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Table: 4, Figs : 2

Herbicidal potential of (*Sorghum bicolor* [L.] Moench) for weed control in soybean (*Glycine max* L.)

Fábio Santos Matos, Larissa Pacheco Borges and Alinne Coelho de Melo
Master's Degree in Plant Production, State University of Goiás, highway GO 330, Km 241, ring road, CEP: 75780-000, Ipameri, Goiás, Brazil.
E-mail: fabio.agronomia@hotmail.com

ABSTRACT

This study aimed to identify the allelopathic potential of sorghum for weed control. The no-till field experiment was done in split-plot design. Initially, the entire experimental area was divided into two mains plots, (i). Grain sorghum cultivation and (ii). Corn cultivation to grow straw. Subsequently, the plots were used for soybean cultivation and to conduct a weed control trial constituting the subplots. There were five replicates consisting of five plots of 1.5 x 5 m. Applications of sorghum aqueous extract diluted to 75 % in a volume of 150 L ha^{-1} were carried out with a jet directed to the weeds at three moments throughout the soybean cycle: at 30, 45 and 60 days after germination. Soil cover with sorghum straw and the use of extract from its leaves represent an important alternative for weed control due to the physical action of straw in restricting luminosity and controlling soil temperature, and due to the chemical effects of allelochemicals on soil seeds and the action of the extract in reducing photosynthesis and controlling weed development.

Keywords: Allelochemicals, corn, field study, *Glycine max,* herbicidal, invasive plants, phenols, sorghum, sorghum bicolor, *Sorgoleone*, soybean, straw, straw extract, weed control.

INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) is an annual specie (Poaceae family), grown during the off-season period after soybean in the Brazilian Midwest. Sorghum grains are good substitute for corn in animal feed. The plant is extremely useful in very hot and dry regions, owing to the fibrous root system and xerophytic characteristics (high stomatal sensitivity), sorghum gave satisfactory production under extreme conditions (9,18). Sorghum is an allelopathic plant due to its high levels of secondary compounds. It is rich in nutrients and substances (calcium, iron, potassium, phosphorus, protein, fiber, and good antioxidants that contain B vitamins such as thiamine and riboflavin) that are important for human and animal nutrition. Phytochemical analysis of different sorghum varieties revealed the presence of steroids, glycosides, volatile oils, saponins, tannins and flavonoids (21).

Phytochemical analysis of *Sorghum halepense* leaf extract for antifungal evaluation identified the saponins, alkaloids, coumarins, flavonoids, and tannins (22). Besides, sorghum extract has considerable amount of lipids and phenolic acids that exert important allelopathic action (13,25). Phenols extracted from sorghum can be a bioherbicide to control narrow- and broad-leaved weeds, causing leaf lesions and impairing photosynthesis (24,30). The production and release of allelochemicals occurs throughout the growth of sorghum plants (4). The main allelochemical of sorghum is sorgoleone, (a lipid benzoquinone) produced in leaves and roots and constantly exuded through root hairs. In addition to sorgoleone, the sorghum plant also certain levels of total phenolic compounds that reduces the growth and concentrations of photosynthetic pigments, blocking respiration and

*Correspondence author

inhibiting PSII of photosynthesis, these effects inhibit the development of weeds (10,27,32). *Lupinus luteus* L. germination, growth and dry mass of roots and shoots was reduced, when sprayed with aqueous extract of sorghum.

The high competitive potential of weeds can reduce crop yields and increase production costs (17,19), so it is important to study sustainable alternatives to control invasive plants and allelopathy represents an essential path in a rational approach to this agricultural practice. Leaf extracts and root exudates of sorghum plants reduce the growth of the aerial part of weeds and susceptible species such as lettuce and other vegetables by < 50 % (11).

No-tillage with the use of straw is a common cropping system in grain-producing regions of Brazil, where corn and sorghum straws are constantly used; however, covering the soil with sorghum straw has a physical and chemical effect on weed control (18). Sorgoleone produces lesions in leaves of *Nicotiana benthamiana* and impairs the photosynthesis of this species (24). According to (29,33) sorghum extract alters soil microbiology, interferes with nitrification process by inhibiting the abundance of ammonia-oxidizing archaea and the activity of *Nitrosomonas*. Many plant species are used as substrates for bioherbicides, by adding their straw to the soil. However, the type of straw is specific to each region of the world, with no comprehensive plant straw produced in different agricultural crops. Therefore, each substrate needs to be studied in detail (2).

Reducing the use of herbicides is a goal of sustainable agriculture that seeks environmentally safe, renewable and low-cost alternatives. The herbicides, are costly and generates negative impacts on the environment. In this context, the sustainability of plant production is sought in the modern agriculture model, through the use of renewable technologies with preservation of soil microbiota and environment as a whole. The use of bioherbicides in an integrated manner with other agricultural practices enhances weed control, as the mode of action of bioherbicides is different than chemical herbicides (2). Thus, the use of allelopathic plants may be an important sustainable alternative for weed control. This study aimed to identify the allelopathic potential of sorghum in weed control.

MATERIAL AND METHODS

The experiment was conducted two times in the experimental field, State University of Goiás, South campus, Ipameri unit, Goiás, Brazil (Lat. 17° 43' 19" S, Long. 48° 09' 35" W, Alt. 773 m) for two consecutive years [March 2021 to April 2022 (year 1) and from March 2022 to April 2023 (year 2)]. This region has a tropical climate with dry winter and humid summer (Aw) according to the Köppen classification and an average temperature of 20 °C. (1). An area with 4- years of soybean cultivation and sorghum and corn straw formation was used for planting the plant species. The soil in the experimental area has a slope of 3 % and a uniform appearance without stains or any other physical or chemical difference. The soil is classified as medium-textured *Latossolo Vermelho-Amarelo distrófico* (Oxisol) (5). After chemical analysis of the soil (Table 1), fertilization was done according to technical recommendations for soybean crop (19).

Table 1. Soil chemical analysis of (top 0-20 cm layer) was done in 2021 (1st) and 2022 (2nd) in Ipameri, GO, Brazil.

Depth/Year	**pH**		**OM**	**P(1)**	**K(1)**	**Ca(1)**	**Mg(1)**	**H+Al**	**V**
0-20 cm	**$CaCl_2$**		**%**	**Mg/dm^3**	**------------mmol$_c$/dm^3--------------**				**%**
2021	5.5		1.5	8.2	0.26	2.2	0.8	2.4	57.6
2022	6.1		1.6	6.7	0.45	3.7	1.3	1.1	54.5

(1) Mehlich

The experimental treatments consisted of 3-factors, (a). Main plot: Grain sorghum and corn (b) Sub-plot: Soybean crop, (c). Sub-sub-plot: pre-emergence weed control treatments (i) Sorghum extract spray, (ii). Control (spray). The treatments were replicated 5-times in split plot design and subplots of 1.5 m x 5 m. The experiment was done in two consecutive years (2022,2023) in a split-plot design. The grain sorghum (DOW 1G100) and common corn (SHS 7990 PRO3) were grown in the off-season (first week of March of each year) to produce straw, while the subplots were presence and absence of weed control using the sorghum aqueous extract.

Field Study: The experimental area was divided into two main plots, (i). Grain sorghum cultivation off-season and (ii). Corn cultivation off-season, both grown to produce straw. After the harvest of main plots crops, these were followed soybean planted in sub-plots. In soybean crop, 2 sub-sub-plot for weed control were prepared: (a) Spray of aqueous extracts of sorghum leaves for weeds control in plots and (b) no weed control treatment.

Aqueous Extract: Sorghum aqueous extracts were prepared from 30-day-old grain sorghum plants grown in field. Their leaves were washed in running water, pat dried with filter paper and dried in oven for 72 h at 70 °C. The dried plants were crushed in hammer mill, mixed in ethanol at 3 g per 60 mL ethanol, left for 72 h at 40 °C and then filtered (11).

The solution was used at a concentration of 750 ml L-1 applied to the plants using a knapsack sprayer with a dosing valve, properly calibrated to supply a volume of 150 L/ha. Soybean followed main crops and sown in corn and sorghum straws and, during its development, post-emergence weed control was done by foliar spraying of sorghum extract without incorporation into the soil (treatment corresponding to subplot). The sorghum aqueous extract was sprayed at 3- phenological stages V_3, R_1 and R_5. The evaluations were done at the phenological stage R_9 of soybean.

Corn and grain sorghum were planted in the off-season (first week of March of each year) and were cut with manual brush cutter and deposited on the soil surface as straw. Soybean was planted in October and November in the first and second years, respectively.

The seeds were treated with fungicide/insecticide (active ingredients Pyraclostrobin, methyl thiophanate and Fipronil and inoculated with *Bradyrhizobium japonicum*, in the minimum proportion of $12x10^{-5}$ cells of the bacterium per seed). At the phenological stage R_2, fungicide with the active ingredients Fluxapyroxad and Pyraclostrobin, was sprayed.

Evaluations were done out using a wooden square (50 cm x 50 cm). In each plot (1.5 m x 5 m), the square was thrown thrice in different locations to perform the evaluations (replicate) and the data were averaged.

Growth and species abundance variables

Weed evaluations were done when soybean plants were at the R_9 stage. The plant height was measured with a tape, measured from the ground until the apex of dominant weed of greatest height, highest biomass and high frequency. Shoot dry mass was determined by removing the entire dominant weed and oven dried at 70 °C for 72 h. In 2-years of evaluations, the dominant weed was *Ipomoea nil* (L.) Roth. Weed species, number of plants of each species in the plots and their families were also identified.

Variables in soybean plants

Number of pods per plant, grain mass per plant, number of grains per plant and yield were measured at the reproductive stage R_9 and adjusted to moisture content of 13 %.

Statistical procedures

The data of two years was statistically analysed. Analysis of variance and Newman-Keuls means comparison test were performed at 5 % probability level. Multivariate analysis based on principal components was done using RBIO software (3) and Statsoft software (31).

RESULTS AND DISCUSSION

The phytosociological survey of weeds spp (Table) 2 demonstrated a great diversity in the experimental area in sufficient quantity to cause economic loss. This survey is important to direct weed control actions. The phytosociological survey is a crucial tool for recommendations of management and cultural practices (28). Despite the large number of broad-leaved weeds, there was dominance of narrow-leaved species in terms of area. Although the allelopathic action of sorghum was effectively controlled the monocot and dicot weeds (5), as the extract was more efficient to control broad-leaved species than narrow-leaved species (35).

Table 2. Effects of corn straw or sorghum straw on weeds in soybean crop in no-tillage system.

Corn straw	**Sorghum straw**
Bidens pilosa (L.)	*Amaranthus spinosus* (L.)
Brachiaria brizantha (CV.)	*Ambrosia artemisiifolia* (L.)
Brachiaria ruziziensis (CV.)	*Brachiaria ruziziensis* (CV.)
Chamaesyce hirta (L.)	*Cenchrus echinatus* (L.)
Commelina benghalensis (L.)	*Chamaesyce hirta* (L.)
Desmodium tortuosum (SW.) DC	*Chloris gayana* (Kunth.)
Digitaria ciliaris (Retz.) Koeler	*Cynodon dactylon* (L.) Pers
Echinochloa colonum (L.)	*Cyperus rotundus* (L.)
Eleusine indica (L.) Gaertn	*Desmodium tortuosum* (SW.) DC
Emilia fosbergii (D.)	*Digitaria insularis* (F.)
Emilia sonchifolia (L.)	*Echinochloa colonum* (L.)
Glycine max (L.)	*Eleusine indica* (L.) Gaertn
Ipomoea nil (L.) Roth	*Emilia sonchifolia* (L.)
Miscanthus giganteus (C.)	*Emilia sonchifolia* (L.) DC.
Rhynchelytrum repens (Willd.)	*Euphorbia heterophylla (C.)*
Richardia brasiliensis (L.) Gomes	*Galinsoga parviflora* (A.)
Spermacoce verticallata (L.) G.Mey.	*Glycine max* (L.)
Stellaria alsine (G.)	*Ipomoea nil* (L.) Roth
Zea mays (L.)	*Miscanthus giganteus* (C.)
Zinnia elegans (J.)	*Oxalis sp.* (L.)
	Paspalum dilatatum (P.)
	Rhynchelytrum repens (Willd.)
	Senna obtusifolia (L.) I. E. Barneby
	Spermacoce verticallata (L.) G.Mey.
	Spigelia anthelmia (L.)
	Stellaria alsine (G.)
	Turnera subulata (W.) Schult
Total weed spp. 20	Total weed spp. 27

The effects of treatments on the production of soybean plants are presented in Table 3. Grain yield, number of pods per plant and yield per plant showed no significant differences to treatments applied; only the number of grains per plant showed a small variation that did not interfere in the final yield. Thus, there was little influence of sorghum straw on soybean yield, because even with the release of allelopathic substances in the soil with the decomposition of straw, the effects on soybean development are virtually non-existent. As sorghum is harvested in July and August and soybean is sown in October and November, in this interval of 60 to 90 days, the allelochemicals are most likely inactivated in the soil. According to (15,16), the sorgoleone produced in sorghum roots is strongly adsorbed to the soil colloids with high clay and organic matter contents causing little mobility and restricted action. Allelochemicals generally show an inverse relationship between mobility in soil and toxic effect on plants. Despite the absence of negative effects of sorghum allelochemicals on soybean plant production, it is important to pay attention to allelopathic action on other plant species, as cases of autotoxicity in sorghum are common (34).

Table 3. Effects of straw type (sorghum and corn) and sorghum extract (750 ml/L) spray on soybean yield.

Treatment	Yield parameters			
	Grain yield (kg/ ha)	Pods/Plant	Grains/plant	Yield/plant (g)
Sorghum straw	4282.7aA	56.7aA	127.2aA	21.0aA
Corn straw	4283.5aA	58.1aA	118.2aAB	21.0aA
Control (No spray)	4359,6aA	55.0aA	113.7bB	20.8aA
Sorghum Extract spray	4206.6aA	59.8aA	131.8aA	21.5aA
Main Plot: Crops straw	> 0.05	> 0.05	> 0.05	> 0.05
Sub Plot: Weed control	> 0.05	> 0.05	*	> 0.05
Main Plot : Sub Plot	> 0.05	> 0.05	*	> 0.05

Mean followed by the same lowercase letter within each treatment or uppercase letter in broad comparison do not differ from each other at 5 % probability level by the Newman-Keuls means comparison test. *Significant at 5 % probability level.

Weed density was strongly affected by the use of sorghum straw (Table 4). Sorghum straw considerably reduced weed density, hence showed that, in addition to its physical importance, this straw also has a chemical implication due to its marked allelopathic effects. This result is in line with that obtained in Figure 1A, as the latter refers to the importance of treatments in weed control through the percentage reduction in the plant population. An increase in weed population under corn straw (CS+S) and sharp reductions in weed populations under sorghum straw were observed. Sorghum straw has a marked allelopathic effects and imposes significant restrictions on weed development (5,20).

Table 4. Effects of straw type (sorghum and corn) and sorghum extract (750 ml/L) spray on weed development in soybean.

Treatment	Dominant Weed Yield parameters			
	Weed Density (plants/m^2)	Biomass/Plant	Plant height (cm)	Root length (cm)
Sorghum straw	84.0bB	21.3aA	80.1aA	8.3bB
Corn straw	106.4aA	6.9bB	81.6aA	10.9aA
Control (No spray)	90.8bB	22.8aA	95.6aA	10.5aA
Sorghum Extract spray	99.6aA	5.4bB	66.1bB	8.7bB
Main Plot: Crops straw	*	*	> 0.05	*
Sub Plot: Weed control	*	*	*	*
Main Plot : Sub Plot	> 0.05	*	> 0.05	*

Mean followed by the same lowercase letter within each treatment or uppercase letter in broad comparison do not differ from each other at 5 % probability level by the Newman-Keuls means comparison test.

Weed density was more strongly affected by the effects of straw than leaf extract spray, because the extract was used as the post-emergent control (after the weed has germinated) and increased its density, while the straw interfered with germination, so different straws had more promising effects on weed density. Physiologically, due to the effects of competition, less development of the dominant weed was expected in place with higher plant density and so it did; however, as the development of the dominant weed depends on the ability of the seeds to germinate and overcome the effects of straw and then develop overcoming the effects of sprayed extract, it can be inferred that this variable is under strong influence of the treatments applied in the plot and subplots. The lower biomass and height of the dominant weed *Ipomoea nil* (L.) Roth treated with sorghum extract demonstrated the importance of this management in the post-emergent control of weeds. The phenolic acids found in sorghum extract reduces shoot growth by interfering with respiration and photosynthesis (5,10,32).

Sorghum straw root system length and use of pulverized sorghum, as the allelochemicals present in the sorghum extract slowed down the development of the root system. These results are in line with those obtained in Figure 1B, which demonstrated the inhibition (20 %) in root growth system of dominant weed under sorghum straw and subjected to foliar spraying of sorghum extract (SS+S). These results proved the effects of allelopathic action of sorghum extract in weed control. The sorghum extract showed strong allelopathic interference of sorghum in root system development, as well as in the absorption of water and nutrients (12,20). Straw alters the soil microbiota and promotes changes in the development environment of the root system. Sorghum straw and the use of sorghum leaf extract have an important influence on the soil microbiota (6), causing a reduction in microbial biomass carbon and basal respiration and an increase in the soil metabolic quotient, modulating the quantity, diversity and functionality of the soil microbiota.

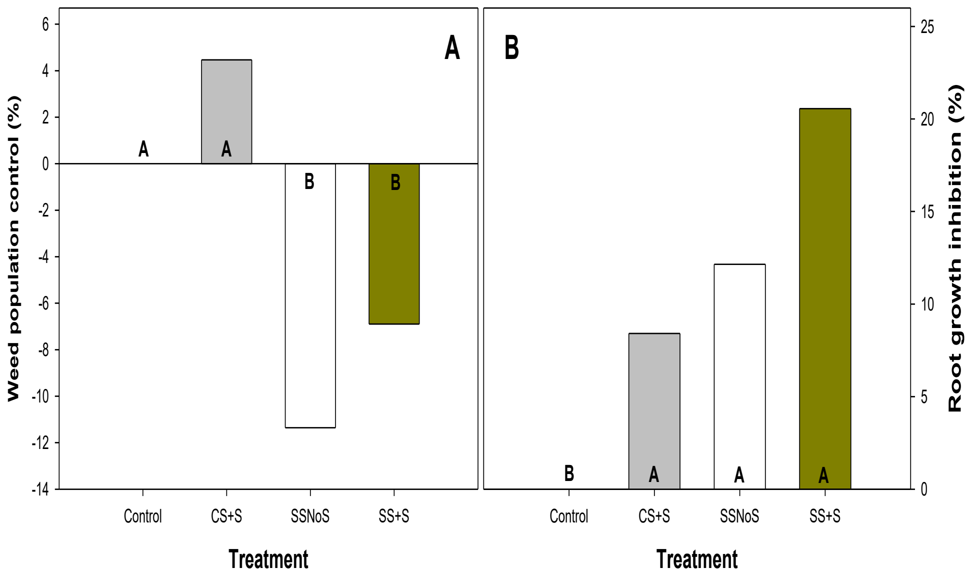

Figure 1. Percentages of control or stimulation of weed population and inhibition of the growth of the main root of the dominant weed in soybean crop cultivated under different management conditions: Corn straw without weed control (Control), Corn straw with spray (CS+S), Sorghum straw without sorghum extract spray (SSNoS) and Sorghum straw with sorghum extract spray (SS+S).

The principal component analysis (Figure 2) showed the variables in two axes and represents 98.5 % variation in the data as a function of the treatments applied. Analysis of the results from axis 2 shows that this same axis grouped the treatments based on the type of straw, so that treatments with corn straw were located in the upper portion of axis 2 and treatments with sorghum straw were located in the lower portion; there was a higher weed density under corn straw and greater development of the dominant weed under sorghum straw. These results are in line with the others presented previously, which point to greater development of the dominant weed in an environment with lower weed density. According to (18), this occurred due to the competition factor, because with smaller number of plants around, the dominant plant extracts had more resources for its development. This indicates that agronomic care should be taken in commercial crops regarding the control of dominant weeds, even in small quantities. As they thrive under low densities, they can produce more seeds and become future problems.

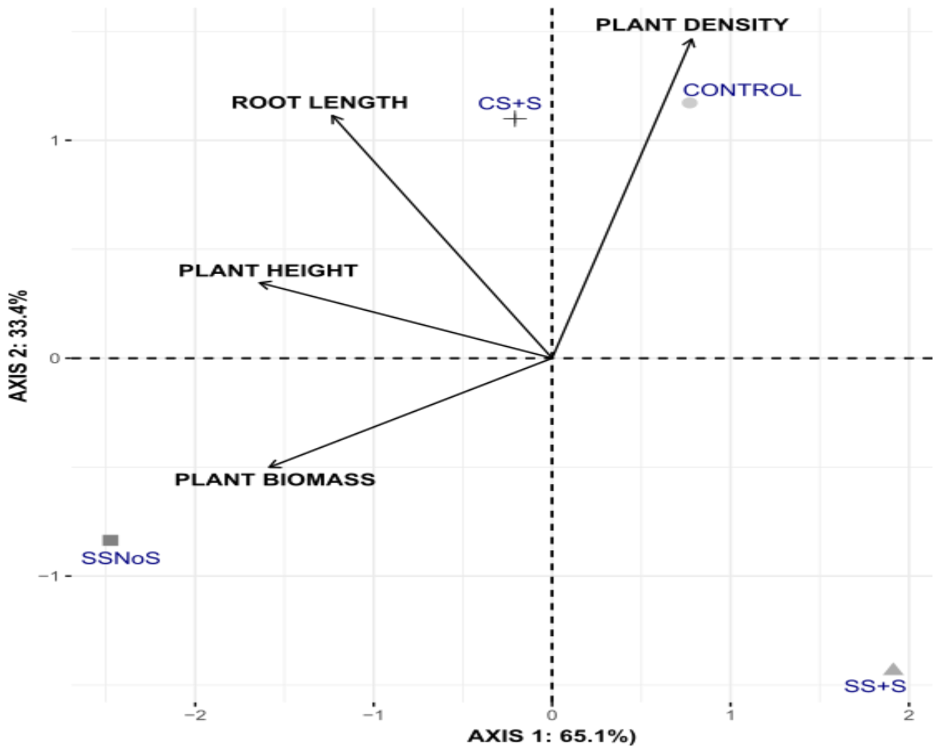

Figure 2. Principal component analysis for ordering the variables related to the dominant weed (plant biomass, plant height and root length) and weed density in soybean crop cultivated under different management conditions: Corn straw without weed control (Control), Corn straw with spray (CS+S), Sorghum straw without sorghum extract spray (SSNoS) and Sorghum straw with sorghum extract spray (SS+S).

The allelopathic effects of sorghum plants and their efficiency in weed control has potential for use in no-tillage systems, where straw deposition on the soil is practiced. In addition, it is important to note that the interval between straw deposition and sowing, the conditions of moisture, radiation and chemical properties of the soil interferes with the action of allelochemicals to the point of not compromising the yield of soybean plants. These results need to be validated for other plant species, as the allelopathic effects can in some cases be verified in weeds and crops; horticultural plants such as lettuce demonstrate high sensitivity to sorghum extract (23).

CONCLUSIONS

(i). Sorghum straw maintenance is an important practice for weed control due to its negative interference in seed germination and reduction of plant density.

(ii). Sorghum extract applied by foliar spraying represents an important alternative to inhibit weed development.

(iii). Soil cover with sorghum straw and the use of extract from its leaves represent an important alternative for weed control due to the physical action of straw in restricting light and controlling soil temperature, and due to the chemical effects of allelochemicals on soil seeds and the action of the extract in reducing photosynthesis and controlling weed development.

(iv). This study sheds light on the development of further research to validate the technique of using sorghum extract by identifying the allelopathic action of sorghum in crops (non-target plants) as well as isolating and identifying the chemical components with allelopathic action in sorghum extract.

AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration with all authors. All authors finally approved and drafted the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest. All authors agree to publish it.

DECLARATION

We declare that all authors of this Ms. have made substantial contributions. We did not exclude any author who substantially contributed to this Ms. We have followed our ethical norms established by our respective institutions.

ETHICAL STATEMENT

In this study, we did not involve any animal and human studies.

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