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Sustainable Weed Control and Enhancing Nutrient Use Efficiency in Crops through Brassica (*Brassica compestris* L.) Allelopathy

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Abstract: Weed–crop competition and reduced soil fertility are some of the main reasons for decreased crop yields in Pakistan. Allelopathy can be applied to combat the problems of environmental degradation by reducing pesticide use and through reduction of herbicide-resistant weeds. A two-year field experiment (2014–2015) was conducted to assess the impact of incorporation of various levels of brassica residues and brassica water extract on the growth of mung bean and soil attributes. Two brassica water extract levels (10, 20 L/ha) and two residue levels (4, 6 t/ha) were tested, and a treatment with no water extract and residue incorporation was used as the control. The results showed that the water extract and residue incorporation had diverse impacts on soil fertility indices and weed dynamics, where treatment with 6 t/ha had more significant impacts. Compared with the control, reductions of 61% in dry weight of weeds and 52% in weed density were observed. After cropping, improved soil properties in terms of available potassium, available phosphorus, soil organic matter, and total nitrogen were higher in the rhizosphere (0–15 cm) soil after the treatments of residue incorporation, i.e., 59–91%, 62–84%, 29–45%, and 52–65% higher than the control, respectively. Meanwhile, alkaline phosphatase and dehydrogenase concentrations in the rhizosphere soil were 26–41% and 52–74% higher than with the control, respectively. The highest economic return with a high benefit–cost ratio was recorded with residue incorporation. In conclusion, addition of crop residues at 6 t/ha was the most effective and economical treatment with the highest net benefit rate of returns. This approach can provide a potential alternative for implementing sustainable weed control in mung bean with significant improvement in soil properties and can be a part of sustainable and eco-friendly agriculture.

Keywords: allelopathy; sustainable; profitability; soil health; crop residues; brassica

1. Introduction

Since the Green Revolution of the mid-1900s, intensive agriculture has dominated global food production through the utilization of synthetic fertilizers, pesticides, irrigation technology, chemical

herbicides, and improved crop varieties. Although these developments improve food production, they have also contributed to land degradation, habitat destruction, and environmental depletion, along with health problems related to the widespread use of toxic chemicals in the food supply chain [1,2]. Weeds are known to be a potential pest, creating more than 45% loss in crop yields, compared to 25% from pathogens, 20% from insects, 15% from storage and various pests, and 6% through rodents [3,4]. Weed control management accounts for almost one third of the overall cost of the yield of field crops [5,6].

The use of herbicides is generally practiced in agricultural systems because it is an effective and practical method of weed control. Moreover, after application, herbicides can follow various pathways in the soil and the environment. Persistent herbicides may remain available in the environment for a longer period, potentially leading to soil pollution [7]. Herbicides have extreme physiological and morphological impacts on weed plants, like cupping of leaves, stunted growth, delayed flowering, necrosis, burning symptoms, deformed flowers, etc. [8]. According to the UN COMTRADE international trade database, Pakistan imported pesticides (herbicides, rodenticides, plant growth regulators, fungicides, and insecticides) in a total amount of around 3.41 million USD in 2019, only from Malaysia. According to official statistics, the utilization of the herbicide glyphosate has increased in Pakistan. Approximately 1100 tons of glyphosate were imported in 2015. These figures rose to 1700 tons in 2016, with a variety of local and international pesticide companies importing it [9].

Allelopathy is the discharge of biologically active chemical compounds into the environment by one sort of species that affects other plants, very often in an inhibitory way [10–12]. Throughout the previous four decades, statistics showed that dependence on chemical herbicides for the control of weeds has been decreased due to allelopathic impacts of crops on weeds [13–15]. Numerous crops like sorghum, sunflower, brassica, rice, and wheat have been recorded to even have allelopathic ability for weeds, and significant combinations have been investigated between many cultivars with the same plant species under greenhouse and field conditions [16,17].

Brassica is an essential genus of the Brassicaceae family with considerable allelopathic potential. It is comprised of approximately 100 species, including *Brassica oleifera* L. and *Brassica napus* L., usually termed as the oilseed crop [18]. Several brassica species have been utilized by various methods, particularly cover cropping, crop rotations, water extract application, mulching, intercropping, and crop residue incorporation [19]. Water derivatives of *B. nigra* L. (black mustard) plant parts like roots, stems, leaves, and flowers inhibit the germination and development of seedlings of radish, oat, lentil, and alfalfa [20–22]. In a field study, Smith et al. [23] stated that the use of rye mulch not only minimized weed biomass, but it also increased the production of soybean. Narwal et al. [24] also conducted a field experiment and stated that some accessions of *B. juncea* and *B. nigra* caused a significant reduction of 75–82% at 75 days after germination and 75–98% at harvest (120 days) in the density of weeds, namely *Rumex retroflexus, Melilotus alba, Chenopodium album, Cirsium arvense, Avena ludoviciana,* and *Phalaris minor*, respectively. In greenhouse conditions, incorporation of rapeseed residues in soil prior to sowing of cotton reduced germination of *Amaranthus retroflexus* and *Amaranthus theopherasti,* while cotton germination remained unaffected [25,26]. Turk and Tawaha [21] studied an experiment to check the allelopathic potential of black mustard against wild barley (*Hordeum spontaneum*). They observed that wild barley growth was highly suppressed when grown in soil that was incorporated with cropped black mustard. Soil incorporation of both roots and shoots of black mustard reduced emergence, height, and weight of wild barley as compared with the control (no residues) under greenhouse conditions. A lower number of research works are documented concerning the impact of allelopathic activities on soil quality and health [27,28]. A soil can be declared as healthy only if it sustains animal and plant life, recycles nutrients, conserves water, separates and buffers potential contaminants, and supports the soil itself and the plants [3,29].

Root-specific metabolites are present in root exudates, which have critical ecological impacts on soil health (macro- and microbiota), as well as on the whole plant itself. Through the exudation of various compounds, they support beneficial symbioses and alter the soil properties, like chemical and physical

properties [30]. The effects of these metabolites on ion uptake are closely related to concentrations and classifications. For example, a low concentration of dibutyl phthalate and diphenylamine stimulates the absorption of N and K [31].

Luckily, sustainable agriculture is a reliable business model that delivers superior economics over conventional agriculture systems with a wide range of parameters, such as soil health, production costs, net income per acre, crop yields, gross income per acre, individual farm income, and much more. Every acre transformed into one with organic, sustainable practices is one acre closer to the sustainability tip of society, or at least one acre less as a source of damage [32]. Addition of crop residues is a sustainable way for improving the soil health on a long-term basis; initially, it increases the input cost, but on a long-term basis, it results in improvement of soil health (i.e., soil organic carbon sequestration, microbial biomass C, and activity and species diversity of soil biota), increase in soil organic matter, reduction in the fertilizer cost, and weed control, which ultimately results in better production [33]. For this study, we hypothesized that brassica water extracts and residues can have impacts on weed infestation, soil health, and mung bean (*Vigna radiata* L.) grain yield, which is an essential product in developing regions, as this is the foremost option to come across given the need for food of the increasing population. This research was planned with the specific objective of measuring the results of brassica (*Brassica compestris* L.) residues and their water extracts on weed dynamics, soil health, and productivity of spring-planted mung bean.

2. Materials and Methods

2.1. Soil, Site, and Climate

This two-year field study was executed at the Student Research Farm of the Department of Agronomy, University of Agriculture of Faisalabad, Pakistan (Latitude = 31°-26′N, Longitude = 73°-06′E, Altitude = 184.4 m). The experimental site soil belongs to the Lyallpur soil series (mixed, Aridisol–fine–silty, hyper-thermic Ustalfic, and Haplic Yermosols in the Food and Agriculture Organization (FAO) classification, and Haplargid in the US Department of Agriculture (USDA) classification). The experimental site is in a subtropical climate region, with mean temperatures ranging from 6 to 21 °C in winter and from 27 to 39 °C in summer. The average annual rainfall is around 300 mm, half of which is recorded between July and August as monsoons. The weather information concerning temperature (minimum and maximum), relative humidity, and rainfall during both courses of crop growth (March, April, May, June, and July, 2014–2015) is shown in Figure 1.

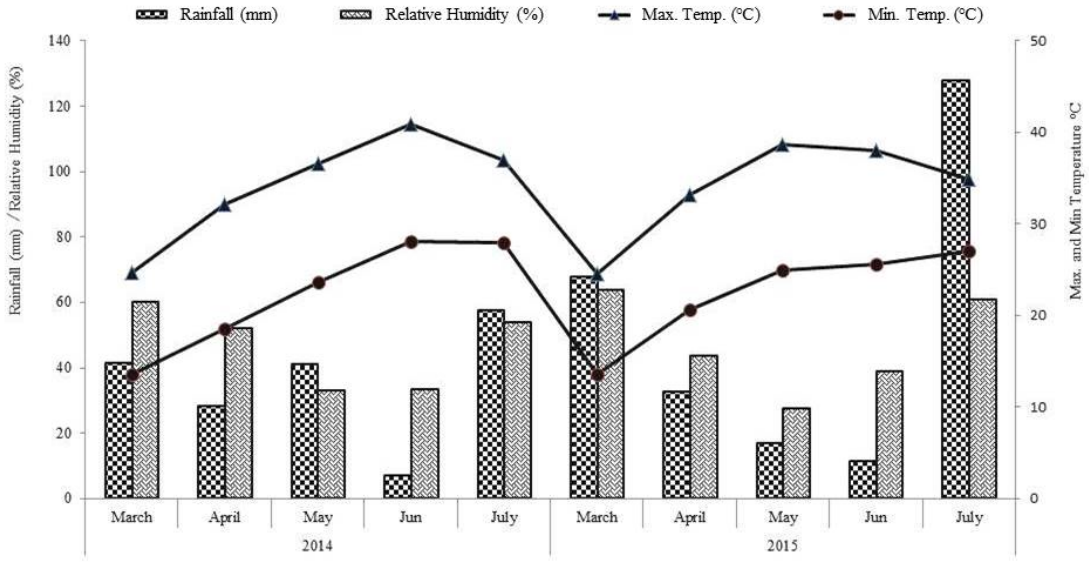

Figure 1. Monthly meteorological data for the current study (2014 and 2015).

2.2. Experimental Design

This experiment was planned in randomized complete block design (RCBD) with three replications in the spring seasons of both years. The area of each plot was 3.0×5.0 m. The experiment was comprised of a control (plots with no extract application or crop residues), brassica residue at the rate of 4 t/ha, brassica residue at the rate of 6 t/ha, brassica water extract at the rate of 10 L/ha, and brassica water extract at the rate of 20 L/ha.

2.3. Land Preparation and Crop Management

The experimental site was cultivated two times per test crop, followed by planking. Flat wooden planks were used for the breakage of clods, and leveling was done with a laser leveler. There was wheat as a fore-crop for mung bean. After land preparation, test crop seeds were directly drilled in each treatment on 15 and 20 March in 2014 and 2015, respectively. Sowing was carried out with a hand-operated drill that used a seed rate of 25 kg/ha in rows 30 cm apart. The mung bean (cultivar NM-92) seed was collected from National Institute of Agriculture and Biology, Faisalabad (NIAB). It was planted in the spring of 2014 and 2015. Nitrogen, phosphorus, and potash fertilizers were applied at 23 kg N, 58 kg P_2O_5, and 63 kg K_2O ha^{-1} in the form of urea, diammonium phosphate, and sulphate of potash, respectively. The recommended full doses of P, K, and one third of the N in the form of diammonium phosphate (DAP), sulphate of potash (SOP), and urea, respectively, were drilled at sowing time. Two thirds of the N were applied in two equal splits, i.e., one third at the first irrigation and remaining one third as a top dressing at the second irrigation. A first irrigation of 7.5 cm was applied 10 days after sowing the crop, while subsequent irrigations were applied as and when needed. Broad-spectrum insecticide (Ranger; Fipronil 11.73% *w/w* ha^{-1} and Rider; Emamectin Benzoate 5.03% *w/w* ha^{-1}) was applied at the vegetative and pod development stages to control termites and pod borers, respectively. The harvesting of the crop was done on the 10 and 15 July of 2014 and 2015, respectively.

2.4. Brassica Crop Water Extract Preparation

Brassica (*Brassica compestris* L. cv. Punjab Sarsoon) plant residues were collected from the Student Research Farm (Department of Agronomy, University of Agriculture of Faisalabad, Pakistan). The mature brassica plants were collected, dried in shade conditions, and sliced into 3–4 cm sections with an electric fodder blade. All of these fragments were soaked in water for 24 h at a ratio of 1:10 *w/v* of brassica residue to water [34]. The filtrate was utilized fresh. The brassica water extracts were sprinkled at rates of 10 and 20 L/ha (15 and 30 mL/ha, respectively), 15 days after the sowing (3–5 leaf stage) of the mung bean plants. The spraying was done using a knapsack sprayer fitted with a T-jet nozzle. The volume of the spray was 300 L/ha (450 mL/plot), determined by calibration prior to spraying [35].

2.5. Brassica Crop Residue Preparation

Brassica plant residues were collected from the Student Research Farm (Department of Agronomy, University of Agriculture of Faisalabad, Pakistan). The mature brassica plants were collected, dried under shade, and sliced into 3–4 cm sections with an electric fodder blade. All of these plant residues were added into the upper 15 cm layer of soil by a rotavator before being sown, as per treatment (4 and 6 t/ha).

2.6. Soil Sampling

Soil samples were collected from the rhizosphere of the mung bean plants 20 days after sowing and after harvesting. A composite sample of ten soil samples (0–15 cm) was taken from the experimental site before the start of the experiment, while for the enzymatic attributes and microbial counts of the soil samples, another composite sample was taken after the harvesting of the crop from the same field.

The soil samples were treated by drying in air, grinding, and sieving (sieved with a 2 mm sieve), and were analyzed for all parameters, excluding microbial culturing and dehydrogenase activity. For both dehydrogenase and microbial culturing, soil samples were stored at 4 °C. The basic physio-chemical characteristics of the original experimental site were assayed, as shown in Table 1.

Table 1. Response of soil enzyme activities, nutrient dynamics, microbial populations, and soil enzyme activities of experimental soil prior to sowing (2014 and 2015).

Soil Properties	2014	2015
Soil bulk density (g/cm^3)	1.48	1.45
Total soil porosity (%)	43.10	44.30
Soil pH	7.85	7.79
Electrical conductivity (dS/m)	1.11	1.19
Total soil organic matter (%)	0.53	0.61
Available P_2O_5 (mg/kg)	6.74	6.95
Exchangeable K_2O (mg/kg)	123.00	131.00
Total nitrogen (soil) (g/kg)	0.24	0.29
Bacteria (cfu/g×10^5)	35.00	45.00
Fungi (cfu/g×10^4)	5.00	8.00
Activity of alkaline phosphatase (µg NP/g soil/ha)	135.00	143.00
Activity of dehydrogenase (µg TPF/g soil/ha)	21.00	25.00

2.7. Observations, Measurements, and Data Analysis

The total density of weeds (0.25 m^{-2}), dry weight (g 0.25 m^{-2}), and fresh weight (g 0.25 m^{-2}) were reported from two randomly selected 50×50 cm quadrates in each field after thirty days of sowing. The weeds were calculated and trimmed just above the surface of the land, and then fresh weight was registered. All of the fresh samples were dried in sun for 48 h and shifted to the oven at the temperature of 70 °C for 72 h for further drying. The dry weight of weeds was recorded when samples were of constant weight. Soil properties like total porosity of soil (TP) and soil bulk density (BD) were calculated by the processes reported by Blake and Hartge [36] and Vomocil [37], respectively. Electrical conductivity (EC) and soil pH were checked as per Ryan et al. (2001) [38]. To measure soil EC and pH, a water/soil suspension at a ratio of 2:1 was utilized. The value of EC was calculated using a Jenway Model 4510 digital conductivity meter (U.S. Salinity Lab. Staff, 1954). Soil pH value was measured using a Kent Eil 7015 pH meter [39]. Total nitrogen (TN), available potassium (K), available phosphorus (P), and SOM (soil organic matte) were observed through the process reported by Bremner and Mulvaney [40], Walkley and Black [41], Olsen and Sommers [42], and Helmke and Sparks [43], respectively. Microbial colonies were assessed on agar plates through spiral plating of sequential dilutions of every soil sample. The total amount of culturable bacteria was estimated on half-strength R2A agar plates [44–46], and all of the fungi that were culturable were coated with dextrose agar of bengal rose potato [47]. Clonal population tests were conducted after 48 h of cultivation.

The activity of dehydrogenase was examined as defined by Min et al. [48]. A total of 5 g of soil was inoculated at 37 °C for 12 h in 5 mL of 2, 3, 5-triphenyl-tetrazolium chloride (TTC) solution (pH 7.4, 5 g TTC in 0.20 M Tris HCl buffer). Immediately after incubation, two drops of concentrated H_2SO_4 were applied to bring an end to the reaction. The samples were again combined with 5 mL of toluene and stirred for 30 min, followed by centrifuging for 5 min at 2268 x g to extract triphenylformazan (TPF). The optical density of the supernatant red-color extract was calculated at 492 nm through the use of an ultraviolet–visible (UV-Vis) spectrophotometer (UV-1201, Shimadzu Corp, Japan). The activity of soil dehydrogenase was described in µg TPF g^{-1} 12 h^{-1}. The activity of alkaline phosphatase was calculated spectrophotometrically as defined in Tabatabai and Bremner [49]. One gram of soil was mixed in a 50 mL Erlenmeyer flask and processed with 1 mL p-nitrophenol phosphate, 4 mL modified universal buffer (MUB) (pH 11), and 0.25 mL toluene solution in the same buffer. Then, the contents of the flask were blended and incubated at 37 °C for 1 h. A total of 4 mL of NaOH

(0.5 M) and 1 mL of $CaCl_2$ (0.5 M) were added into the flask after 1 h of incubation. The colored soil suspended solution was filtered by using Watmann No. 2, and the filtrate absorbance was calculated at 400 nm. The activity of phosphatase was represented as μg p-nitrophenol g^{-1} h^{-1}. The standard protocols were adopted for calculating the data of yield components, i.e., number of pods $plant^{-1}$, number of seeds pod^{-1}, yield kg/ha, and weight of 1000 seeds (g). The numbers of seeds from the 10 randomly picked plants were calculated and the average numbers of pods per plant were taken. Ten pods were randomly selected to decide the actual number of seeds per pod. The average number of seeds pod^{-1} was determined. A total of 1000 seeds were obtained from each plot and weighed. Two samples of one square meter were each taken randomly from the middle of each plot. Plants were threshed periodically; the product of each plot was recorded and converted to kg/ha. Net benefits were calculated by subtracting the total variable cost from the total benefits of each treatment combination. Input and output costs for each treatment combination were converted into Rs ha^{-1} [50]. Statistical assessment of the results was done using Statistix 8.1 (Analytical Computer Software, Statistix 8.1; Tallahassee, FL, USA, 1985–2003) utilizing RCBD with a factorial arrangement by choosing year as a factor. An LSD test (Least Significance Difference test) at 5% probability was applied to compare the means of all treatments [51].

3. Results

3.1. Physical and Chemical Indicators of Soil Health

At the end of the experiment, the physical indicators of soil health, like bulk density and soil porosity, were considerably different among different allelopathic weed control techniques (Table 2). The impact of the year was statistically significant as well for soil physical indicators, but the physical phenomenon (year×allelopathic weed management techniques) was not significant (Table 2). In the situation of chemical indicators of soil health like N (nitrogen), EC (electrical conductivity), P (phosphorus), pH, K (potassium), and SOM (soil organic matter), they significantly differed among different allelopathic weed control techniques (Table 2). The effect of year was significant as well for all soil chemical indicators, except available K. The relationship (year×allelopathic weed control strategy) was statistically significant for available P, N, and SOM. However, for available K, soil EC, and pH, the connection was not significant (Table 2).

The minimum bulk density and highest soil porosity in contrast to the control were observed in treatments when brassica residues were added at the rate of 6 t/ha, while the least bulk density and highest soil porosity were observed in the second year of research (Table 2). In the context of SOM, N, and available P, the highest values in contrast to the control were observed during the second year when brassica residues were added at the rate of 6 t/ha. Over all allelopathic weed control methods, the statistically highest soil EC and available K values were obtained with the application of brassica residues at the rate of 6 t/ha. The statistically lowest numbers for all parametric factors presented above were observed in the control, which was statistically the same as with brassica water extracts at the rate of 10 and 20 L/ha (Table 2). It was observed that there is a linear growth in available K and soil EC over the entire time period, and the indicators (available K and soil EC) had maximum values in the second year of study (Table 2). In the context of soil pH, a decreasing trend was observed. The lowest soil pH was observed with the application of brassica residues at the rate of 6 t/ha, and the maximum level of soil pH was observed in the control, which was statistically the same as with brassica water extract at the rate of 10 and 20 L/ha (Table 2).

Table 2. Effect of brassica (*Brassica compestris* L.) water extracts and residues on soil conditions and nutrient distributions in the mung bean rhizosphere during harvesting.

Treatment	2014	2015	Mean Treatment (T)	2014	2015	Mean Treatment (T)
	Soil bulk density (g/cm^3)			Total soil porosity (%)		
[a]Control	1.48	1.47	1.47 A	42.82	44.06	43.44 C
[b]BWE 10 L/ha	1.47	1.47	1.47 A	43.52	44.10	43.81 C
BWE 20 L/ha	1.48	1.47	1.47 A	43.83	44.12	43.97 C
[c]BR 4 t/ha	1.45	1.34	1.41 B	45.40	46.99	46.19 B
BR 6 t/ha	1.42	1.28	1.34 C	45.96	48.51	47.23 A
Mean Year (Y)	1.46 A	1.40 B		44.30 B	45.56 A	
LSD ($p \leq 0.05$)		T = 0.06; Y = 0.04			T = 1.02; Y = 0.77	
	Soil pH			Soil [d]EC (dS/m)		
Control	7.77	7.74	7.76 A	1.07	1.10	1.09 C
BWE 10 L/ha	7.77	7.73	7.75 A	1.09	1.13	1.11 C
BWE 20 L/ha	7.77	7.73	7.75 A	1.11	1.14	1.12 C
BR 4 t/ha	7.49	7.46	7.48 B	1.19	1.24	1.21 B
BR 6 t/ha	7.46	7.26	7.36 C	1.29	1.32	1.30 A
Mean (Y)	7.65 A	7.58 B		1.15 B	1.19 A	
LSD ($p \leq 0.05$)		T = 0.09; Y = 0.06			T = 0.05; Y = 0.03	
	Total soil organic matter (%)			Total soil nitrogen (g/kg)		
Control	0.68 d	0.69 d	0.68 C	0.19	0.20	0.19 C
BWE 10 L/ha	0.67 d	0.69 d	0.68 C	0.20	0.20	0.20 C
BWE 20 L/ha	0.68 d	0.70 d	0.69 C	0.20	0.20	0.20 C
BR 4 t/ha	0.89 c	1.18 ab	1.03 B	0.28	0.33	0.30 B
BR 6 t/ha	1.04 b	1.26 a	1.15 A	0.30	0.38	0.34 A
Mean (Y)	0.80 B	0.91 A		0.23	0.26	
LSD ($p \leq 0.05$)		T = 0.11; Y = 0.07; T×Y = 0.15			T = 0.03	
	Available potassium (mg/kg)			Available phosphorous (mg/kg)		
Control	118.38	121.95	119.59 C	6.72 d	6.75 d	6.73 C
BWE 10 L/ha	119.55	120.66	120.66 C	6.75 d	6.76 d	6.76 C
BWE 20 L/ha	119.52	121.00	120.76 C	6.77 d	6.78 d	6.77 C
BR 4 t/ha	170.35	181.47	175.95 B	7.93 c	9.09 b	8.51 B
BR 6 t/ha	183.33	198.33	190.85 A	9.09 b	10.12 a	9.60 A
Mean (Y)	142.22	148.48		7.45 B	7.89 A	
LSD ($p \leq 0.05$)		T = 12.44			T = 0.39; Y = 0.25; T×Y = 0.56	

In Table 2, any two means within a column followed by the same letter are not significantly different at $p \leq 0.05$ according to the least significant difference (LSD) test; the figures of primary interaction and effects without lettering do not vary significantly ($p \leq 0.05$) according to the least significant difference test; [a]Control = plots with no extract application or crop residues; [b]BWE = brassica water extract; [c]BR = brassica residues; [d]EC = electrical conductivity.

3.2. Microbiological and Biochemical Indicators of Soil Health

Microbiological and biochemical indicators are also useful indicators of soil health. They are more sensitive than chemical and physical qualities to environmental changes. Microbiological indicators, such as population of bacteria and fungi twenty days after sowing and harvest, varied greatly among several allelopathic weed control practices (Table 3). The effect of the year was still significant for all variables. The integrated effect of year and allelopathic weed control techniques was significant for the colonies of fungi, but non-significant for the bacterial population twenty days after planting and harvesting. Biochemical indicators like soil enzymes (dehydrogenase and alkaline phosphatase) varied significantly among different allelopathic weed management techniques at harvest (Table 3). For all of the above parameters, the effect of the year was also significant. The interactive effect of year and allelopathic weed control approaches was significant for dehydrogenase and alkaline phosphatase activity (Table 3).

Table 3. Effect of brassica (*Brassica compestris* L.) water extracts and residues on microbial population, microbial activity, and soil enzymatic activity in the rhizosphere of mung bean.

Treatment	2014	2015	Mean Treatment (T)	2014	2015	Mean Treatment (T)
	Bacteria (cfu/g × 10^5) 20 [(d)]DAS			Fungi (cfu/g × 10^4) 20 DAS		
[(a)]Control	42	43	43 C	7 d	8 d	7 C
[(b)]BWE 10 L/ha	42	44	43 C	7 d	8 d	8 C
BWE 20 L/ha	44	45	45 C	8 d	9 cd	8 C
[(c)]BR 4 t/ha	55	65	60 B	11 c	15 b	13 B
BR 6 t/ha	67	78	71 A	16 b	20 a	18 A
Mean Year (Y)	50 B	55 A		10 B	12 A	
LSD ($p \leq 0.05$)		T = 9.05; Y = 3.95			T = 1.88; Y = 1.19; T × Y = 2.65	
	Bacteria (cfu/g × 10^5) [(e)]AH			Fungi (cfu/g × 10^4) AH		
Control	19	20	20 C	5 e	6 de	5 D
BWE 10 L/ha	21	21	21 C	6 de	6 de	6 CD
BWE 20 L/ha	21	21	21 C	6 de	8 de	7 C
BR 4 t/ha	30	32	31 B	8 d	13 b	10 B
BR 6 t/ha	33	37	35 A	10 c	16 a	13 A
Mean (Y)	25 B	27 A		7 B	10 A	
LSD ($p \leq 0.05$)		T = 3.21; Y = 1.65			T = 1.47; Y = 0.93; T×Y = 2.08	
	Microbial activity (mg CO_2-C kg^{-1} d^{-1}) 20 DAS			Microbial activity (mg CO_2-C kg^{-1} d^{-1}) AH		
Control	3.58	3.70	3.64 C	2.97	3.12	3.04 C
BWE 10 L/ha	3.61	3.75	3.68 C	3.07	3.15	3.11 C
BWE 20 L/ha	3.65	3.78	3.72 C	3.09	3.18	3.14 C
BR 4 t/ha	4.48	4.75	4.62 B	3.69	3.85	3.77 B
BR 6 t/ha	4.96	5.22	5.09 A	4.08	4.28	4.18 A
Mean (Y)	4.06 B	4.24 A		3.38 B	3.51 A	
LSD ($p \leq 0.05$)		T = 0.45; Y = 0.15			T = 0.31; Y = 0.11	
	Alkaline phosphatase (µg NP/g soil/h)			Dehydrogenase (µg TPF/g soil/h)		
Control	134.77	134.80	134.78 C	20.65 d	22.35 d	21.51 C
BWE 10 L/ha	134.82	134.91	134.86 C	22.16 d	22.67 d	22.42 C
BWE 20 L/ha	135.12	135.18	135.15 C	22.86 d	23.25 d	22.56 C
BR 4 t/ha	159.22	163.35	161.28 B	27.33 c	33.35 b	30.33 B
BR 6 t/ha	175.48	186.44	180.96 A	33.67 b	38.33 a	35.00 A
Mean (Y)	147.88 B	150.94 A		24.74 B	27.99 A	
LSD ($p \leq 0.05$)		T = 6.51; Y = 2.99			T = 2.61; Y = 1.65; T×Y = 3.69	

In Table 3, any two means within a column followed by the same letter are not significantly different at $p \leq 0.05$ according to the least significant difference test; on the other hand, the figures of interaction and main effects without lettering do not vary significantly ($p \leq 0.05$) according to the least significant difference test; [(a)]Control = fields with no crop residues or extract application; [(b)]BWE = brassica water extract; [(c)]BR = brassica residues; [(d)]DAS = days after sowing; [(e)]AH = after harvesting.

The interaction (year×allelopathic weed control techniques) was significant for the fungal population. The highest fungal population was recorded with the application of brassica residues at the rate of 6 t/ha in both phases of the second year of research, i.e., at harvesting and 20 days after sowing. However, the highest bacterial population was recorded with the application of brassica residues at the rate of 6 t/ha in both phases, i.e., at harvesting and twenty days after sowing. The minimum populations of both bacteria and fungi were observed in the control (Table 3). A linear uplift in the population of bacteria twenty days after sowing and at the harvesting stage was observed over time, and the maximum bacterial population was observed during the second year. In the context of soil enzymes, the interactive effect of year and allelopathic weed control techniques reflected a significant effect on the behavior of both enzymes—dehydrogenase and alkaline phosphatase. Maximum value was observed with the application of brassica residues at the rate of 6 t/ha during the second year, which was followed by same treatment in the first year. The lowest value was recorded in the control (Table 3).

3.3. Weed Dynamics

The dominant weed flora of the research site in both years, examined 30 days after sowing of spring-planted mung bean, belong mainly to *Trianthema portulacastrum* L. (horse purslane), which is wide-leaved weed, and *Cyperus rotundus* L. (purple nutsedge), which belongs to sedges. According to this study, purple nutsedge and horse purslane density showed significant differences with several allelopathic weed control strategies (Table 4), but dry weight of purple nutsedge was non-significant. The effect of the year was also significant for all of the above-mentioned parameters of horse purslane, but was non-significant for purple nutsedge (Table 4). The interactive (year and allelopathic weed control strategies) effect on both weeds was non-significant. In the context of dry weight and total weed density, the study showed significant differences with several allelopathic weed control techniques (Table 4). The year effect was significant as well for total weed density, but non-significant in the case of total dry weight. The interaction of the year and allelopathic weed control techniques for total dry weight was non-significant, and was significant for total weed density (Table 4).

Table 4. Effect of brassica (*Brassica compestris* L.) water extracts and residues on weed dynamics in mung bean.

Treatment	2014	2015	Mean Treatment (T)	2014	2015	Mean (T)
	Trianthema portulacastrum density (m^2)			*T. portulacastrum* dry weight (g/m^2)		
[a]Control	164	164	164 A	196	192	194 A
[b]BWE 10 L/ha	160	156	158 A	184	184	184 A
BWE 20 L/ha	144	140	142 B	164	164	164 B
[c]BR 4 t/ha	108	80	94 C	124	96	110 C
BR 6 t/ha	80	64	72 D	88	64	76 D
Mean Year (Y)	131 A	120 B		38 A	35 B	
LSD ($p \leq 0.05$)	T= 14.96; Y= 9.48			T= 19.44; Y= 9.40		
	Cyperus rotundus density (m^2)			*C. rotundus* dry weight (g/m^2)		
Control	40	40	40 A	12	12	12
BWE 10 L/ha	40	40	40 A	8	8	8
BWE 20 L/ha	32	32	32 B	8	8	8
BR 4 t/ha	24	28	26 C	4	4	4
BR 6 t/ha	20	24	22 D	4	4	4
Mean (Y)	31	33		7	7	
LSD ($p \leq 0.05$)	T= 3.36			NS		
	Total weeds density (m^2)			Total weeds dry weight (g per 0.25 m^2)		
Control	229.25 a	231.20 a	230.23 A	226.20	223.32	224.76 A
BWE 10 L/ha	216.76 a	215.72 a	216.24 A	211.00	209.40	210.20 B
BWE 20 L/ha	183.20 b	181.84 b	182.52 B	191.08	188.36	189.72 C
BR 4 t/ha	161.20 b	123.84 c	142.52 C	143.84	116.16	130.00 D
BR 6 t/ha	121.40 c	101.68 c	111.54 D	110.76	85.92	98.34 E
Mean (Y)	182.36 A	170.86 B		176.58 A	164.63 B	
LSD ($p \leq 0.05$)	T= 17.80; Y= 10.24; T×Y= 25.16			T= 13.40; Y= 11.72		

In Table 4, any two means within a column followed by same letter are not significantly different at $p \leq 0.05$ according to the least significant difference test; on the other hand, the figures of interaction and main effects without lettering do not vary significantly ($p \leq 0.05$) according to the least significant difference test; [a]Control = plots with no crop residues or extract application; [b]BWE = brassica water extract; [c]BR = brassica residues.

The lowest horse purslane and purple nutsedge densities were recorded with brassica residues at the rate of 6 t/ha in contrast to the control. The maximum values were determined in the control, which was statistically the same as with brassica water extracts at the rate of 10 L/ha (Table 4). Horse purslane dry weight and density were reduced over time, and the lowest values were observed during the second year (Table 4). The interactive effect of the year, total density of weeds, and allelopathic weed control techniques had statistically significant results. The minimum total density of weeds was found with brassica residues at the rate of 6 t/ha during second year, as compared to the control (Table 4). The lowest total weed dry weight was noted with brassica residues at the rate of 6 t/ha, and the highest total density of weeds was reported in the control (Table 4).

3.4. Yield Components

Yield and yield parameters, such as the weight of 1000 seeds, the number of seeds per pod, and the number of pods per plant, varied significantly among the different allelopathic weed control techniques (Table 5). Similarly, the effect of the year was significant across all yield parameters, with the exception of the 1000 seed weight. For yield, the relationship between year and allelopathic weed control techniques was significant (Table 5). Moreover, the relation was not significant for the weight of 1000 seeds, the number of seeds per pod, or the number of pods per plant (Table 5).

Table 5. Effect of brassica (*Brassica compestris* L.) water extracts and residues on yield and yield components of mung bean.

Treatment	2014	2015	Mean Treatment (T)	2014	2015	Mean Treatment (T)
	Number of pods per plant			Number of seed per pod		
[a]Control	14.03	15.17	14.60 E	5.29	6.17	5.73 D
[b]BWE 10 L/ha	16.92	18.18	17.55 D	6.35	7.03	6.69 C
BWE 20 L/ha	17.67	21.27	19.47 C	6.55	7.18	6.87 BC
[c]BR 4 t/ha	19.29	22.74	21.01 B	7.04	7.68	7.36 B
BR 6 t/ha	21.25	23.03	22.14 A	9.14	9.56	9.35 A
Mean Year (Y)	17.83 B	20.08 A		6.87 B	7.53 A	
LSD ($p \leq 0.05$)	T= 1.08; Y= 0.68			T= 0.51; Y= 0.32		
	Weight of 1000 seeds (g)			Yield (kg/ha)		
Control	50.14	50.26	50.20 D	743.2 f	773.9 e	758.5 E
BWE 10 L/ha	52.28	53.19	52.74 C	785.1 de	795.9 d	790.5 D
BWE 20 L/ha	53.06	53.26	53.16 B	842.0 c	852.7 c	847.4 C
BR 4 t/ha	53.66	53.70	53.68 B	923.6 b	924.9 b	924.3 B
BR 6 t/ha	54.29	55.38	54.84 A	1005.0 a	1009.7 a	1007.3 A
Mean (Y)	52.69	53.16		859.78 B	871.41 A	
LSD ($p \leq 0.05$)	T= 0.53			T= 8.53; Y= 5.40; T×Y= 12.07		

In Table 5, any two means within a column followed by same letter are not significantly different at $p \leq 0.05$ by the least significant difference test; Same as, the figures of main interaction and effects without lettering, does not vary significantly ($p \leq 0.05$) by the least significant difference test; [a]Control= (fields with no crop residues or extract application); [b]BWE= brassica water extract; [c]BR= brassica residues.

The results showed that the highest yield was noted with brassica residues at the rate of 6 t/ha during the second year as compared to the control (Table 5). Between the allelopathic weed control techniques, the highest values of weight of 1000 seeds, number of seeds per pod, and number of pods for each plant were recorded with brassica residues at the rate of 6 t/ha. The lowest values of weight of 1000 seeds, number of seeds per pod, and number of pods per plant were observed in the control (Table 5). A linear increase in the number of seeds per pod and number of pods per plant—but not the weight of 1000 seeds—was noted over time, and all of the above observations had significant increases in values during the second year of study (Table 5).

4. Discussion

Incorporation of residues of allelopathic crops is an alternative and cost-effective method to reduce weed pressure in field crops, and it also acts as a green concept for improving the physical, chemical, and biological qualities of soil health [33]. Our study showed a significant improvement in soil health and the weed suppression potential of incorporation of brassica residues and water extracts. This approach led to a considerable decrease in dry weight and weed density of weed varieties in mung bean (Table 4) due to the existence of isothiocyanates, isothayanates, isoprenoids, and benzenoids with a broad range of biological mechanisms, including allelopathy [52–54]. The Brassicaceae family produces GSLs (glucosinolates), which are biologically inactive. When plant tissue is damaged, GSLs are hydrolyzed to a variety of products. Isothiocianates (ITCs) are phytotoxic and produced as the main breakdown products [52]. Presence of glucosinolates in brassica species makes them strongly allelopathic crops [55]. The herbicidal mechanism of five liquid ITCs (isothiocyanates) (m-tolyl, o-tolyl,

3-fluorophenyl, tert-octyl, and benzoyl) on yellow and purple nutsedge was evaluated, and it was found that all ITCs were more efficient in removing purple nutsedge than yellow nutsedge [56]. The rapeseed (*B. compestris* L. ssp. oleifera DC.) shoot extract and turnip (*B. compestris* sub spp. rapa L.) root extract exhibited inhibition of seed germination of cut-leaf ground cherry (*Physalis angulata* L.) by 58.8% and 54.4%, respectively [57]. Lignans from *B. fruticulosa* showed strong inhibition of germination of *Lactuca sativa* [58]. Narwal et al. [59] stated that some accessions of *B. juncea* and *B. nigra* caused significant reductions of 75–82% at 75 days after germination and 75–98% at harvest (120 days) in the density of weeds, namely *Rumex retroflexus, Avena ludoviciana*, *Melilotus alba, Chenopodium album*, *Cirsium arvense,* and *Phalaris minor*, respectively. Incorporation of rapeseed residues in soil prior to sowing of cotton reduced germination of *Amaranthus retroflexus* and *Amaranthus theopherasti,* while cotton germination remained unaffected; this was probably due to the release of some growth inhibitor substances (phytochemicals) from decomposed rapeseed [26,60].

Our results indicate that the enhanced quantity of crop debris decreased the bulk density and enhanced the total soil porosity throughout the time period (Table 2). Shaver [61] stated that porosity of soil is directly proportional to bulk density; with the increase of soil porosity, the soil bulk density decreases. In the context of soil characteristics, brassica compounds as an allelopathic weed control strategy boosted available P, K, N, and SOM in soil (Table 2). Incorporation of plant residues enhanced the quality of the soil and improved the soil nutrient conditions [62,63]. Moisture persistence is the primary advantage of the incorporation of residues. This is induced through an evaporation of surface water and decline in runoff [64]. Increased availability of moisture due to the incorporation of residues also showed that soil water-holding ability was increased, and salinity was available for extended periods to sustain plant development [65]. This rise in moisture-retaining characteristics could reduce the irrigation requirements for crops, which should be studied in future research. The improvement in accumulation of nutrients (especially K and P) could be linked to an increase in soil moisture retention due to the incorporation of residues, which improved the bioavailability of these minerals in the soil [66,67]. The crop residue rectification also maximizes N accessibility in soil and can reduce the fertilizer usage in soil [68]. Sharma et al. [69] also reported a massive increase in the available phosphorus and nitrogen levels of soil with the application of crop residues. In our research, a linear drop in soil pH was observed through the use of brassica debris as an allelopathic weed control technique (Table 2). Gong et al. [70] indicated that the inclusion of oil crop residues in soil decreases the pH of the soil. *Parthenium hysterophorus* residues in soil have modified soil chemistry. It has been revealed that use of *P. hysterophorus* in soil reduced the pH, while the EC of the soil was improved [71,72].

Concerning enzymatic activities and microbial populations of soil as a result of using brassica debris as an allelopathic weed control technique in mung bean, the results showed significant improvement (Table 3). Soil enzymes and microbial abundance are biological events of soil that are the most significant measures of quality of soil [73]. The inclusion of residues of various crops changed biochemical characteristics, e.g., soil enzymatic activity and soil microbial population [74–76]. Soil enzyme actions can also be utilized as significant parameters of fertility management and cycling processes of nutrients, especially in long-term conventional and organic farming practices [77]. Dehydrogenase is essential for SOM (soil organic matter) oxidation. This shifts electrons and hydrogen from substrates to acceptors. Regulation of the soil enzymes phosphatase and dehydrogenase depends on the form of crop debris incorporated in the soil, and also relies on the soil temperature and moisture content. They influence dehydrogenase activity by altering the soil oxidation and reduction status [78,79]. Induction of tobacco crop residues in soil enhanced the activity of phosphodiesterase and amylase. In Akola, Maharashtra, Ravankar et al. [80] stated that soil incubation with a mixture of 1% xanthium organic residues, a grass complex with seeds, sunflower straw, parthenium with seeds, green gram stover, ground nut husk, sugarcane trash, safflower straw, wheat straw, soybean stover, sorghum stubble, and cotton stalks with seeds exhibited broad changes in the microbial population rate, C:N ratio, and decomposition at various intervals. Actinomycete, bacterial, and fungal populations were maximized at an incubation of 30 days. Bacteria predominated over fungi and actinomycetes.

The various allelopathic weed management strategies utilized in this research had major effects on yield of the crops. This increase in crop yield can be attributed to the suppression of weeds in the significant growth phase of the crop and the transformation of soil health. Plant extracts obtained from different crop residues influence crop growth and yield [81]. Effective weed resistance often increases the resource availability, including nutrients, water, space, and light [82]. A new research on wheat residue addition in the Mediterranean geographic region by Stagnari et al. [83] determined that, particularly along the crucial growth cycle of the test crop, the soil moisture retention capability was enhanced. Residues that are fully decomposed in soil not only have allelochemistry, but are also part of crop nutrition. They provide nitrogen through liberation in the rhizosphere of the tested crop. By applying plant debris as a biological weed control, they incapacitate nitrogen, which can reduce the immediate nitrogen input [84]. It was found that decomposed residues of rapeseed release secondary metabolites, which significantly suppress the growth of weeds, reducing weed crop competition and enhancing the crop yield [85]. However, in the next phases of crop production, the abundance of nitrogen was increased by mineralization, which ensures that this sustained nitrogen supply is a steady source of nutrients for test crops as well as for other crops.

So, brassica residue induction improved soil properties, viz. moisture sustainability, restored physical properties, and enhanced microbial activity and nutrient cycling [86–88]. It also suppressed weeds due to physical difficulty, reduction of the possibility of light entrance, and the suppressive ability of allelochemicals that were released from this plant debris [89,90]. Due to all of the above activities, the spring-planted mung bean crop resulted in a better yield of seeds and achieved maximum profitability (Table 6).

Table 6. Economics of mung bean cultivated using different allelopathic weed control techniques during 2014 and 2015.

Treatments	Yield (kg/ha)	Adjusted Yield (kg/ha)	Gross Income [e]$/ha	Total Cost $/ha	Net Benefits $/ha	Benefit Cost Ratio
[a]Control	759	683	765	615	150	0.24
[b]BWE 10 L/ha	791	712	797	624	173	0.28
BWE 20 L/ha	847	762	854	625	228	0.36
[c]BR 4 t/ha	924	832	931	653	278	0.43
BR 6 t/ha	1007	906	1015	668	347	0.52
Remarks	$ 44.67/40 kg	10% less than actual				1$ = 98.5 [d]PKR

[a]Control = fields with no extract application or crop residues; [b]BWE = brassica water extract; [c]BR = brassica residues; [d]PKR = Pakistani rupees; [e]$ = US dollar.

5. Conclusions

Herbicides have harmful effects on plants and soil microorganisms due to their direct mode of action on the soil surface. The allelopathy of the brassica crop had a significant impact on weeds and soil health. A high suppression of dry weight and weed density was observed when brassica residues were added to soil at the rate of 6 t/ha. Evidently, the soil properties were favorably influenced by the residues; these included soil enzyme development, microbial populations, and nutrient dynamics, which ultimately resulted in the highest economic return, improvement of soil structures and weed suppression, better harvesting of the seed yield, and increased productivity in the spring-planted mung bean. With its major improvement in soil properties, this approach can provide a potential alternative for sustainable weed management for spring-planted mung beans. Future studies would research the interactions of micronutrients in soil under multiple allelopathic weed management techniques in the field. In addition, N and weed control under various allelopathic approaches still remain germane problems to be examined. At the same time, these results might vary in different climatic and soil conditions.

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