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Enhancing Food Security Through Sustainable Agriculture: Investigating the Allelopathic Effects of Sorghum on Weed Management in Field Pea (*Pisum sativum* var. *arvense*)

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ABSTRACT

Allelopathy can be a viable approach to address the issues of environmental degradation by reducing the use of herbicides and herbicide-resistant weeds. Allelopathic crop residues have a lot of potential for improving soil quality and suppressing weed growth. A field experiment at an agronomic research farm, Lovely Professional University in Phagwara, Punjab, examined the effects of water extracts and crop residues from sorghum on the population of weeds, indices of weed management, and the productivity of field peas. The experiment during the year 2022-2023 comprised in randomized block design with 2 levels of Sorghum water extract (1:10, 1:20 w/v), 3 levels of Sorghum stalk soil incorporation @ 2, 4, 6 Mg.ha^{-1}, Sorghum surface mulching at 10tonnes ha^{-1}, Field pea and rabi sorghum intercropping at 2:1, Weedy check and hand weeding. The findings showed that the sorghum surface mulching, addition of sorghum water extract, and sorghum stalk incorporation significantly altered the dynamics of weeds which was comparable with hand weeding. In the case of weed density (9.17 no.m^{-2}), weed fresh (7.66g), and dry weight (3.0g) hand weeding gave the best result which was followed by sorghum surface mulching with 10.77 weeds no.m^{-2}, 10.11 g weed fresh weight and 4.26gm weed dry weight. The highest weed control efficiency (80.9%) was recorded in hand weeding which was followed by sorghum water extract (1:10) and sorghum stalk incorporation (4 Mg.ha^{-1}). The weed management index, weed persistence index, and agronomic management index showed an inverse relationship with weed control efficiency. Hand weeding (20, 40, 60 DAS) gave the highest grain yield (2897 kg.ha^{-1}) of field pea followed by Sorghum surface mulching. Yield attributes were calculated which prescribed that all the treatments significantly reduced the weed infestation and increased the yield attributes over a weedy check. Hand weeding gave the best result, but it is not economical due to the intensive labor requirement. Initiating sustainable weed control and significantly improving the nutrient content of field peas can be achieved through sorghum surface mulching, sorghum stalk incorporation at 4 Mg.ha^{-1}, and sorghum water extract (1:10). These practices can contribute to environmentally friendly and sustainable agriculture.

INTRODUCTION

In addition to food security, "nutritional security" is currently a major concern for the scientific community on a global scale. A frequent term for pulse crops is "poor man's meat." It can be strongly considered a potential alternative in the battle against nutritional insecurity due to its high protein content. Grown mostly in milder temperate zones, field peas (*Pisum sativum* L.) are an important grain legume crop for the winter season. Garden and field peas are the two types of grown peas. When garden peas are collected fresh, they are either preserved or cooked fresh for later use (Reddy et al. 2023). Typically, field peas are cultivated for their dry seeds, which are used to make dal and a variety of snack dishes. It is very nutrient-dense and rich in readily digested carbohydrates, protein, minerals, and vitamins. The following components are included in 100g of dried edible portion: 11g of moisture, 22.5g of protein, 1.8g of fat, 62.1g of carbohydrates, 64g of calcium, 4.8g of iron, riboflavin (0.15g), thiamine (0.72g), and 2.4g of niacin. According to (Jaswal et al. 2022), field peas make up about 3% of India's total pulse area and approximately 5% of its overall pulse production.

Field peas are produced worldwide on an area of 7.04 million hectares, yielding an estimated 12.40 million tonnes of yield annually in 2021. Field peas are produced on

7.45 lakh hectares of land in India, and between 2020 and 2021, they will produce roughly 9.10 lakh tonnes annually. This crop's average productivity has grown significantly over time, reaching 1.4 tonne ha^{-1} currently. Orissa, Bihar, Assam, U.P., and MP are the principal growing regions for field peas. About 43,860 hectares of pea are grown in Punjab, producing 4, 0,450 tonnes of pea (Singh et al. 2022). India, a developing nation, has a severe problem with nutritional imbalance. Most of the nation's population lives in poverty and has little access to animal protein in their regular diet. The WHO recommends that people consume 80 g of pulse crops per day, yet our country's yearly report on pulse availability shows that people only consume 36 gm of pulses per day. Rather than nutritional security, the pursuit of food security may be what led to this concerning situation. Field pea yield can only be increased through a variety of biotic and abiotic variables, as there is limited opportunity to expand its area inside the nation (1, 3). Field pea productivity is limited by several factors, including inadequate irrigation and drainage techniques, stagnant water, flower drop issues caused by temperature fluctuations, an increased area entirely devoted to wheat and rice crops, a lack of high-yielding disease-resistant cultivars, small land holdings, cultivation on marginal land, and pest and weed infestation (Singh et al. 2023).

Weeds are a major component among the many biotic and abiotic variables limiting field pea productivity and production. Weed infestations hinder yield by posing competition for nutrients, space, light and moisture, and make pea picking more challenging. According to (Raje et al. 2022), weed competition causes pea yield losses ranging from 40 to 70% and an average 63% increase in weed control. The lack of labor availability causes this issue. Peas are related to a variety of weeds. Any crop's level of weeds changes depending on the agroecological conditions and the various management techniques used. The major weeds found in pea crop are *Chenopodium album* (bathua), *Fumaria parviflora* (gajri), *Lathyrus* sp. (chatri-matri), *Melilotus alba* (senji), *Vicia sativa* (ankari), *Lepidium sativum* (wild hallon), *Cyprus rotandus* (Purple nut sedge), *Phlaris minor* (canary grass), *Poa annua* (annual blue grass*), Spergulla arvensis* (corn spurrey), *Trigonella polycerata* (Jungli fenugreek) (Lake et al. 2021).

The manual weeding method used in earlier times performs best when labor is affordable and readily accessible. However, because of increasing wages and a labor shortage, field pea weeding has become a challenging operation. As a result, they are forced to choose a simpler, less expensive, and alternative way of chemical weed management (Kovács et al. 2023). Herbicides and chemical weed control both significantly increase crop productivity by suppressing weed growth. Chemical weed control is a particularly effective means of doing this. However, overuse and carelessness in the application of herbicides can result in agricultural damage, health issues for humans and animals, contamination of soil and water, and herbicide resistance (Raje et al. 2022). The demand for alternative weed control methods has emerged because of environmental degradation and the danger that inappropriate or excessive usage of plant-protection agents poses to human and animal health (Hetta et al. 2023). Sustainable management principles are respected as decisions are made to optimize plant production. The use of less hazardous plant protection techniques, like biological techniques, that pose less of a threat to the environment is becoming more and more common. This pattern is indicative of the development of greener technologies across many domains of human endeavor. One of the possible strategies for reducing the usage of herbicide may be the use of natural substances and allelopathy manipulation of the environmental population (Abbas et al. 2021). The allelopathic manipulation can be utilized by crop rotation, using sorghum extract (sorgaab), sorghum stalks soil incorporation, and hand weeding. By using sorghum water extracts (sorgaab), the biomass of weeds was decreased by 33–35%. It works in combination to lessen the need for herbicides. As new methods are discovered and old ones are improved, organic farmers are getting access to a greater variety of weed management choices (Blaise et al. 2020). Considering these factors, the current study examined the effectiveness of allelopathic water extract and sorghum soil inclusion for weed management in field peas (*Pisum sativum* var. *arvense*). Additionally, various weed indices of treatments were computed since weed indices offer logistical support for impact assessments, interpretations, and deriving relevant findings in research on weed control.

MATERIALS AND METHODOLOGY

During the Rabi season of 2022, a field experiment was carried out at Lovely Professional University's agriculture research farm in Phagwara, Punjab. The research aimed to examine the management of weeds in field pea (*Pisum sativum* var. *arvense*) through the application of allelopathic water extract and sorghum soil incorporation. The testing location was 228 meters (748 feet) above sea level at 31.25° North, 75° East. The location, which is underneath Punjab's middle plain, has a subtropical monsoon climate with 600 mm of rainfall on average. Punjab-89 was the variety that was used for this experiment, which was sowed on November 15th, 2022, with a 30 cm × 10 cm spacing. The current study's experiment material, which included three replications and nine treatments, was designed using a randomized block design as represented in Fig. 1. Treatments details are

T_0-Weedy check (control), T_1- Sorghum surface mulch, T_2- Field pea and rabi sorghum intercropping (2:1), T_3- Sorghum stalk soil incorporation (2 $Mg.ha^{-1}$), T_4-Sorghum stalk soil incorporation (4 $Mg.ha^{-1}$), T_5- Sorghum stalk soil incorporation (6 $Mg.ha^{-1}$), T_6-Sorghum water extract (1:10), T_7- Sorghum water extract (1:20), T_8- Hand weeding (20, 40, 60 DAS). The hand-weeding plots were maintained in such a way that as and when the weed emerged weeding was done. Generally, hand-weeding was done at an interval of 20, 40, and 60 DAS. The sorghum water extract was applied at 20 DAS 1:10 and 1:20 (volume) ratio means 1 mL of extract in 10 mL of water and 1 mL of extract in 20 mL of water. Sorghum stalks soaked in clean water for 24 hours. Then filtered and filtrate was collected. At last, the filtrate boiled and reduced volume to 10%. Sorghum stalk cut into small pieces with a chaff cutter 16 inches in length and 5.25 inches in width and incorporated into soil before sowing. Dried leaves of sorghum are used for mulching and spread after the germination.

Yield Parameters: Each net plot's pods were threshed and cleaned, and their seed weight was noted. The yield per hectare was calculated and given in $kgha^{-1}$. A random sample of 100 seeds was selected from each treatment's product, and these samples were counted and weighed, and the seed index was expressed in grams (g). The number of pods on each plant and the number of Seeds pod^{-1} counted were calculated by averaging the number of pods on each plant.

Weed parameters- Different weed management indices were calculated to advocate the results as per the following formulas:

Weed Density ($No.m^{-2}$): Using the quadrant method, the number of weeds was counted from a randomly selected 0.16 m^2 (quadrant size) area and converted on a m^2 basis.

Weed Control efficiency: Formula was used to calculate the weed control efficiency on a dry weight basis.

$$WCE = \frac{\text{Dry matter of weeds in weedy check} - \text{Dry matter of weeds in treated plot}}{\text{Dry matter of weeds in weedy check}} \times 100$$

Weed dry weight (g): After being removed, the weeds in the quadrant area were placed in brown bags. The weeds were allowed to air dry before being dried at 65–70˚C in a hot air oven until a consistent weight was reached.

Weed fresh weight (g): The weeds present in the quadrant area were uprooted and then transferred to a brown bag. After cutting the weed fresh weight of the weed samples was taken with the help of weighing balance.

Weed persistence index: This index, which was calculated using the provided formula as recommended by (Mishra & Mishra 1997), shows the resistance in weeds against the tested treatments and confirms the efficacy of the specified treatments:

$$WPI = \frac{\textit{Weed dry weight in treated plot}}{\textit{weed dry weight in control plot}} \times \frac{\text{Weed population in control}}{\textit{Weed population in treated plot}}$$

Weed management index: WMI was calculated using the following method, representing the ratio of yield acquired over control due to weed management and the percentage of weeds controlled by the associated treatment.

$$WMI = \frac{\text{Yield of treated plot.} - \text{Yield of control plot.}}{\text{Yield of control plot}} \Big/ \frac{\text{Weed dry weight in control (unweeded)plot} - \text{Weed dry weight in treated plot.}}{\text{Weed dry weight in control (unweeded) plot.}}$$

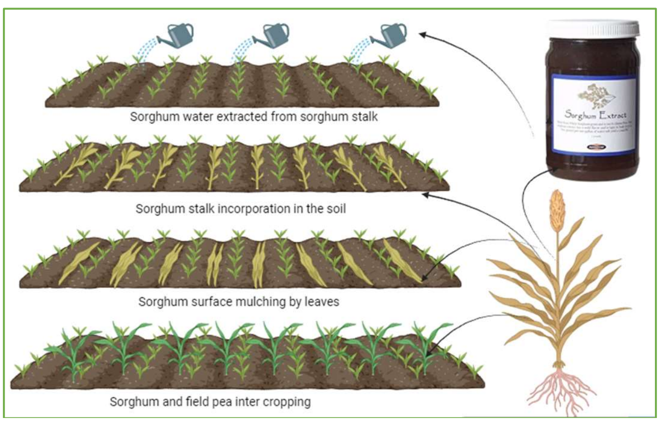

Fig. 1: Representing how different parts of sorghum used as allelopathy for weed control in field pea field viz. Sorghum water extract extracted from the stalk of sorghum is used as a foliar spray, sorghum stalk is chopped into small pieces and incorporated in the soil, sorghum dried leaves is used as mulching between the rows of field pea, sorghum is used as an intercrop between the rows of field pea.

Agronomic management index:

$$\frac{\dfrac{\text{Yield of treated plot} - \text{Yield of control plot}}{\text{Yield of control plot.}} - \dfrac{\text{Weed dry weight in control (unweeded)plot} - \text{Weed dry weight in treated plot}}{\text{Weed dry weight in control (unweeded) plot}}}{\dfrac{\text{Weed dry weight in control (unweeded)plot} - \text{Weed dry weight in treated plot}}{\text{Weed dry weight in control (unweeded) plot}}}$$

Nutrient uptake by weeds and plants: Nitrogen in plant material can be determined by using KELPLUS digestion and distillation processes. Estimation of Phosphorus by Colorimetric Method. By comparing the intensity of the color of unknown samples with the standard curve, the concentration of phosphate in the unknown sample can be estimated. Total potassium in plant and weed samples is determined by flame photometer reading for the standard solutions (0, 2, 4, 6, 8 and 10 ppm K) and construct a standard curve with the readings.

Statistical analysis: Analysis of variance (ANOVA) was used to analyze the experiment's data, which was presented via a randomized block design. SPSS (Statistical Package of Social Services Version 2022) software was used to analyze the data. To examine the variation between the treatments, the Duncan Multiple Range Test (DMRT) is employed. Pearson's correlation was used to determine the relationship between the growth parameters at the 5% significance level (to assess the significance and non-significant parameters).

RESULTS

The most dominant weed species found in the experimental site were *Fumaria parviflora*, *Cornopus didymus*, *Spergula arvensis*, *Cannabis sativa*, *Chenopodium album, Rumex* sp., *Melilotus* sp., *Cynodon dactylon, Phalaris minor, Solanum nigrum, Cyperus* sp.

Yield attributes: The various weed management practice treatments had a substantial impact on the yield-attributing parameters seeds pod^{-1}, harvest index, pod length (cm), and seed index (100-grain weight). When compared to the weedy check, all weed control methods had a substantial impact on the yield attributes.

Pods plant^{-1}, Seeds pod^{-1}, Pod length (cm): Table 1 revealed that among the treatments highest no. of pods plant^{-1} (18.79) was reported in hand weeding followed by sorghum surface mulching@10 tonnes ha^{-1} at harvest. However lowest number of pods plant^{-1} (7.25) was reported in the weedy check at harvest. The highest number of seed pods^{-1} (8.33) was reported in hand weeding followed by sorghum surface mulching@10 tonnes ha^{-1} and sorghum stalk soil incorporation @ 4 Mg ha^{-1} at harvest. Significantly lowest no. of seeds pod^{-1} (4.67) was reported in the weedy check. The highest Pod length (9.21cm) was reported in hand weeding followed by sorghum surface mulching@10 tonnes ha^{-1}. The lowest Pod length (7.81cm) was reported in the weedy check.

Table 1-Effect of Different Weed Control Treatment on Yield Attributes

Treatments	No. of pods plant^{-1}	Pod length (cm)	Seeds pod^{-1}	Seed index (g)	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest index (%)
Weedy check	7.25^{h}± 0.41	7.81^{c}± 0.59	4.67^{e}82. 0±	13.41^{d}± 2.11	980.23^{f}± 16.37	1387.29^{e}± 78.42	41.44^{d}± 1.25
Sorghum surface mulch	15.08^{b}± 0.35	9.2^{a}± 0.27	7.66^{b}± 0.72	18.02^{a}± 0.25	2060.43^{b}± 67.09	2566.16^{b}± 84.49	44.54^{c}± 1.62
Field pea and rabi sorghum intercropping (2:1)	10.33^{f}± 0.31	8.66^{b}± 0.07	5.78^{d}± 0.54	16.75^{bc}± 0.96	1677.23^{e}± 40.38	2085.40^{d}± 43.84	44.57^{c}± 0.43
Sorghum stalk soil incorporation (2 Mg.ha^{-1})	10.5^{fg}± 0.42	8.79^{b}± 0.51	7.00^{bc}± 0.72	16.67^{bc}± 0.52	1813.60^{d}± 41.04	2116.05^{d}± 19.55	46.15^{ab}± 0.78
Sorghum stalk soil incorporation (4 Mg.ha^{-1})	11.00^{d}± 0.54	8.90^{b}± 0.85	7.55^{b}± 0.42	15.09^{c}± 1.99	1907.20^{cd}± 65.21	2355.62^{c}± 7.84	44.73^{c}± 0.80
Sorghum stalk soil incorporation (6 Mg.ha^{-1})	10.75^{ef} ± 0.24	8.30^{b}± 0.46	6.00^{c}± 0.27	16.94^{b}± 0.76	1980.61^{bc}± 64.63	2367.18^{c}± 16.88	45.54^{b}± 0.78
Sorghum water extract (1:10)	12.05^{c}± 0.67	8.09^{b}± 0.46	6.78^{c}± 0.32	16.95^{b}± 1.18	2010.53^{bc}± 64.98	2418.57^{c}± 49.84	45.39^{b}± 0.66
Sorghum water extract (1:20)	10.17^{de}± 0.31	8.40^{b}± 0.50	6.44^{c}± 0.42	17.34^{ab}± 0.30	1804.07^{d}± 53.29	2077.32^{d}± 87.37	46.49^{ab}± 1.31
Hand weeding (20, 40, 60 DAS)	18.79^{a}± 0.59	9.21^{a}± 0.66	8.33^{a}± 0.42	18.57^{a}± 0.84	2897.43^{a}± 62.34	3172.84^{a}± 81.99	47.74^{a}± 1.11

*Original Data given in parenthesis were subjected to square root $\sqrt{}$(x+1) transformation before analysis

Table 2-Weed density, weed fresh weight, weed dry weight as affected by different weed control treatment of Field pea

Treatments	Weed density at (30 DAS) ($No.m^{-2}$)	Weed density at (60 DAS) ($No.m^{-2}$)	Weed density at (90 DAS) ($No.m^{-2}$)	Weed fresh weight (gm^{-2}) at 30 DAS	Weed fresh weight(gm^{-2}) at 60 DAS	Weed fresh weight(gm^{-2}) at 90 DAS	Weed dry weight (gm^{-2}) at (30 DAS)	Weed dry weight (gm^{-2}) at (60 DAS)	Weed dry weight (gm^{-2}) at (90 DAS)
Weedy check	12.22(137.25^{a}± 0.74)	15.24(217.33^{a}± 1.12)	14.8(205.25^{a}± 0.82)	2.86 (5.58^{a}± 0.11)	9.24 (76.45^{a}± 1.03)	13.63(172.36^{a}± 0.61)	1.94(2.08^{a}± 0.39)	4.34(14.78^{a}± 0.66)	7.23(45.28^{a}± 0.61)
Sorghum surface mulch	10.10(92.08^{f}± 1.43)	12.51(144.33^{f}± 0.66)	10.77(105.50^{h}± 0.74)	1.84 (1.81^{e}± 0.49)	6.21 (32.59^{g}± 0.95)	10.11(92.29^{g}± 0.76)	1.04(0.29^{e}± 0.11)	2.3 (3.23^{g}± 0.24)	4.26(14.13^{d}± 0.82)
Field pea and rabi sorghum intercropping (2:1)	10.51(100.23^{d}± 0.75)	12.97(155.42^{e}± 0.72)	13.69(174.08^{b}± 0.72)	2.38(3.54^{bc}± 0.33)	7.96 (55.66^{b}± 1.07)	11.73(126.17^{c}± 0.76)	1.19(0.47^{de}± 0.09)	4.05(12.59^{b}± 0.32)	5.55(25.48^{b}± 0.84)
Sorghum stalk soil incorporation (2 Mg.ha-^{1})	10.82(106.42^{c}± 1.03)	13.7(174.25^{c}± 0.74)	12.76(150.33^{c}± 0.85)	2.41(3.65^{b} ± 0.38)	7.60 (50.35^{c}± 0.67)	11.01(110.44^{d}± 0.89)	1.67(1.38^{b}± 0.19)	3.42(8.51^{e}± 0.78)	5.07(20.93^{c}± 0.60)
Sorghum stalk soil incorporation (4 Mg.ha-^{1})	10.26(95.33^{e}± 1.12)	13.73(175.15^{c}± 0.64)	11.39(118.50^{f}± 0.54)	2.21(2.94^{cd}± 0.30)	7.41(47.72^{d}± 0.70)	10.87(107.44^{e}± 1.13)	1.44(0.89^{bcd}± 0.05)	3.28(7.72^{e}± 0.35)	5.15(21.58^{c}± 0.63)
Sorghum stalk soil incorporation (6 Mg.ha-^{1})	10.76(105.23^{c}± 0.75)	13.88(179.08^{b}± 0.72)	11.95(131.17^{d}± 0.72)	2.08 (2.49^{d}± 0.26)	7.24(45.48^{e}± 1.09)	10.86(107.24^{e}± 0.95)	1.23(0.54^{cde}± 0.02)	3.89(11.46^{c}± 0.40)	5.16(21.71^{c}± 0.54)
Sorghum water extract (1:10)	10.10(92.17^{f}± 1.33)	12.95(155.08^{e}± 0.92)	11.09(112.25^{g}± 0.74)	2.04(2.37^{de}± 0.29)	6.99(42.15^{f}± 0.61)	10.26(95.35^{f}± 0.96)	1.09(0.35^{e}± 0.07)	2.90(5.74^{f}± 0.53)	5.11(21.26^{c}± 0.91)
Sorghum water extract (1:20)	10.96(109.33^{b}± 0.51)	13.21(161.50^{d}± 0.82)	11.69(125.15^{e}± 0.64)	2.08 (2.51^{d}± 0.15)	7.31(46.32^{de}± 0.68)	12.63(147.12^{b}± 1.37)	1.51(1.01^{bc}± 0.52)	3.68(10.11^{d}± 0.54)	5.22(22.30^{c}± 1.30)
Hand weeding at (20, 40, 60 DAS	8.34(61.50^{g}± 0.94)	8.78(68.50^{g}± 0.94)	9.17(75.25^{i}± 0.54)	1.78 (1.65^{f}± 0.16)	3.84 (11.18^{h}0.35±)	7.66 (51.26^{h}0.75±)	0.91 (0.17^{e}0.03±)	2.25(3.06^{g}± 0.73)	3.0(6.27^{e}± 0.69)

*Original Data given in parenthesis were subjected to square root $\sqrt{(x+1)}$ transformation before analysis

Table 3- Effect of Different Weed Control Treatment on Weed Control Index (WCI), Weed Persistence Index (WPI), Weed Management Index (WMI), Agronomic Management Index (AMI)

Treatments	Weed control efficiency (%) at 30 DAS	Weed control efficiency (%) at 60 DAS	Weed control efficiency (%) at 90 DAS	Weed persistence index at 30 DAS	Weed persistence index at 60 DAS	Weed persistence index at 90 DAS	Weed management index	Agronomic management index
Weedy check	-	-	-	-	-	-	-	-
Sorghum surface mulch	$46.7^{de}\pm 0.67$	$47.1^{b}\pm 0.25$	$41.1^{b}\pm 0.75$	$0.65^{d}\pm 0.41$	$0.70^{d}\pm 0.66$	$0.81^{b}\pm 0.41$	$1.26^{ab}\pm 0.61$	$0.23^{b}\pm 0.08$
Field pea and rabi sorghum intercropping (2:1)	$72.8^{a}\pm 0.59$	$12.9^{g}\pm 0.56$	$39.5^{c}\pm 0.58$	$0.71^{c}\pm 0.33$	$1.10^{a}\pm 0.31$	$0.83^{b}\pm 0.33$	$1.32^{a}\pm 0.42$	$0.33^{a}\pm 0.05$
Sorghum stalk soil incorporation (2Mg.ha^{-1})	$22.6^{g}\pm 0.69$	$22.9^{e}\pm 0.44$	$38.8^{d}\pm 0.27$	$0.97^{a}\pm 0.59$	$0.88^{c}\pm 0.27$	$0.82^{b}\pm 0.59$	$1.27^{ab}\pm 0.77$	$0.28^{ab}\pm 0.07$
Sorghum stalk soil incorporation (4 Mg.ha^{-1})	$29.8^{f}\pm 0.53$	$31.1^{d}\pm 0.52$	$41.1^{b}\pm 0.41$	$0.88^{b}\pm 0.16$	$0.84^{c}\pm 0.51$	$0.93^{a}\pm 0.16$	$1.24^{b}\pm 0.47$	$0.25^{ab}\pm 0.06$
Sorghum stalk soil incorporation (6 Mg.ha^{-1})	$49.1^{d}\pm 0.65$	$14.1^{f}\pm 0.62$	$40.2^{bc}\pm 0.52$	$0.72^{c}\pm 0.66$	$0.98^{b}\pm 0.85$	$0.89^{ab}\pm 0.66$	$1.30^{a}\pm 0.66$	$0.30^{a}\pm 0.06$
Sorghum water extract (1:10)	$69.2^{b}\pm 0.28$	$37.3^{c}\pm 0.44$	$41.1^{b}\pm 0.12$	$0.68^{cd}\pm 0.80$	$0.78^{d}\pm 0.46$	$0.94^{a}\pm 0.8$	$1.26^{ab}\pm 0.35$	$0.27^{ab}\pm 0.09$
Sorghum water extract (1:20)	$39.9^{e}\pm 1.25$	$22.9^{e}\pm 0.58$	$39.2^{c}\pm 0.42$	$0.87^{b}\pm 0.44$	$0.98^{b}\pm 0.50$	$0.92^{a}\pm 0.4$	$1.31^{a}\pm 0.61$	$0.31^{a}\pm 0.12$
Hand weeding (20, 40, 60 DAS)	$68.3^{bc}\pm 0.73$	$56.9^{a}\pm 0.46$	$80.9^{a}\pm 0.49$	$0.69^{cd}\pm 0.17$	$0.64^{e}\pm 0.59$	$0.67^{c}\pm 0.8$	$1.0^{4b}\pm 0.54$	$0.04^{c}\pm 0.13$

Seed Index, pod yield (kg.ha^{-1}), haulm yield (kg.ha^{-1}) and harvest Index (%): Significantly highest seed index (18.57 g) was reported in hand weeding which was statistically at par with sorghum surface mulching @ 10 tonnes.ha^{-1}. Lowest seed index (13.41g) was reported in the weedy check (Table 1). Significantly highest Pod yield (2897.43 kgha^{-1}) and Haulm yield (3172.84 kg.ha^{-1}) were reported in hand weeding where three hand weeding at 20, 40, 60 DAS was done which was followed by sorghum surface mulching @ 10-tonnes.ha^{-1}. Significantly lowest Pod yield (980.23 kg.ha^{-1}) and Hulm yield (1387.29 kg.ha^{-1}) were reported in the weedy check. Significantly maximum Harvest index (47.74%) was observed in hand weeding which was statistically at par with sorghum water extract (1:20) and sorghum stalk soil incorporation. The lowest harvest index (41.44%) was observed in the weedy check as indicated in Table 1.

Weed density (no. m^{-2}): Table 2 revealed that there was significant variation recorded in weed density with different weed management practices. Significantly highest weed density (12.22 m^{-2}, 15.24 m^{-2}, 14.8 no.m^{-2}) was recorded under weedy check at 30, 60, and 90 DAS. However, significantly Lowest weed density (8.34 no.m^{-2}, 8.78 no. m^{-2}, 9.17 no.m^{-2}) was recorded in Hand weeding (20, 40, 60 DAS) followed by Sorghum surface mulching@ 10 tonnes ha^{-1} at 30, 60, 90 DAS.

Weed Fresh weight and Dry weight (gm): Table 2 revealed that significantly the highest weed fresh weight (2.86 g, 9.24 g) and dry weight (1.94g, 4.34g) was reported in the weedy check at 30,60 DAS. However lowest weed fresh weight (1.78g, 3.84g) and dry weight (0.91g, 2.25 g) was reported in Hand weeding (20, 40 and 60 DAS) was followed by Sorghum surface mulching @ 10 tonnes.ha^{-1} at 30, 60 DAS. At 90 DAS, the significantly highest weed fresh weight (13.63g) and dry weight (7.23g) were reported in the weedy check. However, the lowest weed fresh weight

Table 4: Pearson's correlation of Weed indices

Correlations					
		WCE	WPI	AMI	WMI
WCE	Pearson Correlation	1	-.770*	-.949**	-.961**
	Sig. (2-tailed)		.026	.000	.000
	N	8	8	8	8
WPI	Pearson Correlation	-.770*	1	.715*	.694
	Sig. (2-tailed)	.026		.046	.056
	N	8	8	8	8
AMI	Pearson Correlation	-.949**	.715*	1	.989**
	Sig. (2-tailed)	.000	.046		.000
	N	8	8	8	8
WMI	Pearson Correlation	-.961**	.694	.989**	1
	Sig. (2-tailed)	.000	.056	.000	
	N	8	8	8	8

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 5: Nutrient content % (N, P, K) in plants and weed samples

Treatments	Nitrogen content in plant (%)	Nitrogen content in weed (%)	Phosphorous content in plant (%)	Phosphorous content in weeds (%)	Potassium content in plant (%)	Potassium content in weed (%)
Weedy check	$1.69^{e}\pm 0.45$	$3.19^{a}\pm 0.32$	$0.41^{b}\pm 0.34$	$0.68^{a}\pm 0.15$	$0.43^{b}\pm 0.42$	$1.02^{a}\pm 0.13$
Sorghum surface mulch	$3.08^{b}\pm 0.62$	$2.95^{ab}\pm 0.25$	$0.65^{a}\pm 0.75$	$0.55^{ab}\pm 0.41$	$0.60^{a}\pm 0.66$	$0.64^{c}\pm 0.41$
Field pea and rabi sorghum intercropping (2:1)	$2.94^{bc}\pm 0.54$	$2.6^{b}\pm 0.51$	$0.60^{a}\pm 0.58$	$0.41^{b}\pm 0.33$	$0.53^{ab}\pm 0.31$	$0.98^{a}\pm 0.33$
Sorghum stalk soil incorporation (2 $Mg.ha^{-1}$)	$2.69^{c}\pm 0.61$	$2.35^{c}\pm 0.42$	$0.60^{a}\pm 0.27$	$0.25^{c}\pm 0.59$	$0.53^{ab}\pm 0.27$	$0.80^{c}\pm 0.59$
Sorghum stalk soil incorporation (4 $Mg.ha^{-1}$)	$2.33^{d}\pm 0.53$	$2.49^{bc}\pm 0.47$	$0.63^{a}\pm 0.41$	$0.43^{b}\pm 0.16$	$0.56^{ab}\pm 0.51$	$0.62^{c}\pm 0.16$
Sorghum stalk soil incorporation (6 $Mg.ha^{-1}$)	$3.00^{b}\pm 0.60$	$2.88^{ab}\pm 0.59$	$0.55^{ab}\pm 0.52$	$0.44^{b}\pm 0.66$	$0.60^{a}\pm 0.85$	$0.56^{c}\pm 0.66$
Sorghum water extract (1:10)	$3.67^{a}\pm 0.28$	$2.77^{b}\pm 0.43$	$0.54^{ab}\pm 0.12$	$0.46^{b}\pm 0.80$	$0.63^{a}\pm 0.46$	$0.65^{c}\pm 0.8$
Sorghum water extract (1:20)	$3.22^{ab}\pm 0.34$	$2.94^{ab}\pm 0.54$	$0.65^{a}\pm 0.42$	$0.34^{bc}\pm 0.44$	$0.48^{b}\pm 0.50$	$0.83^{b}\pm 0.4$
Hand weeding (20, 40, 60 DAS)	$3.55^{a}\pm 0.73$	$2.5^{bc}\pm 0.42$	$0.60^{a}\pm 0.49$	$0.58^{ab}\pm 0.17$	$0.56^{ab}\pm 0.59$	$0.88^{b}\pm 0.8$

(7.66 g) and dry weight (3.0 g) was reported in Hand weeding (20, 40 and 60 DAS) followed by Sorghum surface mulching @ 10 tonnes ha^{-1}.

Weed Control efficiency (%) and Weed persistence index: Table 3 revealed that at 30 DAS significantly highest WCE (72.8%) and lowest WPI (0.65) was observed in Field pea and Rabi sorghum intercropping (2:1) which was statistically at par with Sorghum water extract (1:10) in terms of WPI (0.68). At 60, 90 DAS significantly highest WCE (80.9%, 56.9%) and lowest WPI (0.64, 0.67) was reported in hand weeding where three hand weeding at 20, 40 and 60 DAS was done which was followed by sorghum surface mulch with WCE 47.1,41.1% and WPI (0.70,0.81).

Weed management index (WMI) and Agronomic management index (AMI): There was a significant effect of treatments observed in WMI and AMI. The highest WMI and AMI (1.32 and 0.33) were observed under field pea and sorghum intercropping whereas no significant effect was observed between Sorghum water extract (1:20) and sorghum stalk incorporation (6 Mg ha^{-1}). The lowest WMI (1.04) and AMI (0.04) were observed under hand weeding plots which was followed by sorghum surface mulching. WCE and yield increase are inversely correlated with WMI and AMI. Higher WMI or AMI indicates lower WCE or/and relatively lower addition of yield due to treatment effect, whereas lowest values of WMI and AMI show greater WCE or/and comparatively higher addition of yield occurs due to treatment effect.

Correlation between WCE, WPI, WMI and AMI: From Table 4 of correlation, it is found that Weed control efficiency was negatively correlated with the weed persistence index, weed management index and agronomic management index. This indicated that higher WCE lowers the WMI, AMI and WPI.

Nutrient Content uptake by weeds and crop: Table 5 summarizes and presents the data on N, P, and K uptake by weeds and crops as influenced by various weed management techniques. A review of the data showed that the weedy check plot had the greatest value of nitrogen uptake by weeds, whereas the treatments produced the lowest value. The different weed control methods caused a considerable variation in the nitrogen uptake by weeds. Under the weedy check, a much higher value of N depletion by weeds was reported (3.19%), which was comparable to that of sorghum water extract (1:20) and surface mulch (2.95% and 2.94%). Incorporation of sorghum stalks (2 $Mg.ha^{-1}$) recorded the lowest (2.35%) of N. The weedy check had the highest P depletion by weeds (0.68%), whereas the Sorghum stalk incorporation (2 $Mg.ha^{-1}$) had the lowest (0.25%). The P uptake by weeds over weedy check was significantly reduced upon adoption of the weed control option. The K (0.56%) depletion rate by weeds under Sorghum stalk integration (6 $Mg.ha^{-1}$) was the lowest. The findings showed that different weed management treatments considerably reduced the quantity of potassium lost as compared to the weedy check (1.02%), which was comparable to the intercropping of field pea and rabi sorghum (2:1) with (0.98%). When weed management was implemented, weeds' uptake of potassium was significantly reduced compared to weedy check as represented in Figs. 2, 3. In the case of field peas significant variation was recorded in nutrient content among different weed management practices. The highest nitrogen content in the plant (3.67%) was recorded in Sorghum water extract (1:10) which was at par with hand weeding with 3.55% and the minimum nitrogen content in the plant (1.69%) was recorded in weedy check plots. Maximum P content in plants (0.65% and 0.63%) was recorded in Sorghum surface mulch, Sorghum water extract (1:20) and Sorghum stalk soil incorporation (4 $Mg.ha^{-1}$) whereas minimum content of phosphorous (0.41%). Maximum K uptake (0.63%) was recorded in Sorghum water extract (1:20)

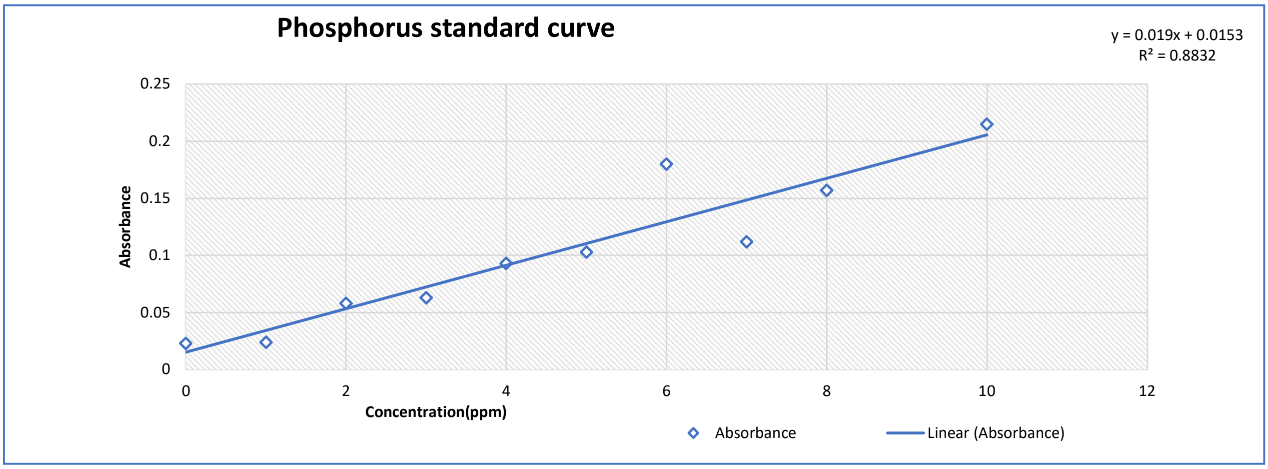

Fig. 2: Phosphorus standard curve for estimation of nutrient content from plant samples.

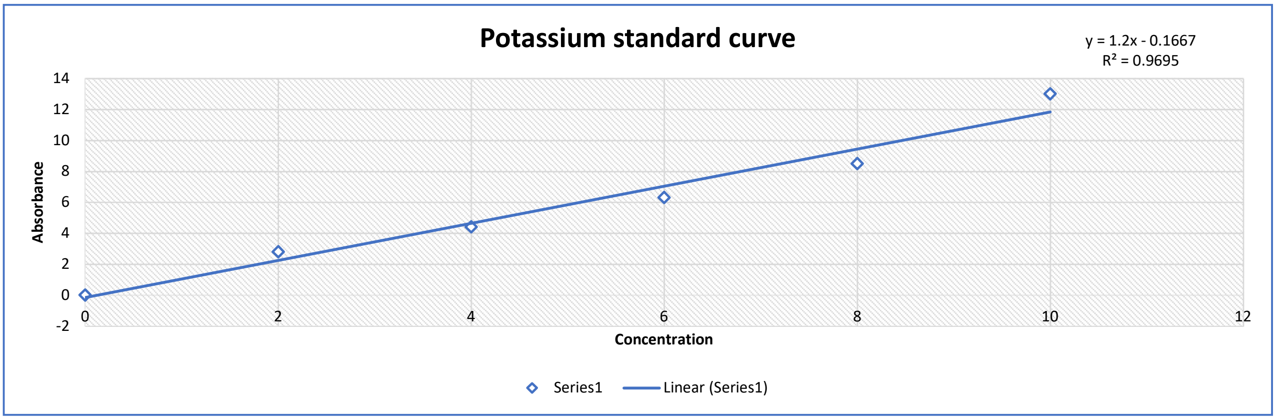

Fig. 3: Potassium standard curve for estimation of nutrient content from plant samples.

which was at par with Sorghum surface mulch and Sorghum stalk soil incorporation whereas the least K content (0.43%) was recorded in weedy check.

DISCUSSION

Effect of sorghum allelopathy on weed management: An environmentally friendly way to control weeds in field crops is to incorporate allelopathic crop residues. With a multitude of allelochemicals that inhibit weed growth, sorghum (*Sorghum bicolor* L.) is one of the possible allelopathic crops. Plant stems, leaves, and roots all contain allelochemicals. Additionally, different plant sections may have different allelopathic potentials (Khan et al. 2021, Farooq et al. 2020). Kristó et al. (2022) revealed that in sorghum plants, numerous vital secondary metabolites have been found, including polyphenols, alkaloids, flavonoids, and terpenoids. The phenolic acids found in sorghum include gallic acid, ferulic acid, syringic acid, coumaric acid, benzoic acid, and caffeic acid. According to our findings, adding sorghum stalk and water extract significantly increased the potential for weed suppression (Kumar et al. 2016). The field pea weed species' fresh weight, dry weight, and weed density were all reduced to a maximum by this method. Motmainna et al. (2021) revealed that Phenolic substances, such as phenolic acids (Dhurrin, p-hydroxybenzaldehyde, sorgleone, vanillic acid, p-hydroxybenzoic acid, p-hydroxybenzaldehyde, p-coumaric acid, and ferulic acid), which have a variety of biological functions, including allelopathy, were released when this reduction occurred. Sahu et al. 2022 found that sorghum allelochemicals have an inhibitory effect on weeds with grassy and broad leaves. Using water extract from mature sorghum crop plants reduced weed density and biomass by 35–49% when compared to the control group. In comparison to sorghum water extract treatments, sorghum residue treatments demonstrated the greatest weed suppression. By adding 2-4 $Mg.ha^{-1}$ of sorghum to the soil, weed biomass was reduced by 40–50%. Shiv et al. 2023 revealed that the addition of crop wastes has the potential to inhibit weeds and alter their frequency and distribution. The physical resistance of the sorghum residues integration or the chemicals released from them may have contributed to the growth inhibition of the dominant weed biota in this experiment. Allelo chemicals generated by various plant components are influenced by a multitude of parameters, including the crop family used, the amount and size of mulch applied, the rate of decomposition, the moisture level, the soil's texture, and the soil microbiota (Won et al. 2023). The amount of allelopathic products taken has a direct impact on the level of weed control. The overall amount of allelochemicals released and present in the mulch increases with the amount of plant material used, which results in a higher concentration of allelochemicals in the soil (Tibugari et al. 2021). In general, it was found that weed suppression increased with the amount of crop waste added. Ullah et al. (2022, 2020) found that in comparison to the weedy control, the integration of sorghum residue greatly decreased the density of weeds and increased the production of broad beans. Sorghum water extract applied topically decreased the weight and density of dry weeds relative to the control. Selectivity and extract concentration are key factors in sorghum's allelopathic activity. When allelochemical concentrations are low, they have stimulatory effects on weed growth and germination, but when they are higher, they demonstrate inhibitory effects Won et al. (2013), Meleta et al. (2024). The fact that allelochemicals function as herbicides in high concentrations and as hormones in low concentrations may account for the greater suppression of weeds with concentrated extract. The findings of Ullah et al. (2023) and Khamare et al. (2022), who observed that the inhibitory effect on germination indices increased as water extract content grew from 25 to 100%, are consistent with our observations. Our findings are consistent with those of Murimwa et al. (2022), Bailey-Elkin et al. (2021) who described a noteworthy reduction in the density of weeds using an allelopathic crop water extract. Allelochemicals were found to be present and efficacious in both materials based on the suppression of weed density observed with leaf and stem water extracts. According to Murimwa et al. (2022) and Georgieva 2021, foliar application of sorghum leaf and stem water extract significantly reduced the density of weeds. These results are consistent with their findings. Similarly, due to allelopathy (Georgieva 2021, Scavo & Mauromicale 2021, Sharmili & Yasodha 2021) found that plant extract had a major impact on other plants' growth. When sorghum was interplanted with maize, the weight of black pigweed, field bindweed, and *Cyperus rotundus* was minimal. The hydrophilic chemicals (phenolic acids and their aldehyde derivatives) and hydrophobic compounds (sorgleone and its analogs) present in the mixture dictate its potential to control weed growth. To assess allelopathic effects on weed and crop growth, sorghum residues are used as a mulch or integrated into the soil in place of sorgaab in another kind of study. Sorghum wastes in container studies can be pulverized or chopped and mixed into the soil (Alsaadawi et al. 2019, Scavo et al. 2019, Głąb et al. 2017). Using a disc plow, sorghum residues are integrated into the soil twice during field experiments. Additionally, several researchers have investigated how intercropping sorghum with a primary crop can reduce weeds due to its allelopathic properties (Georgieva et al. 2016, Singh et al. 2016).

Effect of sorghum allelopathy on yield attributes: Effective allelopathic weed management strategies increased field pea yield in our study by more than 34%. Jabran et al. (2015) stated that improved soil characteristics and less weed competition during the crucial stages of crop growth may be the reasons for this increase in the production of crops. Reducing weeds effectively also makes resources like light, moisture, nutrients, and yield more accessible. Increased soil moisture conservation, particularly throughout the experimental crop's crucial growth stage (Ashraf & Akhlaq 2007). Along with contributing nutrients to crop plants, fully decomposed residues in the soil also supply allelochemicals. Therefore, a plant with enough nutrients produces more pods overall, more seeds within each pod, and pods that fully develop (Cheema et al. 2007). Cheema (2000a) found that applying sorghum residues as biological weed management may have contributed to the increase in pod count per plant, number of seeds per pod, pod length, and seed yield observed with sorghum stalk incorporation, mulching, and intercropping. This process aids in nitrogen mineralization and improves nitrogen availability in the rhizosphere. But later in crop growth, mineralization improved the obtainability of nitrogen, thus this constant supply of nitrogen provided test crops and subsequent crops with a constant source of nutrition (Farooq et al. 2020). Because of the phenolic compounds present in the residues, the incorporation of sorghum residues improved the moisture retention, physical qualities, microbial activity, and physical hindrance of the residue (Won et al. 2013, Meleta et al. 2024, Georgieva 2021). Additionally, the presence of allelochemicals released from the residues reduced light penetration and suppressed weed growth. Ultimately, the incorporation of sorghum residues improved field pea profitability and seed yield (Farooq et al. 2020). In addition to improving nodulation and nitrogen fixation processes, as well as the physical, chemical, and nutritional statuses of field soils, the addition of sorghum residues had a positive impact on weed population and biomass reduction (Hetta et al. 2022, Abbas et al. 2021, Murimwa et al. 2022). Significant increases in grain output with hand weeding and SWE spraying may be the result of reducing the density of weeds in these plots, which lessened resource competition and allowed more nutrients to get to the seed and photosynthesis to move to reproductive regions. These findings are consistent with studies by Scavo et al. (2019) and Alsaadawi et al. (2019) who observed increased grain yields following foliar application of allelopathic crop water extract.

Effect of allelopathy on nutrient content: The main source of organic matter supplied to the soil is crop residues, which are also excellent suppliers of nutrients. They improve the soil's ability to hold water and release nutrients. The primary advantage of residue incorporation is moisture retention (Meleta et al. 2024, Ullah et al. 2023, Georgieva 2021). It results from less water evaporating from the land and less runoff. One possible explanation for the increased nutrient buildup (particularly P and K) could be improved soil moisture retention. Increased soil moisture availability as a result of residue assimilation also suggested that the soil's ability to store water had increased and that soil moisture was accessible to promote plant growth for longer periods. Field peas compete less with weeds for nutrients, such as nitrogen, phosphate, and potash, as well as other resources like space, light, and water, which are necessary in sufficient amounts for healthy growth and development. This could lead to a higher yield (Głąb et al. 2017).

CONCLUSIONS

Weed infestation can cause a 40–70% reduction in field pea yield. The allelopathy of the sorghum crop had a major effect on field pea yield and weeds. We found that different treatments of applying water extract and sorghum residue had variable levels of weed suppression. Allelopathic water extract, sorghum surface mulching, and sorghum soil inclusion are excellent methods for managing weeds in field pea. Additionally, by applying the experimental treatment dose, weed indices in field pea can be effectively improved. Nonetheless, the results indicate that when compared to other treatments, hand weeding and sorghum surface mulching had superior outcomes in terms of field pea output and weed management indices. Field pea yields increased, and profitability increased as a result of improved soil conditions and weed suppression. As a result, applying sorghum surface mulch at a rate of 10 tonnes per hectare proved to be a profitable and efficient substitute for the current field pea weed control advice, which calls for three-hand weeding at 20, 40, and 60 DAS.

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