and predation [10], and prevention of weed seed set and dispersal [5]. Furthermore, some cover crops such as stooling rye (*Secale cereal* L.), barley (*Hordeum vulgare* L.), and black sunnhemp (*Crotalaria juncea* L.) have demonstrated allelopathic activity [11–13]. Ferreira and Reinhardt [14] reported the possibility of using cover crops to manage herbicide-resistant weeds.

Allelopathy, a phenomenon occurring in natural or agricultural communities of plants is defined as the inhibitory or stimulatory effects of one plant species on another through the release of chemicals called allelochemicals [15]. Allelochemicals are released by live plants directly into the environment as volatiles, leachates, and/or root exudates [16]. The allelochemicals are also released when the residues of the plants decompose [17]. According to Ayeni [18], allelopathy can be exploited to achieve reduced application of synthetic herbicides, since most allelochemicals do not have residual effects and can, therefore, be exploited for early season weed control in arable fields without affecting successive crops in crop rotations. Barberi and Lo Cascio [19] reported that the maize-cover crop rotations reduced weed density under field conditions demonstrating the possibility of exploiting allelopathic cover crops for effective weed control in IWM.

The fact that allelopathic effects from decomposing cover crop residues were reported to be more pronounced on small seeds and early emerging species compared to large-seeded crops, which offers an opportunity for exploiting them for selective weed control in arable crop production [20]. Aqueous extracts of velvet bean (*Mucuna pruriens* L) and Jack bean (*Canavalia ensiformis* L.) reduced weed germination and early seedling development [21, 22].

Most of the cover crops being proposed for adoption in smallholder CA are legumes with a low carbon to nitrogen (C : N) ratio resulting in a faster decomposition than cereal residues that have higher C : N ratios [23]. As such, when allelopathic materials of leguminous cover crops are applied in the field, a considerable amount of nutrients are added, which may cause stimulation of weed growth due to mineralisation [23, 24] and hormesis. The need for finding allelopathic cover crops whose phytotoxicity outweighs their weed growth stimulation activity is, therefore, indispensable [25]. This work aimed at the assessment of the allelopathic potential of leaf, stem, and root aqueous extracts and incorporated biomass of eight cover crops that are being promoted for the adoption in smallholder CA in Zimbabwe. The hypothesis tested in the present study was that aqueous extracts and soil-incorporated cover crop biomass suppress blackjack (*Bidens pilosa* L.) and goose grass [*Eleusine indica* (L.) Gaertn] germination, emergence, and early seedling growth.

2. Materials and Methods

2.1. Experimental Site. The study was carried out at the University of Zimbabwe (UZ) situated at 17.78°S; 31.05°E with an altitude of 1523 m above sea level. Laboratory bioassays were carried out in Petri dishes in the Weed Science laboratory, and pot experiments were carried out in a greenhouse at the Department of Plant Production Sciences and Technologies between January 2015 and June 2016. Average day and night temperatures in the glasshouse were 28.1°C and 15.2°C. No artificial light was used in the glasshouse.

2.2. Biomass Preparation. The GMCCs used in the study were grown under irrigation in a field at UZ's Department of Plant Production Sciences and Technologies in September 2014. The GMCCs were grown in soils with 18% clay, 16% silt, and 66% sand with a pH ($CaCl_2$) of 5.2. Exchangeable cations in milliequivalents percent (me %) of soil were 7.61, 4.17, and 0.32 for calcium, magnesium, and potassium, respectively. Green manure cover crops were grown in the field at the University of Zimbabwe as described in Rugare et al. [26]. The preparation of dry biomass powder was done following the method described by Rugare et al. [21] without any amendments.

2.3. Aqueous Extract Preparation. Fifty grams of GMCC powder were soaked in 1000 ml distilled water to produce a 5% wv^{-1} solution on a dry weight basis. The solution was then stirred for 24 hours at room temperature (25°C) on an orbital shaker at 100 rpm. The extracts were then strained through four layers of cheese cloth before being centrifuged at 4000 rpm for 15 minutes. The clear solution was pipetted to separate it from the supernatant. This stock solution was then stored in parafilm sealed bottles at 4°C for 24 hours before being used. The stock solution was then diluted with distilled water to produce 1.25%, 2.5%, and 3.75% plant extracts prior to use. Conductivity of the 5% wv^{-1} aqueous extract concentrations of the ten GMCCs was measured using a conductivity meter (Model SX713 version 2.0 2013-7-30), and the values obtained were used to calculate the osmotic potential using the following formula [27]:

> Osmotic potential (in MPa) = conductivity (in mS) $*$ −0.036.
>
> Osmotic potential values for the different stock solutions (5% wv^{-1} concentrations) of the different GMCC tissue aqueous extract treatments ranging from −0.26 to −0.09.

In order to ascertain whether the inhibitory activity exhibited by different extract concentrations of the cover crop tissues was not due to differences in the osmotic pressure of the solutions, germination bioassays were conducted using polyethylene glycol (PEG) 6000 solutions at 0.00, 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30 MPa (i.e., the range of osmotic potentials of the 5% wv^{-1} of the cover crop tissues).

2.4. Effect of Cover Crop Aqueous Extracts on Weed Seed Germination and Early Seedling Growth. The weed bioassays were carried out in the Weed Science laboratory between January and March 2015. The weed laboratory bioassays for individual GMCCs were laid out as 3 ∗ 5 factorial experiments with two factors in a completely randomized design (CRD) with four replications. The factors were extract tissue type at three levels (leaf, stem, and root) and extract concentration at five levels (0, 1.25, 2.50, 3.75, and 5%). In all the laboratory experiments, distilled water was used as the control. Each weed species was considered a separate experiment, and the experiments were repeated once. Twenty-five seeds of the respective weeds were counted, sterilised in 1% sodium hypochlorite for 10 minutes, rinsed four times with distilled water, and placed in 90 mm diameter Petri dishes lined with Whatman No. 2 filter paper. The seeds in the Petri dishes were treated with 10 ml of the respective extract concentration, sealed with parafilm, and placed randomly on a table in the laboratory at room temperature (approximately 25°C day temperature). Data on germination, plumule, and radicle length were collected from five randomly selected plants on day 10 and day 14 in blackjack and goose grass, respectively. Germination was considered to have occurred when the radicle was 2 mm long. Germination percentage ($G\%$) and germination vigor indices (VI) were calculated using the formulae given below

$$G\% = \left(\frac{a}{b}\right) * 100, \quad (1)$$

where a is the number of germinated seeds and b is the total number of seeds in each Petri dish.

VI = Germination (%) ∗ (radicle + plumule length) [28].

2.5. Greenhouse Experiment. The glasshouse study was carried out using the method described by Rugare et al. [21]. Each pot experiment was laid out as a completely randomized design (CRD). The effect of the different cover crop tissues on the emergence and seedling growth of goose grass and blackjack were compared separately (i.e., leaves of the different cover crops and the stems and roots were evaluated separately). No cover crop residues were put in the control pots. The pot experiments were replicated four times, and only goose grass experiments were repeated once. The soil used in the goose grass bioassays was granite-derived sands from Domboshava (17° 37′ S, 31° 10′ E and 1560 metres above sea level), whereas UZ red soils were used in the blackjack bioassay in order to mimic edaphic factors under which the two weeds exert their dominance [22]. The chemical and physical properties of the soils used are shown in Table 1.

Pots measuring 90 mm bottom diameter, 105 mm top diameter, and 65 mm height were filled with 400 g of soil in which one Gram of compound D (7% N, 14% P_2O_5, 7% K_2O) was added. The respective cover crop tissue powder was thoroughly mixed with soil at a concentration of 1% [cover crop biomass concentration adopted from Caamal-Maldonado et al. [29] and Fujii [30]] aiming to provide a concentration of the cover crop residues similar to what would be obtained by the cover crops in nutrient depleted soils under dry land conditions. Thereafter, 25 seeds of the respective weed species were counted and placed on the soil surface in the pots after which they were covered with a thin layer of soil. A uniform amount of tap water of 150 ml was applied to the pots daily using a perforated cup. The number of emerged goosegrass and blackjack seedlings in the pots was recorded daily until no further emergence was noted. The final emergence percentage was calculated using the following formula:

$$\text{emergence percentage} = \frac{\text{number of emerged seeds}}{\text{total number of seeds in each pot}} \times 100. \quad (2)$$

On day 21 after planting of the weed seeds, the seedlings were harvested and washed gently with tap water to remove any soil from the roots. The uprooted weeds were oven-dried for 72 hours at 70°C to obtain the dry weight of the weeds. The seedling vigor index (SVII) was calculated using the formula adopted from Abdul-Baki and Anderson [28] as follows:

$$\text{SVII} = \text{seedling emergence \%} \times \text{seedling dry weight (g)}. \quad (3)$$

The inhibition of different cover crop plant parts was evaluated using the method of Hong et al. [24], where inhibition magnitudes were ranked based on the mean inhibition of leaf, stem, and root soil incorporated biomass in descending order. The average inhibition percentages were then grouped into three categories where more than 80%, 50%, and 20% were classified as the first, second, and third strongest inhibitory degree, respectively. The inhibition percentage was calculated as follows:

$$\text{inhibition percentage} = \left[1 - \frac{\text{treatment}}{\text{control}}\right] * 100. \quad (4)$$

2.6. Data Analysis. The data were tested for normality using the Shapiro–Wilk test and subjected to analysis of variance (ANOVA) using Genstat 18th edition. The seedling vigor index (SVII) data did not meet the assumptions of ANOVA and were $\sqrt{(x+0.5)}$ transformed before being analysed

Table 1: Physical and chemical properties of soil that was used in the study.

Soil properties	% Clay	% Silt	% Sand	Ca me %	Mg me %	K me %	Na me %	CEC me %	% H_2O	% Organic carbon	pH ($CaCl_2$)	% Organic matter
UZ red soil	18	16	66	7.61	4.17	0.32	0.22	12.32	2.98	1.66	5.20	3.32
Domboshava sand soil	7	5	88	4.6	0.2	0.23	0.46	2.81	1.76	0.41	0.05	0.61

me (%) = milliequivalents percent.

using Genstat version 18. Significantly different means were separated using Fischer's protected least significance difference (LSD) at 5% significance level.

3. Results

3.1. Germination and Early Seedling Growth of Blackjack and Goosegrass in PEG 6000 Solutions. The seedling vigor index of goose grass seeds was significantly ($p < 0.05$) affected by the different PEG solutions (Table 2). On the other hand, there were no significant differences in the seedling vigor index of blackjack in PEG 6000 solutions of different osmotic potentials (Table 2).

Table 2: Effect of different osmotic potentials of polyethylene glycol (PEG) solutions on the seedling vigor index of blackjack and goose grass.

PEG solution osmotic potential (MPa)	Goose grass	Blackjack
0.00	1634.2^{b}	5807.2
0.05	2479.7^{a}	6088.3
0.10	2433.3^{a}	5624.0
0.15	1772.6^{b}	6046.6
0.20	1542.9^{b}	5926.6
0.25	2471.0^{a}	5201.8
0.30	2088.8^{ab}	6005.1
p value	0.013	0.202
LSD	652.63	NS

Means followed by different letters in the same column are significantly different at $p < 0.05$.

3.2. Effect of GMCC Aqueous Extracts on Goose Grass and Blackjack Germination Parameters. The interaction of extract tissue and concentration was significant ($p < 0.05$) on the germination percentage of goose grass and blackjack across all the GMCCs (Table 3). Leaf extracts reduced the germination of both weeds significantly better than the stem and root extracts. Similarly, the interaction between extract tissue and concentration was significant ($p < 0.05$) on radicle and plumule length of goosegrass and blackjack across all GMCCs (Tables 4 and 5, respectively). GMCC aqueous extracts exhibited phytotoxic activity on radicle growth in the order leaf > root > stem. Consequently, leaf extracts significantly ($p < 0.5$) reduced the germination vigor index better than the other tissue extracts across all the GMCCs except radish, whose root extracts showed greater phytotoxic activity than the other extract tissues (Table 6).

3.3. Effect of Cover Crop Soil-Incorporated Residues on Emergence, Dry Weight, and Seedling Vigor Index of Blackjack. The emergence of blackjack was significantly ($p < 0.05$) affected by different cover crop leaf, stem, and root soil-incorporated residues (Table 7). Leaf, stem, and root soil-incorporated biomass inhibited blackjack seedling emergence by 42–96%, 49–94%, and 46–93%, respectively. Generally, the leaf tissues were more inhibitory than the stem and root tissues. Overall, tephrosia and hyacinth bean residues inhibited blackjack emergence significantly ($p < 0.05$) better than the other cover crops with a percentage mean inhibition of above 80%. Leaf, stem, and root soil-incorporated residues of all cover crops significantly ($p < 0.05$) suppressed the dry weight of blackjack (Table 7). Results showed that among the eight cover crop species, common bean, hyacinth bean, and tephrosia exhibited the greatest average suppression on dry weight of blackjack with a mean inhibition above 80% over the control. A showy rattlebox showed the least mean inhibition of 46%. The seedling vigor index of the blackjack was significantly ($p < 0.05$) reduced by different tissue residues of the cover crops (Table 7). Percentage inhibition ranged from 82–99%, 76–100%, and 73–97% over control where leaf, stem, and root residues were used, respectively. Overall, all the cover crops were ranked to be in the first level of allelopathic potential with mean inhibition above 80%.

3.4. Effect of Cover Crop Soil-Incorporated Biomass on Emergence, Dry Weight, and Seedling Vigor Index of Goose Grass. Leaf biomass of all the cover crops except showy rattlebox exhibited significant ($p < 0.05$) phytotoxic activity on the emergence of goose grass with inhibition percentages that ranged from 24–56% (Table 8). Most of the cover crops caused a weak inhibition of goose grass emergence except jack bean, hyacinth bean, red sunnhemp, and common rattlepod that reduced emergence by more than 50% over the control. Similarly, stem residues apart from the showy rattlebox exhibited significant ($p < 0.05$) allelopathic activity on the emergence of goose grass with the highest percentage reduction of 70% being observed where black sunnhemp stem residues were mixed with the soil. Except for showy rattlebox and common bean, soil incorporated root residues of cover crops significantly ($p < 0.05$) reduced the emergence of goose grass. Radish and hyacinth bean caused the highest inhibition percentage over the control compared to the other cover crops. Results in Table 8 show that the effect of the cover crop leaf residue type on the dry weight pot^{-1} of goose grass was significant ($p < 0.05$). The soil-incorporated stem biomass of the cover crops significantly ($p < 0.05$) reduced goose grass dry weight by 57–97%, except showy rattlebox residues that stimulated weed growth by 12% above the

Table 3: Effect of aqueous extracts of eight green manure cover crops on germination percentage of goose grass and blackjack.

Extract tissue	Extract concentration (% w v^{-1})					Extract concentration (% w v^{-1})				
	0	1.25	2.5	3.75	5	0	1.25	2.5	3.75	5
	Goose grass					Blackjack				
Hyacinth bean										
Leaf	30.00^{bc}	28.50^{bcd}	19.50^{de}	3.50^{fg}	0.00^{g}	95.00^{a}	70.00^{d}	49.00^{e}	26.00^{f}	4.00^{g}
Stem	31.00^{bc}	37.50^{b}	27.00^{cd}	9.00^{fg}	0.00^{g}	96.00^{a}	81.00^{bcd}	81.00^{bcd}	71.00^{d}	42.00^{e}
Root	36.00^{bc}	53.50^{a}	49.50^{a}	20.50^{d}	11.00^{ef}	92.00^{ab}	91.00^{abc}	82.00^{bcd}	85.00^{abc}	79.00^{cd}
LSD			9.276					12.710		
Red sunnhemp										
Leaf	37.5^{ab}	46.0^{a}	35.5^{ab}	14.5^{c}	7.0^{c}	96.00^{a}	73.00^{de}	45.00^{f}	28.00^{g}	20.00^{g}
Stem	30.5^{b}	33.5^{b}	37.0^{ab}	30.5^{b}	27.5^{b}	91.00^{ab}	83.00^{bcd}	86.00^{abc}	73.00^{de}	63.00^{e}
Root	32.0^{b}	36.0^{ab}	29.5^{b}	37.5^{ab}	30.0^{b}	94.00^{ab}	86.00^{abc}	82.00^{bcd}	78.00^{cd}	62.00^{e}
LSD			10.601					12.260		
Common rattlepod										
Leaf	36.50^{def}	41.00^{cde}	22.00^{g}	11.50^{h}	4.00^{h}	100.00^{a}	75.00^{cd}	38.00^{e}	16.00^{f}	0.00^{f}
Stem	36.13^{def}	47.50^{abc}	48.50^{abc}	32.00^{efg}	24.50^{g}	94.00^{ab}	91.00^{abc}	88.00^{abc}	88.00^{abc}	68.00^{d}
Root	29.50^{fg}	52.00^{ab}	44.50^{bcd}	56.50^{a}	45.00^{bcd}	91.00^{abc}	98.00^{a}	79.00^{bcd}	69.00^{d}	68.00^{d}
LSD			10.274					16.35		
Common bean										
Leaf	42.50^{ab}	48.50^{a}	35.50^{abc}	12.50^{defg}	7.00^{fg}	97.00^{a}	91.00^{a}	75.00^{bc}	47.00^{e}	18.00^{f}
Stem	43.50^{ab}	24.50^{cd}	23.00^{cde}	30.00^{bc}	8.00^{efg}	97.00^{a}	90.00^{a}	55.00^{de}	21.00^{f}	17.00^{f}
Root	48.50^{a}	47.00^{a}	49.00^{a}	22.00^{cdef}	4.50^{g}	94.00^{a}	86.00^{ab}	93.00^{a}	84.00^{ab}	66.00^{cd}
LSD			15.856					13.090		
Radish										
Leaf	38.50^{bcde}	54.50^{a}	29.00^{e}	12.00^{fg}	2.00^{g}	99.00^{a}	68.00^{c}	35.00^{d}	12.00^{e}	0.00^{e}
Stem	34.00^{cde}	41.00^{bcd}	46.50^{ab}	37.50^{bcde}	15.50^{f}	92.00^{ab}	93.00^{ab}	89.00^{ab}	82.00^{bc}	78.00^{bc}
Root	38.50^{bcde}	44.00^{abc}	34.50^{cde}	30.50^{de}	5.50^{fg}	99.00^{a}	93.00^{ab}	88.00^{ab}	67.00^{c}	41.00^{d}
LSD			10.619					15.980		
Showy rattlebox										
Leaf	32.50^{cd}	31.50^{d}	13.50^{e}	3.00^{f}	1.50^{f}	96.00^{a}	64.00^{ef}	29.00^{g}	17.00^{g}	1.00^{h}
Stem	31.00^{d}	44.00^{ab}	42.00^{abc}	37.50^{abcd}	10.50^{ef}	82.00^{bcd}	86.00^{abc}	73.00^{de}	64.00^{ef}	28.00^{g}
Root	32.00^{cd}	35.50^{bcd}	34.00^{bcd}	46.00^{a}	37.50^{abcd}	87.00^{ab}	92.00^{ab}	74.00^{cde}	70.00^{de}	57.00^{f}
LSD			10.044					13.390		
Tephrosia										
Leaf	32.50^{bc}	34.50^{abc}	34.00^{abc}	29.50^{c}	29.00^{c}	98.00^{a}	90.00^{abcd}	84.00^{cde}	50.00^{g}	26.00^{h}
Stem	38.50^{ab}	19.50^{d}	8.50^{e}	0.00^{f}	0.00^{f}	92.00^{abcd}	95.00^{abc}	89.00^{abcd}	76.00^{ef}	64.00^{f}
Root	32.50^{bc}	33.50^{bc}	41.50^{a}	32.50^{bc}	41.50^{a}	94.00^{abc}	97.00^{ab}	90.00^{abcd}	81.00^{de}	85.00^{bcde}
LSD			7.821					12.216		
Black sunnhemp										
Leaf	32.00^{abcd}	25.00^{de}	21.00^{e}	30.00^{cde}	2.00^{e}	93.00^{a}	46.00^{d}	19.00^{f}	6.00^{g}	0.00^{g}
Stem	38.00^{abc}	42.50^{a}	39.50^{abc}	30.50^{cde}	32.50^{abcd}	80.00^{b}	80.00^{b}	64.00^{c}	60.00^{c}	30.00^{e}
Root	31.50^{bcde}	30.00^{cde}	36.50^{abc}	41.50^{ab}	37.50^{abc}	88.00^{ab}	82.00^{b}	79.00^{b}	84.00^{ab}	67.00^{c}
LSD			10.582					9.834		

Means followed by the same letter for each GMCC are not significantly different at $p < 0.05$.

control. Red sunnhemp, common bean, common rattlepod, and black sunnhemp showed strong allelopathic potential with mean inhibition percentages that were above 80%. Two cover crops (red sunnhemp and common rattlepod) significantly ($p < 0.05$) suppressed seedling vigor of goose grass by more than 80% over the control.

4. Discussion

Results obtained demonstrated that all the GMCC extracts used in this study inhibited the germination and early seedling growth of goosegrass and blackjack. The degree of inhibition varied greatly amongst the different cover crops and tissues within each cover crop with leaf extracts showing the greatest phytotoxic activity followed by the stems, except radish root extracts that were more efficient on goosegrass than the other tissue extracts. The inhibition of germination of both weeds, especially by leaf extracts of all the cover crops except radish on goosegrass suggests the presence of allelochemicals in these GMCCs. The reduced seedling growth caused by the cover crop extracts could also imply reduced early seedling growth, which would give the crops a head start and competitive advantage over the weeds resulting in reduced crop-weed competition during the early stages of crop development when crop seedlings would be sensitive to weed pressure [21]. The seedling vigor index gives the overall effect of the treatments on seedling germination and growth [31]. In this study, leaf extracts of all the GMCCs and root

Table 4: Effect of aqueous extracts of eight green manure cover crops on the radicle length of goose grass and blackjack.

Extract tissue	Extract Concentration (% w v^{-1})					Extract Concentration (% w v^{-1})				
	0	1.25	2.5	3.75	5	0	1.25	2.5	3.75	5
	Goose grass					Blackjack				
					Hyacinth bean					
Leaf	25.1^{a}	20.0^{abc}	10.4^{d}	0.0^{e}	0.0^{e}	33.6^{a}	10.00^{e}	4.40^{f}	2.20^{fg}	0.00^{g}
Stem	20.6^{abc}	20.3^{abc}	16.1^{c}	6.4^{d}	0.0^{e}	35.55^{a}	15.05^{cd}	11.15^{de}	11.70^{de}	8.85^{e}
Root	23.8^{ab}	21.2^{abc}	18.8^{bc}	6.6^{d}	5.8^{d}	34.1^{a}	27.00^{b}	26.65^{b}	17.20^{c}	16.95^{c}
LSD			5.511					3.974		
					Red sunnhemp					
Leaf	22.73^{def}	18.33^{ef}	9.16^{g}	2.15^{h}	2.15^{h}	30.10^{a}	15.85^{e}	4.85^{g}	4.05^{g}	3.60^{g}
Stem	21.41^{def}	32.34^{ab}	29.50^{bc}	24.30^{cde}	17.29^{f}	29.65^{a}	20.60^{d}	24.10^{c}	12.90^{e}	9.15^{f}
Root	26.48^{bcd}	36.25^{a}	29.95^{bc}	24.92^{cd}	17.36^{f}	28.00^{ab}	25.45^{bc}	20.10^{d}	14.45^{e}	9.15^{f}
LSD			6.101					3.184		
					Common rattlepod					
Leaf	37.63^{a}	27.78^{b}	19.23^{de}	16.68^{ef}	2.98^{h}	48.95^{a}	21.55^{ef}	10.90^{g}	5.05^{hi}	0.00^{i}
Stem	28.23^{b}	22.65^{cd}	19.81^{de}	10.43^{g}	8.73^{g}	53.40^{a}	39.30^{b}	31.35^{c}	30.35^{cd}	18.50^{f}
Root	38.53^{a}	33.73^{a}	25.98^{bc}	13.65^{fg}	10.18^{g}	48.70^{a}	34.95^{bc}	25.90^{de}	21.05^{ef}	6.55^{gh}
LSD			5.035					5.162		
					Common bean					
Leaf	33.15^{a}	32.80^{a}	25.95^{ab}	13.90^{cd}	2.09^{fg}	39.70^{b}	13.10^{ef}	11.40^{f}	4.95^{gh}	2.75^{h}
Stem	31.13^{a}	10.65^{de}	8.20^{def}	13.10^{cd}	0.00^{g}	38.70^{b}	19.85^{d}	17.05^{de}	9.05^{fg}	4.75^{gh}
Root	32.75^{a}	19.05^{bc}	9.55^{def}	3.95^{efg}	3.65^{efg}	45.35^{a}	29.75^{c}	18.85^{d}	17.70^{de}	13.20^{ef}
LSD			7.671					5.167		
					Radish					
Leaf	21.75^{bcd}	26.98^{ab}	5.15^{fg}	2.39^{g}	0.13^{g}	46.95^{a}	11.25^{ef}	4.05^{g}	1.23^{g}	0.00^{g}
Stem	19.60^{cd}	32.45^{a}	30.70^{a}	27.80^{ab}	11.13^{ef}	44.55^{a}	33.25^{b}	30.75^{b}	23.40^{c}	17.60^{d}
Root	15.40^{de}	28.58^{ab}	22.83^{bc}	23.15^{bc}	1.44^{g}	48.50^{a}	9.85^{ef}	9.25^{f}	14.05^{de}	11.35^{ef}
LSD			7.066					4.512		
					Showy rattlebox					
Leaf	22.58^{cd}	21.20^{cd}	18.98^{d}	8.48^{ef}	0.56^{f}	45.10^{a}	14.60^{ef}	4.00^{gh}	2.40^{gh}	0.05^{h}
Stem	18.81^{d}	34.95^{a}	27.25^{abcd}	24.16^{bcd}	9.88^{e}	28.55^{bc}	22.60^{cd}	23.90^{bcd}	9.90^{fg}	1.85^{h}
Root	18.98^{d}	31.09^{ab}	28.05^{abc}	35.15^{a}	35.27^{a}	41.10^{a}	30.40^{b}	27.85^{bcd}	20.85^{de}	20.80^{de}
LSD			8.465					7.534		
					Tephrosia					
Leaf	2.64^{cd}	3.06^{abc}	2.83^{bcd}	2.93^{abcd}	3.27^{abc}	37.25^{a}	17.05^{cd}	12.50^{d}	11.48^{d}	1.88^{e}
Stem	2.29^{de}	1.75^{e}	0.10^{f}	0.00^{f}	0.00^{f}	38.03^{a}	22.95^{bc}	19.75^{bc}	12.95^{d}	11.25^{d}
Root	1.95^{e}	3.05^{abc}	2.86^{abcd}	3.46^{ab}	3.52^{a}	39.80^{a}	34.85^{a}	25.70^{b}	25.05^{b}	24.10^{b}
LSD			0.667					6.693		
					Black sunnhemp					
Leaf	3.12^{abc}	2.15^{c}	2.26^{c}	2.23^{c}	0.31^{d}	37.70^{a}	12.40^{de}	6.05^{f}	1.00^{g}	0.00^{g}
Stem	3.36^{ab}	3.39^{ab}	3.67^{a}	2.45^{bc}	2.43^{bc}	38.40^{a}	21.70^{b}	16.80^{cd}	11.20^{e}	9.65^{ef}
Root	2.85^{abc}	3.62^{a}	3.42^{ab}	3.32^{ab}	3.41^{ab}	40.05^{a}	24.70^{b}	21.10^{bc}	20.15^{bc}	10.75^{ef}
LSD			0.997					4.851		

Means followed by the same letter for each GMCC are not significantly different at $p < 0.05$.

extracts of radish reduced the seedling vigor index, demonstrating their effectiveness in suppressing germination and early seedling growth of monocotyledonous and dicotyledonous weeds.

Generally, the inhibitory effects of aqueous solutions in Petri dish experiments could be attributed to factors such as allelopathy and variations in osmotic potential [27, 32]. In this study, the osmotic potentials of the different cover crop aqueous extracts that were equivalent to those of PEG solutions used in the study did not affect seed germination and seedling development, and as such it is highly unlikely that the osmotic potentials observed could have caused any inhibitory effect on germination and early seedling growth of plants [33]. When osmotic potential values show little effect amongst treatments, they probably have no effect on the germination traits evaluated [27]. Therefore, the inhibitory activity of extracts observed in this present study could be attributed to the presence of phytotoxic allelochemicals in aqueous extracts of the cover crops [34].

The inhibition of germination and early seedling development of both goosegrass and blackjack that was observed in this study indicated that the green manure cover crops possess allelochemicals with strong phytotoxic activity. The inhibition that was observed was concentration dependent. The findings corroborate with the earlier findings of Runzika et al. [35] who reported weed germination

Table 5: Effect of aqueous extracts of eight green manure cover crops on the plumule length of goose grass and blackjack.

Extract tissue	Extract concentration (% w v^{-1})					Extract concentration (% w v^{-1})				
	0	1.25	2.5	3.75	5	0	1.25	2.5	3.75	5
	Goose grass					Blackjack				
Hyacinth bean										
Leaf	17.8^{a}	17.2^{a}	11.1^{cd}	1.8^{e}	0.0^{e}	22.85^{bc}	20.75^{bc}	14.05^{de}	5.30^{fg}	0.55^{g}
Stem	18.1^{a}	16.3^{ab}	13.8^{bc}	9.9^{d}	0.0^{e}	23.50^{b}	22.45^{bc}	16.75^{cd}	13.55^{de}	9.40^{ef}
Root	17.8^{a}	15.7^{ab}	18.1^{a}	13.4^{bc}	10.5^{cd}	22.95^{bc}	30.90^{a}	30.15^{a}	19.05^{bcd}	21.10^{bc}
LSD			3.305					6.287		
Red sunnhemp										
Leaf	16.23^{b}	19.30^{ab}	16.90^{ab}	10.28^{c}	3.31^{d}	28.20^{bc}	30.25^{abc}	13.55^{f}	1.45^{g}	4.50^{g}
Stem	16.25^{b}	18.24^{ab}	18.75^{ab}	17.88^{ab}	16.48^{b}	28.60^{bc}	31.90^{ab}	36.00^{a}	21.10^{de}	15.05^{ef}
Root	16.60^{ab}	18.73^{ab}	15.98^{b}	20.28^{a}	16.75^{ab}	30.05^{abc}	33.20^{ab}	28.40^{bc}	24.40^{cd}	19.60^{def}
LSD			3.746					6.321		
Common rattlepod										
Leaf	18.20^{b}	17.78^{bc}	16.83^{bc}	13.78^{c}	4.58^{d}	21.35^{b}	28.60^{a}	15.30^{cd}	6.55^{e}	0.00^{f}
Stem	18.43^{b}	18.70^{b}	17.75^{bc}	16.11^{bc}	16.85^{bc}	20.05^{bc}	32.65^{a}	29.35^{a}	28.95^{a}	20.55^{bc}
Root	25.90^{a}	24.35^{a}	23.03^{a}	18.30^{b}	14.98^{bc}	20.05^{bc}	29.55^{a}	29.95^{a}	27.25^{a}	13.08^{d}
LSD			4.239					5.424		
Common bean										
Leaf	18.18^{ab}	20.23^{a}	19.30^{ab}	12.80^{cde}	6.05^{f}	25.38^{abcd}	23.10^{bcde}	20.55^{def}	15.75^{fg}	6.80^{i}
Stem	1858^{ab}	9.65^{ef}	14.50^{bcde}	12.05^{de}	0.00^{g}	26.55^{abc}	26.90^{ab}	21.75^{cde}	12.25^{gh}	8.75^{hi}
Root	19.44^{ab}	17.95^{abc}	16.53^{abcd}	9.90^{ef}	5.18^{fg}	25.15^{abcd}	28.40^{a}	19.65^{ef}	20.40^{def}	18.25^{ef}
LSD			5.242					5.039		
Radish										
Leaf	17.48^{abc}	19.70^{a}	14.73^{bc}	5.38^{e}	0.25^{f}	20.90^{bcd}	20.25^{cd}	12.45^{e}	5.55^{f}	0.00^{f}
Stem	15.74^{abc}	17.73^{abc}	17.80^{abc}	18.53^{ab}	10.01^{d}	17.55^{cde}	32.35^{a}	32.65^{a}	32.05^{a}	23.25^{bc}
Root	17.25^{abc}	17.45^{abc}	14.25^{c}	14.45^{c}	2.19^{ef}	20.75^{bcd}	30.05^{a}	26.55^{ab}	22.60^{bc}	15.95^{de}
LSD			3.977					6.245		
Showy rattlebox										
Leaf	17.59^{ab}	18.05^{ab}	15.21^{bc}	10.75^{c}	3.56^{d}	29.00^{cde}	29.55^{bcde}	11.80^{f}	5.10^{gh}	0.20^{h}
Stem	17.53^{ab}	18.50^{ab}	20.30^{a}	17.25^{ab}	11.18^{c}	31.45^{bcd}	34.20^{abc}	28.90^{de}	24.90^{e}	8.75^{fg}
Root	18.03^{ab}	18.32^{ab}	19.25^{ab}	19.25^{ab}	18.08^{ab}	28.75^{de}	36.75^{a}	34.75^{ab}	28.65^{de}	27.00^{de}
LSD			4.569					5.237		
Tephrosia										
Leaf	1.67^{c}	1.84^{abc}	1.80^{abc}	1.82^{abc}	1.62^{ab}	22.10^{cde}	17.85^{ef}	15.35^{f}	8.05^{g}	2.85^{h}
Stem	1.92^{ab}	0.91^{d}	0.24^{e}	0.00^{f}	0.00^{f}	22.30^{bcde}	24.15^{bcd}	21.25^{de}	14.35^{f}	13.25^{f}
Root	1.75^{bc}	1.92^{ab}	1.88^{abc}	1.99^{a}	1.98^{ab}	22.85^{bcde}	30.05^{a}	27.35^{ab}	26.60^{abc}	24.75^{bcd}
LSD			0.234					5.089		
Black sunnhemp										
Leaf	1.57^{abcd}	1.49^{bcd}	1.44^{cd}	1.37^{d}	0.28^{c}	30.20^{bc}	25.20^{cd}	8.95^{e}	2.70^{f}	0.00^{f}
Stem	1.66^{abcd}	1.70^{abcd}	1.75^{abcd}	1.48^{bcd}	1.83^{abcd}	29.75^{bcd}	37.45^{a}	29.50^{bcd}	23.95^{d}	14.30^{e}
Root	1.54^{abcd}	1.90^{abc}	2.00^{a}	1.93^{ab}	1.87^{abc}	30.40^{bc}	35.35^{ab}	31.30^{b}	30.25^{bc}	24.45^{cd}
LSD			0.472					6.283		

Means followed by the same letter for each GMCC are not significantly different at $p < 0.05$.

and plumule and radicle growth inhibition of weed seeds treated with whole plant aqueous extracts of these cover crops. In this study, the different tissue aqueous extracts showed variable inhibitory activity suggesting differences in concentrations of potent allelochemicals in the different plant parts or different active compounds. Leaf extracts exhibited higher germination inhibition, suggesting the presence of more potent allelochemicals in the foliage of cover crops than the other tissues. Gulzar and Sidiquie [36] working with different plant parts of *Eclipta alba* (L.) Hassk reported that foliar extracts were generally more potent than stem and root extracts probably due to the greater metabolic activity in the foliage.

Results showed that only radish roots exhibited phytotoxic activity on goosegrass, whereas its leaf residues were more phytotoxic to germination and seedling growth of blackjack. Consistent with the current results, Ali [37] reported the inhibition of germination of other annual grasses including wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), canary grass (*Phalaris canariensis* L.), and black mustard (*Brassica nigra* L.) using aqueous root extracts of radish. The presence of protein synthesis inhibitors, namely, vanilic acid and ferulic acid in the roots of radish has previously been reported [38]. The lack of the phytotoxic activity of radish root extracts on black Jack demonstrated in this study contradicts the findings of Zhou and Yu [39] who reported the inhibitory

Table 6: Effect of aqueous extracts of eight green manure cover crops on the seedling vigor index (SV1) of goose grass and blackjack.

Extract tissue	Extract concentration (% w v^{-1})					Extract concentration (% w v^{-1})				
	0	1.25	2.5	3.75	5	0	1.25	2.5	3.75	5
	Goose grass					Blackjack				
Hyacinth bean										
Leaf	7.07^{a}	6.91^{abc}	5.91^{cd}	0.00^{g}	0.00^{g}	8.59^{ab}	7.65^{c}	6.51^{d}	5.18^{e}	0.77^{f}
Stem	7.05^{ab}	7.18^{a}	5.18^{de}	4.75^{ef}	0.00^{g}	8.64^{a}	8.00^{bc}	7.70^{c}	7.45^{c}	6.60^{d}
Root	7.25^{a}	7.56^{a}	7.35^{a}	5.95^{bcd}	3.70^{8f}	8.56^{ab}	8.56^{ab}	8.43^{ab}	7.99^{bc}	8.00^{bc}
LSD			1.128					0.622		
Red sunnhemp										
Leaf	7.22^{abc}	7.41^{abc}	6.74^{d}	4.92^{e}	4.23^{f}	8.63^{a}	8.10^{abc}	6.55^{f}	4.74^{g}	4.89^{g}
Stem	6.98^{cd}	7.37^{abc}	7.44^{ab}	7.13^{abcd}	6.71^{d}	8.57^{ab}	8.38^{ab}	8.55^{ab}	7.75^{cde}	7.29^{e}
Root	7.21^{abc}	7.52^{a}	7.26^{abc}	7.39^{abc}	7.00^{bcd}	8.60^{a}	8.52^{ab}	8.28^{abc}	8.01^{bcd}	7.46^{de}
LSD			0.489					0.576		
Common rattlepod										
Leaf	7.51^{ab}	7.50^{ab}	6.55^{de}	5.76^{f}	4.47^{g}	8.86^{a}	8.23^{ab}	6.53^{c}	4.85^{d}	0.00^{e}
Stem	7.40^{bc}	7.54^{ab}	7.45^{b}	6.60^{de}	6.35^{e}	8.84^{a}	8.78^{a}	8.58^{ab}	8.56^{ab}	7.86^{b}
Root	7.53^{ab}	7.95^{a}	7.65^{ab}	7.48^{b}	6.96^{cd}	8.74^{a}	8.75^{a}	8.39^{ab}	8.10^{ab}	6.95^{c}
LSD			0.518					0.843		
Common bean										
Leaf	7.63^{a}	7.82^{a}	7.15^{ab}	5.62^{bcd}	1.34^{e}	8.75^{a}	8.09^{cd}	7.76^{de}	6.81^{f}	4.96^{h}
Stem	7.62^{a}	4.35^{d}	5.63^{bcd}	5.15^{cd}	0.00^{e}	8.75^{a}	8.33^{bc}	7.64^{e}	6.08^{g}	5.26^{h}
Root	7.79^{a}	7.43^{ab}	7.07^{abc}	3.83^{d}	1.90^{e}	8.80^{a}	8.51^{ab}	8.13^{bc}d	8.06^{cd}	7.61^{e}
LSD			1.918					0.400		
Radish										
Leaf	7.24^{ab}	7.77^{a}	6.27^{bc}	3.63^{d}	0.40^{f}	8.81^{a}	7.66^{de}	5.99^{f}	4.09^{g}	0.00^{h}
Stem	7.03^{ab}	7.60^{a}	7.67^{a}	7.33^{a}	5.33^{c}	8.64^{ab}	8.71^{ab}	8.63^{ab}	8.42^{abc}	8.04^{bcd}
Root	7.06^{ab}	7.58^{a}	6.98^{ab}	6.85^{ab}	2.25^{e}	8.83^{a}	8.19^{abcd}	8.04^{bcd}	7.77^{cd}	6.97^{e}
LSD			1.020					0.746		
Showy rattlebox										
Leaf	7.13^{ab}	7.05^{abc}	5.71^{c}	3.06^{d}	1.06^{e}	8.87^{a}	7.90^{ab}	5.94^{c}	3.62^{d}	0.35^{e}
Stem	6.14^{bc}	7.74^{a}	7.48^{ab}	7.31^{ab}	3.65^{d}	8.48^{ab}	8.49^{ab}	8.24^{ab}	7.69^{b}	5.63^{c}
Root	6.98^{abc}	7.41^{ab}	7.31^{ab}	7.81^{a}	7.55^{a}	8.71^{ab}	8.73^{ab}	8.43^{ab}	8.13^{ab}	7.88^{ab}
LSD			1.378					1.156		
Tephrosia										
Leaf	7.20^{ab}	7.39^{ab}	7.29^{ab}	7.16^{ab}	7.28^{ab}	8.67^{ab}	8.04^{ef}	7.73^{fg}	6.72^{i}	4.52^{j}
Stem	7.33^{ab}	6.01^{c}	2.07^{d}	0.00^{e}	0.00^{e}	8.62^{abc}	8.40^{abcde}	8.19^{de}	7.62^{gh}	7.34^{h}
Root	7.07^{b}	7.39^{ab}	7.52^{ab}	7.42^{ab}	7.67^{a}	8.68^{ab}	8.75^{a}	8.46^{abcd}	8.33^{bcde}	8.27^{cde}
LSD			0.585					0.378		
Black sunnhemp										
Leaf	4.94^{ab}	3.96^{d}	4.20^{cd}	4.55b^{cd}	1.76^{e}	8.75^{a}	7.41^{d}	5.43^{f}	2.66^{g}	0.00^{h}
Stem	5.20^{ab}	5.31^{ab}	5.33^{a}	4.59^{abcd}	4.86^{abc}	8.60^{ab}	8.46^{abc}	7.97^{abcd}	7.65^{cd}	6.44^{e}
Root	4.86^{abc}	5.00^{ab}	5.20^{ab}	5.33^{a}	5.20^{ab}	8.73^{a}	8.49^{abc}	8.31^{abc}	8.33^{abc}	7.75^{bcd}
LSD			0.894					0.868		

Means followed by the same letter for each GMCC are not significantly different at $p < 0.05$.

activity of radish root extracts on other broadleaved annual plants. The inhibitory activity of radish leaf extracts could be attributed to the presence of isothiocynates that are released by the foliage of this crop [40]. Uludag et al. [41] reported the infestation of Johnsongrass [*Sorghum halepense* (L.) Pers] in cotton (*Gossypium hirsutum* L.) grown after the harvest of garden radish demonstrating the selective activity of allelochemicals produced by radish. Therefore, the insensitivity of blackjack seeds to root extracts of radish underscores that the broad spectrum weed control may best be achieved using whole plants as mulch or sources of extracts.

Aqueous extracts of all the *Crotalaria* species used in this study exhibited phytotoxic activity on the germination of goosegrass and blackjack in the order leaf > stem > root, indicating the presence of more potent allelochemicals in the leaves than any other plant part. These results concur with those of Adler and Chase [42] who reported the germination inhibition of smooth amaranth (*Amaranthus hybridus* L.), bell pepper (*Capsicum annuum* L.), and tomato (*Solanum esculentum* L.) where extracts and mulches of black sunnhemp were used. Black sunnhemp roots, leaves, stems, and seeds are known to contain several dehydropyrrolidizine alkaloids such as junceine, trichodesmine, isohemijunceines A, B, C, and acetyl isohenmijunceines [8]. Pilbeam and Bell [43] identified the nonprotein 5-hydroxy-2-aminohexanoic acid as the allelochemical responsible for the phytotoxic activity exhibited by black sunnhemp. There are no reports of any phytotoxic allelochemicals isolated from common

Table 7: Effect of soil incorporated residues of different plant parts of cover crops on emergence (%), dry weight, and seedling vigor index (SVII) of blackjack.

Cover crop	Leaf	% inhibition	Stem	% inhibition	Root	% inhibition	Mean % inhibition	Rank
			Emergence (%)					
Control	67.0^{a}		67.0^{a}		67.0^{a}			
Hyacinth bean	8.0^{c}	88	14.0^{dc}	79	12.0^{de}	82	83	2***
Red sunnhemp	8.0^{c}	88	29.0^{bc}	57	19.0^{cde}	72	72	4**
Showy rattlebox	39.0^{b}	42	24.0^{bc}	64	5.0^{e}	93	66	8**
Common bean	4.0^{c}	94	29.0^{bc}	57	31.0^{bc}	54	68	7**
Common rattlepod	34.0^{b}	49	34.0^{b}	49	35.0^{b}	48	49	10*
Radish	6.0^{c}	91	28.0^{bc}	58	27.0^{bcd}	60	70	5**
Tephrosia	11.0^{c}	84	4.0^{d}	94	10.0^{e}	85	88	1***
Black sunnhemp	9.0^{c}	87	29.0^{bc}	57	36.0^{b}	46	63	9**
			Dry weight (g)					
Control	0.074^{a}		0.074^{a}		0.074^{a}			
Hyacinth bean	0.009^{c}	88	0.01^{dc}	86	0.008^{c}	89	88	1***
Red sunnhemp	0.020^{bc}	73	0.046^{b}	38	0.018^{bc}	76	62	8**
Showy rattlebox	0.047^{b}	36	0.029^{c}	61	0.044^{b}	41	46	10**
Common bean	0.014^{c}	81	0.028^{c}	62	0.037^{bc}	50	64	6**
Common rattlepod	0.018^{c}	76	0.030^{c}	59	0.028^{bc}	62	66	7**
Radish	0.021^{bc}	72	0.041^{b}	45	0.035^{bc}	53	56	9**
Tephrosia	0.017^{c}	77	0.001^{d}	99	0.022^{bc}	70	82	2***
Black sunnhemp	0.023^{bc}	69	0.023^{dc}	69	0.023^{bc}	69	69	4**
			Seedling vigor index (SVII)					
Control	2.30^{c} (5.007)		2.30^{c} (5.007)		2.30^{c} (5.007)			
Hyacinth bean	0.77^{a} (0.087)	98	0.83^{ab} (0.190)	96	0.79^{a} (0.132)	97	97	1***
Red sunnhemp	0.83^{a} (0.200)	96	1.36^{c} (0.401)	92	0.92^{abcd} (0.359)	93	94	7***
Showy rattlebox	1.50^{b} (0.914)	82	1.15^{abc} (0.031)	99	0.83^{ab} (0.197)	96	92	10**
Common bean	0.76^{a} (0.082)	98	1.15^{abc} (0.873)	83	1.29^{de} (1.207)	76	86	6***
Common rattlepod	0.99^{a} (0.560)	89	1.19^{bc} (0.980)	80	1.12^{abcde} (0.820)	84	84	8***
Radish	0.82^{a} (0.192)	96	1.27^{bc} (1.224)	76	1.21^{cde} (1.016)	80	84	9***
Tephrosia	0.85^{a} (0.225)	96	0.72^{a} (0.016)	100	0.85^{abc} (0.242)	95	97	2***
Black sunnhemp	0.87^{a} (0.280)	94	1.07^{abc} (0.660)	87	1.16^{bcde} (0.960)	81	87	4***

Means followed by the same letter in the same column are not significantly different at $p < 0.05$. ***, **,* represent species with mean inhibition over control ≥80%, ≥50%, and ≥20%, respectively. Data were $\sqrt{(x+0.5)}$ transformed. Untransformed data given in brackets were used to calculate the inhibition percentages.

rattlepod, showy rattlebox, red sunnhemp, and hyacinth bean. However, results obtained in this study indicate the potential of these moderately used cover crops as sources of bio-herbicidal compounds for annual grass and broad leaf control. The fact that the aqueous extracts of the above ground parts of these cover crops were phytotoxic to weeds makes them promising candidates for use as allelopathic cover crops due to the ability of the plants to produce a lot of foliage within a short period of time.

Tephrosia leaves were highly inhibitory to the germination and seedling growth of both weeds. The allelopathic activity of tephrosia leaf extracts and volatiles, as well as soil incorporated biomass, on several weeds was reported previously [44]. These findings corroborate the work of Purohit and Pandya [31] who reported reduced weed germination of Indian Nettle *(Acalypha indica* L.), spiny amaranth (*Amaranthus spinosus* L.), swollen fingergrass (*Chloris barbata* Sw.), and marvel grass (*Dichanthium annulatum* Forssk.) seeds that had been treated with tephrosia extracts. They attributed the inhibitory activity of tephrosia leaves to the presence of coumarins, flavonoids, carotenoids, and quercetin [31].

Furthermore, results obtained in this study proved the hypothesis that soil incorporated biomass of cover crops could suppress the emergence and growth of weeds. The biomass of all the cover crop plant tissues used differentially suppressed the emergence of both weeds. It is suggested that the suppression of emergence and seedling growth observed was due to the presence of allelochemicals that were released by the cover crop residues into the soil. These findings confirm the allelopathic suppression of the weeds that was observed in the laboratory bioassays in this study. The suppression of weed emergence by soil-incorporated biomass of allelopathic plants was also reported by several other authors [3, 13, 42]. The inhibition of weed emergence could be due to the disruption of mitosis, which results in a reduction in root elongation and a concomitant reduction in root volume [45]. As a result, the roots fail to absorb enough moisture to support the emergence of the germinated seedling. For example, Soares et al. [46] reported that L-DOPA, an allelochemical, found in velvet bean and many species of the Fabaceae family caused deformed and malfunctioning roots. This interference with root growth could

Table 8: Effect of soil-incorporated biomass of different plant parts of cover crops on the emergence of goose grass.

Cover crop	Leaf	% inhibition	Stem	% inhibition	Root	% inhibition	Mean % inhibition	Rank
			Emergence (%)					
Control	98.3^{e}		98.3^{e}		98.3^{e}			
Hyacinth bean	44.4^{a}	55	38.1^{ab}	61	32.5^{ab}	67	61	1**
Red sunnhemp	45.7^{a}	54	56.9^{cd}	42	42.5^{bc}	57	51	6**
Showy rattlebox	88.0^{de}	10	89.0^{e}	9	86.0^{e}	13	11	10
Common bean	75.0^{cd}	24	68.5^{d}	30	63.5^{d}	35	30	9*
Common rattlepod	43.5^{a}	56	43.5^{abc}	56	31.5^{ab}	68	60	3**
Radish	48.0^{a}	51	42.0^{abc}	57	26.0^{a}	74	61	1**
Tephrosia	57.5^{ab}	42	35.5^{ab}	64	44.5^{bc}	55	53	5**
Black sunnhemp	71.0^{bc}	28	29.0^{a}	70	44.5^{bc}	55	51	6**
			Dry weight (g)					
Control	1.14^{ef}		1.14^{b}		1.14^{c}			
Hyacinth bean	1.13^{ef}	1	0.09^{a}	92	0.06^{a}	95	63	8**
Red sunnhemp	0.24^{ab}	79	0.04^{a}	96	0.03^{a}	97	91	3***
Showy rattlebox	0.87^{de}	24	1.28^{b}	−12	0.32^{b}	72	28	10
Common bean	0.42^{abc}	63	0.05^{a}	96	0.03^{a}	97	85	4***
Common rattlepod	0.25^{a}	78	0.02^{a}	98	0.02^{a}	98	92	2***
Radish	0.72^{cd}	37	0.05^{a}	96	0.04^{a}	96	76	6**
Tephrosia	0.81^{de}	29	0.02^{a}	98	0.04^{a}	96	75	7**
Black sunnhemp	0.58^{bcd}	49	0.01^{a}	99	0.03^{a}	97	82	5**
			Seedling vigor index (SVII)					
Control	9.75^{de} (111.78)		9.75^{de} (111.78)		9.75^{de} (111.78)			
Hyacinth bean	6.86^{bc} (49.91)	55	1.86^{ab} (3.74)	97	1.34^{a} (1.63)	99	84	8***
Red sunnhemp	3.06^{a} (10.66)	90	1.63^{ab} (2.46)	98	1.37^{a} (1.51)	99	96	3***
Showy rattlebox	8.62^{cd} (76.62)	31	10.64^{cd} (114.16)	−2	4.96^{b} (25.83)	77	35	10
Common bean	5.59^{b} (35)	68	1.84^{ab} (3.29)	97	1.42^{a} (1.68)	98	88	4***
Common rattlepod	3.30^{a} (11.02)	90	1.22^{a} (11.48)	99	1.00^{a} (0.56)	99	96	2***
Radish	5.78^{b} (36.38)	67	1.55^{ab} (2.18)	98	1.18^{a} (0.95)	99	88	6***
Tephrosia	6.81^{bc} (48.22)	57	1.11^{a} (0.77)	99	1.41^{a} (21.63)	99	85	7***
Black sunnhemp	6.38^{b} (42.20)	62	1.55^{a} (0.53)	100	1.44^{a} (21.76)	98	87	5***

Means followed by the same letter in the same column are not significantly different at $p < 0.05$. ***, **, and * represent species with mean inhibition over control ≥80%, ≥50%, and ≥20%, respectively. Data were $\sqrt{(x + 0.5)}$ transformed. Untransformed data given in brackets were used to calculate the inhibition percentages.

be responsible for reduced emergence and seedling dry weight that was observed in this study due to the poor growth of the nutrient and moisture starved plants [47].

The study revealed that the ability of the soil-incorporated biomass of different plant parts varied significantly among cover crops with leaves showing more inhibitory activity than the stems and roots on blackjack, but all the tissues exhibited the same level of germination and growth suppression on goose grass. The presence of more putative allelochemicals in leaf tissues of other plants compared to stems and roots has previously been reported [36] and has been attributed to greater metabolic activity in the foliage than other plant parts, except in radish where roots are the principal storage organ of the plant [13, 41]. The other cover crops showed variable efficacy in inhibiting weed emergence. Variable inhibition was observed on goose grass with leaf and stem biomass of showy rattlebox exhibiting lack of inhibitory activity on this monocotyledonous weed.

Morphological examination showed that the goose grass plants that had emerged turned yellow and slowly became necrotic, a symptom, which is characteristic of photosystem 2 inhibiting herbicides. The fact that chlorosis was only observed in pots where soil was mixed with GMCC biomass but not in the control where the soil was not mixed with GMCC biomass suggests the presence of photosynthesis inhibiting allelochemicals. Alternatively, chlorosis could be a result of the reduced nutrient uptake, which can be caused by a reduction in root volume and function triggered by the phytotoxic activity of allelochemicals on root cells [48]. There is also a possibility that the allelochemicals produced could interact with the soil by increasing cation exchange capacity (CEC), which led to the reduction of nutrient uptake. It is also possible that the allelochemicals could have reacted with nutrients to form insoluble complexes that are not available for plant uptake resulting in chlorosis.

The different cover crop tissues differentially affected the dry weight accumulation and vigor indices of goose grass. The fact that some of the cover crop treatments reduced emergence, but the stimulated dry weight of weeds shows that phytotoxicity lasted for only a short time [25]. Alternatively, the high biomass in pots that had low emergence could be a result of reduced intraspecific competition for resources amongst the plants in the same pot. This could probably be the reason why the goosegrass dry weight in the control and velvet bean was similar to that of hyacinth bean although both had twice as many plants that emerged than the hyacinth bean. Whilst it is possible to ascribe the differences in emergence percentages to the presence of possible allelochemicals in the cover crop tissues, it is probable that many other factors could also be responsible for differences in dry matter accumulation observed. These findings are in agreement with those of Yang et al. [49] who reported that 0.002 g of *Eucalyptus* spp leaf extracts increased the biomass of broadleaved weeds in potted experiments. Growth stimulation was not observed in blackjack, which demonstrates that this dicotyledonous weed is more susceptible to allelochemicals than the monocotyledonous goose grass. These findings contradict those of Runzika et al. [35] who reported the suppression of the dry weight of these two weeds by whole plant extracts of the cover crops used in this study. The differences could be because they used whole plant extracts where allelochemicals from different plant parts could have acted synergistically. Moreover, they used higher residue concentrations of 10% compared to 1% used in this study. The growth stimulation observed can be attributed to high levels of nitrogen in the leaves of these leguminous cover crops [50] or hormetic effects of allelochemicals at low concentrations [3]. Although many studies have demonstrated the allelopathic potential of some cover crops, weed suppression was observed with artificially high concentrations yet allelochemicals exist in very low concentrations under field conditions [51]. As such, these present results are of practical significance since they represent conditions that are most likely to occur under natural conditions. In such cases where hormesis is most likely to occur, it may be necessary to combine the use of allelopathic mulches or extracts with herbicides or other weed control options in order to achieve a satisfactory control of weeds [45].

5. Conclusion

In conclusion, the study indicated that all the GMCCs used in this study contain possible allelochemicals that could be responsible for the inhibition exhibited on goose grass and blackjack germination, as well as seedling growth. Leaf extracts of all the GMCCs were more efficient in inhibiting germination and seedling growth of both weeds, except radish roots extracts that exhibited greater phytotoxic activity than the other tissue extracts. These results provide a reasonable basis for suggesting the use of these eight cover crop aqueous extracts and/or mulches for broad spectrum weed control in maize. Whilst these findings complement the results from previous research studies where these cover crops where used, there is still a knowledge gap on the possible mode of action of these chemicals in susceptible plants. Future studies should, therefore, focus on identifying and quantifying the putative allelochemicals in different plant parts of the cover crops, as well as evaluating their efficacy on weeds and crops when applied postemergence. It is further recommended that the allelopathic potential of these cover crops can be studied under field conditions to determine their efficacy in reducing seed viability and concomitantly weed emergence in arable fields. These GMCCs are also known to be resistant to common pests and diseases, as well as reduces weeds by their smothering effect since they produce a lot of biomass rapidly. Farmers are, therefore, likely to experience remarkable weed germination and growth suppression in the early season in addition to the other known benefits of these cover crops if these cover crop tissues are used at concentrations that are inhibitory to weed growth [52–54].

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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