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The Impact of Different Crop Rotations by Weed Management Strategies' Interactions on Weed Infestation and Productivity of Wheat (*Triticum aestivum* L.)

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Citation: Shahzad, M.; Hussain, M.; Jabran, K.; Farooq, M.; Farooq, S.; Gašparovič, K.; Barboricova, M.; Aljuaid, B.S.; El-Shehawi, A.M.; Zuan, A.T.K. The Impact of Different Crop Rotations by Weed Management Strategies' Interactions on Weed Infestation and Productivity of Wheat (*Triticum aestivum* L.). *Agronomy* **2021**, *11*, 2088. https://doi.org/10.3390/agronomy11102088

Academic Editor: Aritz Royo-Esnal

Received: 12 September 2021
Accepted: 16 October 2021
Published: 19 October 2021

Abstract: Weed infestations significantly reduce the growth and yield of field crops. Herbicides are mostly used for weed management due to their quick results. However, resistant biotypes to available herbicides are rapidly increasing around the word. This situation calls for the development of alternative weed management strategies. Crop rotation and allelopathic water extracts are regarded as the most important alternative weed management strategies. Therefore, this two-year study assessed the impact of different annual crop rotations by weed management strategies' interactions on weed infestation and productivity of wheat crop. Wheat was planted in five rotations, i.e., (i) fallow-wheat, (ii) rice-wheat, (iii) cotton-wheat, (iv) mungbean-wheat and (v) sorghum-wheat. The weed management strategies included in the study were; (i) false seedbed, (ii) application of 12 L ha^{-1} allelopathic plant water extracts (1:1:1:1 ratio of sorghum, sunflower, mulberry and eucalyptus), (iii) herbicide application, (iv) weed-free (weed control) and (v) weedy-check (no weed control). Herbicide application was the most effective treatment in lowering weed densities and biomass during both years followed by false seedbed, while allelopathic crop water extracts were least effective. The lowest weed infestation was noted in sorghum-wheat rotation followed by cotton-wheat and mungbean-wheat, while fallow-wheat had the highest weed infestation. Weedy-check treatment caused significant reduction in wheat growth and yield, whereas the highest grain yield was recorded from weed-free and herbicide application treatments. Grain yield of wheat planted after sorghum was suppressed; however, yield improved when wheat was planted after mungbean. Planting wheat after mungbean in a weed-free environment, achieved through chemical and/or mechanical means, is the best strategy to obtain higher wheat yields.

Keywords: allelopathy; crop rotation; weeds; weed management; wheat

1. Introduction

Wheat (*Triticum aestivum* L.) is annually grown on 220.4 million hectares (ha), which produce 734 million tons of grains globally [1]. Increasing global population will require more wheat production from the same area under cultivation since agricultural areas are shrinking at an enormous pace [2]. However, wheat production is stagnant due to the use of old cultivars [3], weed infestation [4], abiotic stresses [5,6] and several other reasons in various parts of the world. Rice-wheat and cotton-wheat are the popular annual crop rotations spanning on 60% of the total area under wheat cultivation around the globe [7]. Weeds are among the chief reasons reducing the crop productivity in these cropping systems [4,8].

Wheat is the main agricultural crop of Pakistan and is rotated with different crops, particularly cotton and rice [9]. Therefore, wheat provides income to the population of the country reliant on agriculture and contributes towards the country's economy [10]. A 34% increase is expected in the population of Pakistan by 2050, which would require double the current wheat production. However, wheat yield in Pakistan is lower than in most other countries [6] with 2827 kg/ha on average in the 9 million cultivated hectares [10]. Several biotic and abiotic stresses affect wheat production; however, weed invasion is capable of reducing wheat yields by 40% in Pakistan [11]. Weeds are among the chief reasons reducing the crop productivity in these cropping systems. Therefore, sustainable management of weeds is necessary for higher wheat production.

Weed infestations considerably reduce the growth and yield of arable crops, these losses being higher than those produced by pests and diseases [12]. Overall, weeds are considered as most damaging pest of wheat crop causing 24% yield losses [13,14]. A recent study indicated that black grass (*Alopecurus myosuroides* Huds.) infestation in winter wheat reduced grain yield by 3 t ha^{-1} in Germany [15]. The yield losses due to weed infestations in wheat crop may reach up to 50% in Pakistan [16]. Therefore, sustainable weed management strategy will be a key factor in increasing wheat yield [13,17]. Chemical weed control is the most effective weed management strategy [18]. Higher crop productivity in modern agriculture is indebted to the use of herbicides [19]. However, their excessive use has provoked the evolution of herbicide-resistant biotypes [20–22]. Therefore, a recent study has stressed on the need to integrate conventional and modern weed management practices and molecular biology to manage herbicide resistance in weeds [23].

Lowering or shifting weed-crop competition in the favor of crop plants is the prime objective of all weed management strategies [4,8,24]. Crop rotation and allelopathy are capable of shifting competition towards crop plants by suppressing weeds; thus, they are adopted for weed management in different crops [25–28]. Adopting a suitable crop rotation can help in reducing weed infestation [29–33]. For instance, the number of weed seeds was about six times greater in a continuous mono-cropping system than in a rotated system [34]. Thus, crop rotation can be used as an effective ecological weed management approach [8,35,36]. Nevertheless, the crops included in the rotation could exert negative impacts on the growth and yield of the crops following them in rotation in long run [37].

The evolution of herbicide resistance in weeds has increased the importance of alternative and environment-friendly weed management strategies such as allelopathy and false seedbed preparation [26,28,38,39]. False seedbed allows the emergence of weed seedlings that can be killed before planting [28]. Allelopathy is an eco-friendly weed management approach successfully implemented in different crops for reducing weed infestations [26,27,40,41]. Popular allelopathic crops include sorghum, eucalyptus, mulberry and sunflower, and water extracts obtained from different parts of these crops significantly reduced weed infestation [4,26,39,41–44]. Phenolics and sorgoleone in sorghum, terpenes and phenolic compounds in sunflower and steroids, phenols and tannins in mulberry are responsible for weed suppression [38,43,45,46].

Zeller et al. [15] reported that rotation wheat with spring crops reduced black grass density up to 99%. Similarly, rotating herbicides with different modes of action also reduced the density of blackgrass by 23–99% compared to the same mode of action herbicides.

Likewise, a 70% reduction in blackgrass density was noted with false seedbed. A significant reduction in weed density has been noted by maize-winter wheat rotation [47]. Crop rotation combined with half of the recommended dose of herbicides provided 99% control over weeds in maize crop [47]. MacLaren et al. [48] investigated the interactive impact of crop rotation and tillage systems on weed infestation in wheat and reported that crop rotation with reduced tillage lowered weed infestation, whereas crop interaction by zero tillage interaction was unable to reduce weed density. Shahzad et al. [49] recently reported that false seed bed and sorghum-wheat rotation decreased weed density in wheat crop and recommended long term studies for inferring the impacts of both on wheat-based cropping systems.

Previously, the effect of crop rotations [29,30], herbicides or allelopathy has been investigated intensively for weed management in different crops, including wheat [50]. However, an interaction of crop rotation with allelopathic water extracts or herbicides for weed control in wheat has been rarely tested [15]. This two-year field study evaluated the impact of different crop rotations, allelopathic water extract and herbicide application on weed management and productivity of wheat crop. Determining the impact of different crop rotations and weed management strategies on weed infestations was the major objective of the study. It was hypothesized that different crop rotations and weed management strategies will differ in weed infestation and productivity of wheat crop. The results would help to improve weed management and crop productivity through the selection of the most suitable crop rotation and weed management approach.

2. Materials and Methods

2.1. Experimental Site and Soil

This two-year field study was conducted at the Research Farm, Department of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan (71.43° E, 30.2° N and 122 m asl), Pakistan during 2012–2013 and 2013–2014. The experimental soil was silty clay in texture. Before sowing, soil samples were collected and analyzed to determine the physicochemical properties. The samples were air-dried and passed through a 2 mm sieve. The Walkley and Black method [51] was followed to determine organic matter content. Hydrometer method in a sedimentation cylinder using sodium hexametaphosphate as the dispersing agent was used to determine particle size distribution [52]. The pH and electrical conductivity (EC) were measured in a saturated soil paste [53]. Total phosphorus (P) and potassium (K) were analyzed by following Olsen [54] and Carson [55], respectively. Total nitrogen in the soil was determined by the Kjeldahl method [56]. The soil's physico-chemical properties during two growing seasons are given in Table 1. The soil was hyperthermic, sodic haplocambids/Haplic Yermosols according to USDA and FAO classification, respectively. The weather data at the experimental site during the experimental period are given in Table 2. The study area is in the northern irrigated plains of Pakistan and lies in the semi-arid zone of the country. The water requirements of the crops are fulfilled by irrigation using canal water or ground water pumped through tube wells.

2.2. Experimental Details

Wheat was planted in a field vacated by rice (RW), cotton (CW), mungbean (MW), sorghum (SW) or fallow (FW). The experimental field had been under rice-wheat rotation for the last 5 years. The rotations opted in this study were opted in 2011–2012 to initiate the experiment. Wheat and the crop in rotations were cultivated in 2011–2012 to have the impacts of rotation initiated. Therefore, the experimental field had been under the same rotations since the previous year. Weed management strategies included in the study were false seedbed (plowing 15 cm depth), application of allelopathic water extracts and chemical weed control through herbicides. Weed-free and weedy-check were maintained as controls. Weed-free plots were hand weeded, while weeds were allowed to grow freely in the weedy-check treatment. For false seedbed, plots were plowed one week before sowing and at the time of sowing. In chemical weed control, bromoxynil + MCPA (Bromox 40EC; 200 g L^{-1} bromoxynil + 200 g L^{-1} MCPA) was applied (at 1.25 L ha^{-1}: 500 g a.i. ha^{-1}) after the 1st irrigation (35 days after sowing of wheat crop). In the allelopathic water extracts treatment, the water extracts of eucalyptus, sunflower, mulberry and sorghum were mixed thoroughly in a 1:1:1:1 ratio and sprayed at 12 L ha^{-1} after first irrigation (35 days after wheat sowing). The herbicides and allelopathic extracts were applied by a Knapsack hand sprayer with a 4T-jet nozzle at 10:00 a.m. in the direction of wind (1.8 km/h), keeping an operating pressure of 172.36 KPa. Per hectare, 250 L of water as carrier volume was used for spraying herbicides and allelopathic water extracts. For the preparation of allelopathic water extracts, leaves and branches of the plants were prepared according to Cheema et al. [57]. Briefly, the leaves and branches were collected, chaffed into pieces and dried under sun. The dried materials were then soaked in distilled water (1:20 ratio) separately for 24 h. The solutions were filtered after 24 h to obtain the extracts. The resulting extracts were then mixed in a 1:1:1:1 ratio, diluted by 10 times and sprayed.

Table 1. Soil physico-chemical properties of experimental location.

Soil Properties	Year	
	2012–2013	2013–2014
Physical Analysis		
Sand (%)	27.0	26.0
Silt (%)	53.0	54.0
Clay (%)	20.0	20.0
Textural class	Silty clay	
Chemical Analysis		
pH	8.35	8.42
EC (dS m^{-1})	3.29	3.31
Organic matter (%)	0.54	0.59
Total nitrogen (%)	0.03	0.03
Available phosphorus (ppm)	8.87	8.75
Available potassium (ppm)	180	195

Table 2. Weather data at the experimental station during both experimental years (2012–2013 and 2013–2014).

Weather Element	Years	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Mean temp(°C)	2012–2013	33.0	34.0	33.0	32.0	29.0	25.0	20.0	15.0	12.0	16.0	22.0	27.0
	2013–2014	33.0	34.0	34.0	32.0	30.0	28.0	20.0	15.0	13.0	15.0	20.0	26.0
Relative humidity (%)	2012–2013	56.0	61.0	67.0	74.0	83.0	72.0	84.1	83.0	80.0	87.0	76.0	61.0
	2013–2014	55.0	68.0	64.0	72.0	72.0	71.0	79.0	82.0	79.0	82.0	74.0	58.0
Sunshine (hours)	2012–2013	8.5	8.2	7.8	7.0	7.0	8.3	6.1	6.1	5.6	5.7	8.0	7.7
	2013–2014	9.8	8.2	7.9	7.1	8.7	7.1	5.7	4.9	5.5	6.4	7.0	6.3
Rainfall (mm)	2012–2013	1.0	0.0	17.0	11.0	167	3.0	0.0	4.0	0.0	73.0	17.0	1.0
	2013–2014	0.0	51.0	17.0	74.0	0.0	0.0	0.0	0.0	0.0	18.0	33.0	7.0

The experiment was laid out according to a factorial design where crop and weed management strategies were main and sub-factor, respectively. The size of each treatment plot was 15 m^2 (3 m × 5 m) and each treatment had three replications. There were 75 treatment plots (5 crop rotations × 5 weed management strategies × 3 replications) and total area of the experimental area was 1125 m^2.

2.3. Crop Management

During each season, pre-soaking irrigation of 10 cm was given to the experimental fields before seedbed preparation. When the soil reached a workable moisture level, seedbeds were prepared according to each treatment. All crops were irrigated according to their moisture needs to avoid the impacts of water stress. The crops were harvested at maturity. All other agronomic and cultural activities were kept uniform (recommended by the agriculture extension department of the experimental site) to control insect pests and diseases. Details of crops' management are included in Table 3.

Table 3. Details of crop management practices used, for different crops, in the study.

Crops	Sowing Date	Cultivar	Seed Rate (kg ha^{-1})	Fertilizer NPK (kg ha^{-1})	* P-P (cm)	** R-R (cm)	Harvesting Time
Year 2012–13							
Cotton	15 May 2012	MNH-885 (Bt)	25	250-200-0	20	75	30 October 2012 (Last picking)
Sorghum	15 June 2012	JS-2002	10	100-60-0	15	60	30 October 2012
Mungbean	15 June 2012	AZRI-Mung 2006	20	20-60-0	10	30	30 September 2012
Rice i. Nursery ii. Transplanting ***	25 May 2012 25 June 2012	Basmati-2000	0.5 kg per 25 m^2 125 m^2 nursery ha^{-1}	- 150-85-67	- 22.5	- 22.5	30 October 2012
Wheat	15 November 2012	Punjab-2011	125	150-100-0	-	25	15 April 2013
Year 2013–14							
Cotton	10 May 2013	MNH-885 (Bt)	25	250-200-0	20	75	30 October 2013 (Last picking)
Sorghum	11 June 2013	JS-2002	10	100-60-0	15	60	28 October 2013
Mungbean	11 June 2013	AZRI-Mung 2006	20	20-60-0	10	30	28 September 2013
Rice i. Nursery ii. Transplanting	25 May 2013 25 June 2013	Basmati-2000	0.5 kg per 25 m^2 125 m^2 nursery ha^{-1}	- 150-85-67	- 22.5	- 22.5	25 October 2013
Wheat	16 November 2013	Punjab-2011	125	150-100-0	-	25	20 April 2014

* P-P = Plant–plant distance; ** R-R = Row–row distance, *** rice was sown by transplanting. Rice nursery was raised first and then transplanted in the field.

2.4. Field Measurements

2.4.1. Weed Density and Dry Weight

Data relating to weed density and dry weight were recorded at 45 days after sowing (DAS) of wheat crop from each treatment. Three one-square meter quadrats were randomly placed in each plot for sampling weed density. All weed plants falling within the quadrat were uprooted, washed thoroughly, oven-dried at 72 °C (for 48 h) and weighed on an electronic balance to record dry weight. The plants from each quadrat were dried and weighed separately and then averaged to record dry weight of the corresponding replication. The percentage of reduction in weed density and biomass was computed for false seedbed, allelopathic water extracts and chemical control compared to the weedy check treatment of the study. Equations (1) and (2) were used to compute percent reduction in weed density and biomass, respectively.

$$\text{Reduction in weed density } (\%) = \frac{\left(D_{treatment} - D_{weedy-check}\right)}{D_{weedy-check}} \times 100 \quad (1)$$

Here; $D_{treatment}$ = weed density in different weed management strategies except weed-free and weedy check and $D_{weedy\text{-}check}$ is weed density in weedy-check treatment

$$\text{Reduction in weed biomass } (\%) = \frac{\left(B_{treatment} - B_{weedy-check}\right)}{B_{weedy-check}} \times 100 \quad (2)$$

Here; $B_{treatment}$ = weed biomass in different weed management strategies except weed-free and weedy check and $B_{weedy\text{-}check}$ is weed biomass in weedy-check treatment

2.4.2. Yield-Related Traits and Yield of Wheat

Twenty randomly selected spikes from each treatment were harvested to record number of grains per spike. At maturity, all wheat plants in each plot were harvested and sun-dried. The sun-dried samples were threshed manually and grain yield per plot was recorded. Five samples, each of 1000 grains, taken from each treatment were weighed to record 1000-grain weight. Moisture content of grains was recorded by the high-constant temperature oven method. The grain yield was adjusted to a moisture content of 10% and then expressed as t ha^{-1} using the unitary method.

2.5. Statistical Analysis

The collected data on weed density and biomass, growth traits, grain yield and related parameters of both years were analyzed with multifactor analysis of variance (ANOVA). Because weed density and biomass data showed non-normal distribution, these were previously arcsine transformed. Three-way ANOVA was used to test the significance in weed density and biomass, and yield-related traits of wheat (year × crop rotations × weed management strategies). Least significant difference (LSD) post-hoc test at 5% probability was used to compare the means where ANOVA indicated significant differences. All statistical computations were executed on SPSS statistical software version 19 [58]. Due to significant differences among years, data of both years were presented separately for easier interpretation of the results. Two- or three-way interactions were significant for all measured variables; therefore, only interactions were presented and interpreted. Graphical presentation of the data was done by Microsoft Excel program version 2010.

2.6. Economic Analysis

An economic analysis was conducted to compute the profitability of different crop rotations by weed management strategies' interactions. The cost for growing of each crop was computed. The expenditures incurred on land rent, land preparation, seeds, fertilizers, irrigation, pesticides, harvesting and labor cost were added to compute the gross income. Net income was computed by subtracting expenditures from gross income. The income in different years was averaged and presented as overall economic returns from each crop rotation by weed management interaction.

3. Results

3.1. Weed Species

Ten weed species infested wheat crop during both years of the study (Table 4). Five species were dicotyledonous (50%), whereas the remaining five were grasses (50%). Poaceae was the most represented family with three species followed by Amaranthaceae with two species. According to life cycle, six species were annual, while remaining four species were perennial in nature (Table 4).

3.2. Weed Density (Plants m^{-2}) and Biomass (g m^{-2})

Interactive effects of years, crop rotations and weed management strategies significantly altered weed density and biomass (Table 5). Rice-wheat crop rotation during the first year and fallow-wheat crop rotation during second year with weedy check treatment recorded the highest weed density, whereas all crop rotations with chemical control recorded the lowest weed density during both years of the study (Table 6). Similarly, rice-wheat and fallow-wheat crop rotations during the first year and fallow-wheat crop rotation during second year with weedy check treatment recorded the highest weed biomass, whereas all crop rotations with chemical control (with some exceptions) recorded the lowest weed biomass during both years of the study (Table 6).

3.3. Percent Reduction in Weed Density and Biomass

Percent reduction in weed density and biomass was significantly affected by interactive effects of years, crop rotations and weed management strategies (Table 5). Fallow-wheat and mungbean-wheat rotations with chemical control during first year and all rotations except sorghum-wheat with chemical control during second year recoded the highest percent reduction in weed density. Sorghum-wheat rotation with allelopathic water extracts recorded the lowest reduction in weed density during both years of study (Table 6). Fallow-wheat rotation during 1st year and all rotation except fallow-wheat during 2nd year with chemical control recorded the highest reduction in weed biomass. The lowest reduction in weed biomass was observed for most of the rotations with allelopathic water extracts (Table 6).

Table 4. Common and Latin names, family and life cycle of different weed species recorded in wheat crop during both years of the study.

Species	Common Name	Family	Life Cycle
	Dicotyledonous weed species		
Chenopodium murale L.	Fat hen	Amaranthaceae	Annual
Melilotus indicus (L.) All.	Yellow sweet clover	Leguminosae	Annual
Rumex obtusifolius L.	Bitter dock	Polygonaceae	Perennial
Spergula arvensis L.	Corn spurry	Caryophyllaceae	Annual
Chenopodium album L.	Common goosefoot	Amaranthaceae	Annual
	Monocotyledonous weed species		
Polypogon monspeliensis L. Desf.	Winter grass	Poaceae	Annual
Cynodon dactylon (L.) Pers.	Bermudagrass	Poaceae	Perennial
Bolboschoenus maritimus (L.) Palla	Salt marsh	Cyperaceae	Perennial
Phalaris minor Retz.	Little seed canarygrass	Poaceae	Annual
Alhagi maurorum Medik.	Camelthorn	Fabaceae	Perennial

Table 5. Analysis of variance of weed density and biomass in wheat crop grown in different crop rotations under different weed management strategies.

Source of Variation	DF	Sum of Squares	Mean Squares	F Value	*p* Value
		Weed density			
Year (Y)	1	14,896.19	14,896.19	3444.14	<0.0001
Crop Rotation (C)	4	50,580.97	12,645.24	2923.70	<0.0001
Weed Management strategies (W)	3	305,630.01	101,876.67	23,554.84	<0.0001
Y × C	4	725.46	181.36	41.93	<0.0001
Y × W	3	9497.54	3165.85	731.97	<0.0001
C × W	12	80,885.85	6740.49	1558.46	<0.0001
Y × C × W	12	4422.64	368.55	85.21	<0.0001
		Weed biomass			
Year (Y)	1	3.52	3.52	102.86	<0.0001
Crop rotation (C)	4	571.88	142.97	4178.79	<0.0001
Weed management strategies (W)	3	4619.16	1539.72	45,003.46	<0.0001
Y × C	4	58.63	14.66	428.44	<0.0001
Y × W	3	29.14	9.71	283.86	<0.0001
C × W	12	814.60	67.88	1984.11	<0.0001
Y × C × W	12	93.74	7.81	228.33	<0.0001
		Percent reduction in weed density			
Year (Y)	1	24.41	24.41	3.45	0.0680
Crop rotation (C)	4	2944.68	736.17	104.17	<0.0001
Weed management strategies (W)	2	14,733.72	7366.86	1042.39	<0.0001
Y × C	4	2165.09	541.27	76.59	<0.0001
Y × W	2	187.48	93.74	13.26	<0.0001
C × W	8	1081.37	135.17	19.13	<0.0001
Y × C × W	8	883.70	110.46	15.63	<0.0001
		Percent reduction in weed biomass			
Year (Y)	1	614.51	614.51	442.52	<0.0001
Crop rotation (C)	4	1519.69	379.92	273.59	<0.0001
Weed management strategies (W)	2	8645.12	4322.56	3112.72	<0.0001
Y × C	4	905.10	226.28	162.94	<0.0001
Y × W	2	758.19	379.10	272.99	<0.0001
C × W	8	2215.23	276.90	199.40	<0.0001
Y × C × W	8	1573.27	196.66	141.62	<0.0001

Table 6. Effect of different crop rotations and weed managing techniques on total weed density (m^{-2}) and biomass (g m^{-2}) and percentage reduction in weed density and biomass in wheat crop.

Crop Rotations	2012–2013					2013–2014				
	Weed Free	Weedy Check	False Seedbed	Chemical Control	Allelopathic Water Extracts	Weed Free	Weedy Check	False Seedbed	Chemical Control	Allelopathic Water Extracts
Weed density (plants m^{-2})										
Fallow-wheat	N/A	235.33 ± 0.33 b	37.00 ± 1.00 j	3.33 ± 0.33 n	56.33 ± 0.33 g	N/A	201.33 ± 2.60 a	28.33 ± 1.45 f	2.67 ± 0.66 jk	40.00 ± 1.52 e
Rice-wheat	N/A	246.00 ± 0.57 a	29.67 ± 1.20 k	10.33 ± 0.88 m	59.33 ±2.60 fg	N/A	162.33 ± 1.20 b	28.00 ± 0.54 f	2.67 ± 0.33 jk	51.67 ± 0.88 d
Cotton-wheat	N/A	114.67 ± 1.66 d	37.67 ± 1.45 j	2.67 ± 0.33 n	46.33 ± 1.45 i	N/A	86.33 ± 3.17 c	17.33 ± 0.33 h	2.67 ± 0.66 jk	23.33 ± 0.88 g
Mungbean-wheat	N/A	126.00 ± 1.00 c	50.33 ± 0.88 h	2.33 ± 0.33 n	60.33 ± 1.76 f	N/A	87.67 ± 0.33 c	14.00 ± 0.57 h	2.33 ± 0.33 jk	27.33 ± 0.33 fg
Sorghum-wheat	N/A	84.67 ± 2.02 e	22.00 ± 1.52 l	2.00 ± 0.57 n	30.00 ± 0.57 k	N/A	15.67 ± 0.33 h	5.67 ± 0.33 ij	2.00 ± 0.57 jk	9.67 ± 0.88 i
LSD value at *p* 0.05			3.83					4.16		
Weed biomass (g m^{-2})										
Fallow-wheat	N/A	22.63 ± 0.58 a	3.67 ± 0.01 g	0.90 ± 0.02 k	6.22 ± 0.05 e	N/A	29.20 ± 0.11 a	5.57 ± 0.02 e	1.27 ± 0.02 i	6.21 ± 0.01 d
Rice-wheat	N/A	22.25 ± 0.14 a	2.15 ± 0.03 j	2.82 ± 0.02 i	3.53 ± 0.03 gh	N/A	22.09 ± 0.06 b	3.71 ± 0.02 f	0.37 ± 0.02 j	4.07 ± 0.05 f
Cotton-wheat	N/A	13.59 ± 0.08 c	4.19 ± 0.03 g	1.04 ± 0.03 k	5.07 ± 0.03 f	N/A	14.87 ± 0.01 c	2.98 ± 0.05 h	0.25 ± 0.02 j	3.17 ± 0.03 gh
Mungbean-wheat	N/A	14.49 ± 0.06 b	2.92 ± 0.03 hi	1.03 ± 0.02 k	9.98 ± 0.06 d	N/A	14.70 ± 0.04 c	3.63 ± 0.05 fg	0.18 ± 0.03 j	3.82 ± 0.01 f
Sorghum-wheat	N/A	9.71 ± 0.03 d	2.03 ± 0.06 j	0.64 ± 0.02 kl	2.38 ± 0.02 ij	N/A	5.32 ± 0.01 e	1.41 ± 0.17 i	0.16 ± 0.01 j	1.34 ± 0.02i
LSD value at *p* 0.05			0.66					0.47		
Percent reduction in weed density										
Fallow-wheat	N/A	N/A	84.28 ± 0.40 d	98.58 ± 1.11 a	76.06 ± 0.24 e	N/A	N/A	85.94 ± 0.53 bc	98.68 ± 0.67 a	80.11 ± 0.37 cd
Rice-wheat	N/A	N/A	87.94 ± 0.14 c	95.80 ± 0.93 b	75.88 ± 1.39 e	N/A	N/A	82.75 ± 0.31 bcd	98.36 ± 1.09 a	68.17 ± 0.33 ef
Cotton-wheat	N/A	N/A	67.17 ± 0.16 f	97.68 ± 0.27 ab	59.61 ± 1.23 h	N/A	N/A	79.84 ± 1.00 d	96.85 ± 0.89 a	72.92 ± 2.91 e
Mungbean-wheat	N/A	N/A	60.05 ± 0.48 h	98.15 ± 0.76 a	52.11 ± 0.62 i	N/A	N/A	84.03 ± 0.40 bcd	97.34 ± 1.17 a	68.82 ± 3.48 ef
Sorghum-wheat	N/A	N/A	74.06 ± 0.34 e	97.67 ± 0.82 ab	64.54 ± 0.85 g	N/A	N/A	65.38 ± 0.20 f	87.36 ± 0.65 b	38.19 ± 5.93 g
LSD value at *p* 0.05						4.34				
Percent reduction in weed biomass										
Fallow-wheat	N/A	N/A	83.95 ± 0.42 f	96.02 ± 0.07 a	72.46 ± 0.15 i	N/A	N/A	80.90 ± 0.16 cde	95.65 ± 0.27 b	78.77 ± 0.20 e
Rice-wheat	N/A	N/A	90.32 ± 0.12 d	87.31 ± 0.07 e	84.12 ± 0.40 f	N/A	N/A	83.20 ± 0.08 c	98.31 ± 0.36 a	81.56 ± 0.12 cd
Cotton-wheat	N/A	N/A	69.19 ± 0.72 j	92.37 ± 0.27 c	62.73 ± 0.62 k	N/A	N/A	79.96 ± 0.09 de	98.30 ± 0.14 a	78.71 ± 3.39 e
Mungbean-wheat	N/A	N/A	79.85 ± 0.10 g	92.89 ± 0.33 bc	31.17 ± 0.24 l	N/A	N/A	75.31 ± 0.12 f	98.79 ± 0.18 a	73.99 ± 0.19 f
Sorghum-wheat	N/A	N/A	79.03 ± 0.05 g	93.34 ± 0.21 b	75.50 ± 0.10 h	N/A	N/A	73.53 ± 0.08 f	96.98 ± 0.34 ab	74.67 ± 0.44 f
LSD value at *p* 0.05						1.92				

Different letters denote significant differences at $p < 0.05$.—indicates that computation was not possible for the respective treatment either due to absence of weed species or due to comparison of other treatments with the treatment denoted by N/A.

3.4. Yield Parameters and Grain Yield (t ha^{-1})

Yield related parameters and grain yield of wheat crop was significantly affected by interactive effects of years, crop rotations and weed management strategies with some exceptions (Table 7). Fallow-wheat rotation with weed-free treatment during the first year and rice-wheat rotation during the second year recorded the highest number of grains per spike. Sorghum–wheat rotation with weedy-check treatment recorded the lowest number of grains per spike during both years. Rice-wheat rotation during the first year and mungbean-rotation during the second year under a weed-free environment produced the heaviest 1000-grains, whereas sorghum–wheat rotation with weedy-check treatment recorded the lightest 1000-grains during both years. Cotton-wheat and rice–wheat rotations with weed-free treatment during first year and rice-wheat and mungbean-wheat rotations under weed-free environments produced the highest grain yield, whereas sorghum–wheat rotation with weedy-check treatment resulted in the lowest grain yield during both years (Table 8).

The highest and the lowest expenses were incurred on cotton-wheat rotation with weed-free and fallow-wheat with weedy-check treatments, respectively (Table 9). Rice-wheat rotation with weed-free and chemical control treatments generated the highest gross income, whereas fallow-wheat with weedy-check treatment resulted in the lowest gross income. The highest net income and benefit-cost ratio were noted for rice-wheat system with chemical control, whereas the fallow-wheat with weedy-check treatment resulted in the lowest values of these traits (Table 9).

Table 7. Analysis of variance of different yield related traits and grain yield of wheat crop sown in different crop rotations under various weed management practices.

Source of Variation	DF	Sum of Squares	Mean Squares	F Value	*p* Value
		Number of grains per spike			
Year (Y)	1	56.49	56.49	43.45	<0.0001
Crop rotation (C)	4	74.23	18.56	14.27	<0.0001
Weed management strategies (W)	4	776.05	194.01	149.23	<0.0001
Y × C	4	0.79	0.20	0.15	0.9614
Y × W	4	26.77	6.69	5.15	0.0008
C × W	16	10.81	0.68	0.52	0.9315
Y × C × W	16	53.56	3.35	2.57	0.0022
		1000-grain weight			
Year (Y)	1	1.50	1.50	3.18	0.008
Crop rotation (C)	4	20.07	5.02	10.66	<0.0001
Weed management strategies (W)	4	212.56	53.14	112.85	<0.0001
Y × C	4	2.38	0.60	1.26	0.29
Y × W	4	1.45	0.36	0.77	0.55
C × W	16	8.28	0.52	1.10	0.37
Y × C × W	16	5.26	0.33	0.70	0.009
		Grain yield			
Year (Y)	1	0.05	0.05	1.00	0.0032
Crop rotation (C)	4	3.44	0.86	18.55	<0.0001
Weed management strategies (W)	4	14.57	3.64	78.60	<0.0001
Y × C	4	0.04	0.01	0.24	0.92
Y × W	4	0.25	0.06	1.37	0.25
C × W	16	0.60	0.04	0.81	0.67
Y × C × W	16	0.36	0.02	0.48	0.005

Table 8. Effect of different crop rotations and weed managing strategies on yield parameters and grain yield of wheat.

Cropping Rotations	2012–2013					2013–2014				
	Weed-Free	**Weedy Check**	**False Seedbed**	**Chemical Control**	**Allelopathic Water Extracts**	**Weed Free**	**Weedy Check**	**False Seedbed**	**Chemical Control**	**Allelopathic Water Extracts**
					Grains per spike					
Fallow-wheat	58.60 ± 0.94 a	49.00 ± 0.28 jk	53.90 ± 0.20 f–h	55.03 ± 0.42 d–g	53.47 ± 0.18 gh	57.40 ± 0.08 b–d	51.48 ± 0.10 j	54.32 ± 0.08 gh	56.29 ± 0.10 c–f	55.27 ± 0.12 e–g
Rice-wheat	57.58 ± 0.74 ab	48.50 ± 1.25 k	56.27 ± 0.40 b–d	57.45 ± 1.08 a–c	54.90 ± 0.58 d–g	59.26 ± 1.37 a	54.66 ± 2.67 f–h	54.34 ± 0.08 gh	56.89 ± 0.06 b–e	55.72 ± 0.04 d–g
Cotton-wheat	57.67 ± 0.49 ab	50.78 ± 0.14 ij	53.88 ± 0.10 f–h	55.52 ± 0.14 c–f	54.23 ± 0.14 e–g	58.02 ± 0.08 ab	52.26 ± 0.13 ij	55.26 ± 0.05 e–g	57.18 ± 0.06 b–d	55.88 ± 0.07 d–g
Mungbean-wheat	57.88 ± 0.22 ab	51.10 ± 0.15 i	54.00 ± 0.37 e–g	55.97 ± 1.88 b–e	54.50 ± 0.25 d–g	58.25 ± 0.24 ab	52.45 ± 0.10 ij	55.38 ± 0.16 e–g	57.65 ± 0.08 a–c	56.10 ± 0.05 c–f
Sorghum-wheat	55.20 ± 1.11 d–g	48.27± 0.63 k	51.97 ± 0.26 hi	55.45 ± 0.86 c–g	53.67 ± 0.84 f–h	57.17 ± 0.09 b–d	51.11 ± 0.07 j	53.47 ± 0.14 hi	56.16 ± 0.107 c–f	53.52 ± 0.49 hi
LSD ($p \leq 0.05$)			2.01					1.68		
					1000-grain weight (g)					
Fallow-wheat	42.09 ± 1.10 c–g	39.12 ± 0.11 op	40.41 ± 0.22 j–n	42.10 ± 0.34 c–f	41.20 ± 0.45 g–k	42.69 ± 0.04 b–e	39.85 ± 0.06 lm	40.93 ± 0.05 g–l	42.10 ± 0.34 c–h	41.20 ± 0.45 f–l
Rice-wheat	44.47 ± 0.85 a	39.57 ± 0.12 n–p	40.69 ± 0.09 i–m	42.89 ± 0.40 bc	41.16 ± 0.31 h–l	43.29 ± 1.06 a–c	39.95 ± 0.21 k–m	40.69 ± 0.09 i–m	41.89 ± 0.55 d–i	41.57 ± 0.05 e–j
Cotton-wheat	42.75 ± 0.06 b–d	39.33 ± 0.38 op	41.31 ± 0.43 f–i	42.41 ± 0.51 b–e	41.28 ± 0.39 f–j	43.72 ± 0.08 ab	39.97 ± 0.06 k–m	41.29 ± 0.11 f–k	42.25 ± 0.04 c–g	42.01 ± 0.03 c–i
Mungbean-wheat	43.30 ± 0.24 b	39.94 ± 0.13 m–o	41.44 ± 0.23 f–i	42.53 ± 0.13 b–d	41.53 ± 0.17 e–i	44.05 ± 0.09 a	40.00 ± 0.10 k–m	41.46 ± 0.08 e–j	42.94 ± 0.07 a–d	41.53 ± 0.17 e–j
Sorghum-wheat	42.07 ± 0.32 c–g	39.00 ± 0.40 p	40.34 ± 0.08 k–n	42.00 ± 0.50 d–h	40.31 ± 1.17 l–n	42.36 ± 0.04 c–f	39.38 ± 0.05 m	40.87 ± 0.07 h–l	41.97 ± 0.02 c–i	40.27 ± 0.65 j–m
LSD ($p \leq 0.05$)			0.90					1.36		
					Grain yield (t ha^{-1})					
Fallow-wheat	6.35 ± 0.27 a–d	5.43 ± 0.07 jk	5.57 ± 0.07 h–k	6.40 ± 0.30 a–c	5.72 ± 0.04 f–k	6.52 ± 0.31 ab	5.54 ± 0.04 jk	5.69 ± 0.04 g–k	6.01 ± 0.04 d–g	5.65 ± 0.04 h–k
Rice-wheat	6.43 ± 0.31 a	5.54 ± 0.05 h–k	5.71 ± 0.08 f–k	6.43 ± 0.24 a	5.77 ± 0.05 f–j	6.56 ± 0.32 a	5.61 ± 0.06 i–k	5.71 ± 0.07 g–k	6.36 ± 0.23 a–c	5.76 ± 0.05 f–k
Cotton-wheat	6.57 ± 0.16 a	5.53 ± 0.08 h–k	5.84 ± 0.07 f–i	6.25 ± 0.05 a–e	5.88 ± 0.11 e–h	6.39 ± a–c	5.71 ± 0.06 g–k	5.86 ± 0.05 e–j	6.21 ± 0.04 b–d	5.98 ± 0.06 d–g
Mungbean-wheat	6.42 ± 0.05 ab	5.79 ± 0.04 f–j	5.97 ± 0.06 e–g	6.45 ± 0.02 a	6.05 ± 0.06 b–f	6.67 ± 0.06 a	5.88 ± 0.06 d–i	5.98 ± 0.05 d–g	6.50 ± 0.05 ab	6.10 ± 0.05 c–e
Sorghum-wheat	6.03 ± 0.05 c–f	5.34 ± 0.05 k	5.47 ± 0.10 i–k	6.01 ± 0.04 d–g	5.63 ± 0.05 g–k	6.06 ± 0.07 c–f	5.60 ± 0.11 i–k	5.50 ± 0.07 k	5.94 ± 0.04 d–h	5.63 ± 0.0 h–k
LSD ($p \leq 0.05$)			0.38					0.33		

Different letters denote significant differences at $p < 0.05$.

Table 9. Economic analysis of different crop rotations and weed management strategies used in the study.

Crop Rotations/ Weed Management Strategies	Total Expenditure (US$ ha^{-1})	Gross Income (US$ ha^{-1})	Net Income (US$ ha^{-1})	BCR
Fallow-wheat				
Weed-free	1065.00 o	1568.20 n	503.20 p	1.47 op
Weedy-check	970.50 r	1400.70 p	430.20 q	1.44 p
False seedbed	995.70 p	1438.80 op	443.20 q	1.45 p
Chemical control	992.50 p	1561.60 n	569.10 o	1.57 n
Allelopathic water extracts	979.90 q	1478.10 o	498.20 p	1.51 o
Rice-wheat				
Weed-free	1490.10 c	5341.50 a	3851.50 b	3.58 d
Weedy-check	1395.60 g	5187.70 c	3792.10 c	3.72 bc
False seedbed	1420.80 e	5232.70 bc	3812.00 bc	3.68 c
Chemical control	1417.60 e	5339.60 a	3922.00 a	3.77 a
Allelopathic water extracts	1405.00 f	5249.20 b	3844.20 b	3.74 ab
Cotton-wheat				
Weed-free	1574.00 a	4119.30 d	2545.30 e	2.62 m
Weedy-check	1479.50 d	3934.20 f	2454.70 g	2.66 lm
False seedbed	1504.70 b	3991.90 e	2487.30 fg	2.65 lm
Chemical control	1501.50 b	4095.70 d	2594.20 d	2.73 ij
Allelopathic water extracts	1488.90 c	4002.60 e	2513.70 ef	2.69 kl
Mungbean-wheat				
Weed-free	1277.20 i	3469.20 h	2192.00 jk	2.72 jk
Weedy-check	1182.70 n	3263.50 m	2080.80 n	2.76 h–j
False seedbed	1207.90 kl	3309.80 l	2101.90 mn	2.74 ij
Chemical control	1204.70 l	3430.40 hi	2225.70 ij	2.85 ef
Allelopathic water extracts	1192.20 m	3330.20 kl	2138.10 lm	2.79 gh
Sorghum-wheat				
Weed-free	1297.80 h	3537.30 g	2239.50 i	2.73 i–k
Weedy-check	1203.30 l	3361.60 jk	2158.20 kl	2.80 gh
False seedbed	1228.50 j	3395.10 ij	2166.50 kl	2.76 hi
Chemical control	1225.40 j	3531.20 g	2305.90 h	2.88 e
Allelopathic water extracts	1212.80 k	3437.20 hi	2224.50 ij	2.83 fg
LSD value at 5%	6.51	45.50	47.05	0.04

Different letters denote significant differences at $p < 0.05$.

4. Discussion

Different interactions among crop rotations and weed management strategies significantly differed for weed infestation and grain yield of wheat as hypothesized. However, allelopathic crop water extracts and inclusion of sorghum in rotation did not prove to be effective for the control of weeds. The biggest challenge to adopting a crop rotation is its residual effects on the proceeding crop. The current study indicated that sorghum-wheat rotation, although it lowered weed infestation to some extent compared to weedy-check treatment, exerted negative impacts on yield-related parameters of wheat crop. Overall, economic benefits of sorghum-wheat rotation were the lowest, whereas rice-wheat crop rotation had the highest economic returns (data not shown). Therefore, this rotation could not be recommended for adoption. Different weed management strategies decreased the weed density and biomass, resulting in lower weed-crop competition, which ultimately improved the crop productivity. Herbicide application significantly decreased the weed density and biomass compared to non-treated control. There is potential to use false seedbed as an efficient strategy in integrated weed management [13]. The false seedbed controlled weeds better compared to conventional seedbed and improved the crop growth as well [59]. However, looking at the economic analysis of the study, false seedbed generated lesser income than chemical control.

Rice-wheat crop rotation had higher weed density, while sorghum-wheat rotation reduced weed density and biomass (Table 4). Different crop rotations resulted in different weed densities and biomass. The differences in crop rotations can be owed to the residual effects on the following crop [8,60,61]. Several earlier studies have reported that adapting different crop rotations help in lowering density of a particular weed or overall weed density. For example, Zeller et al. [15] reported up to 99% reduction in the density of blackgrass through the inclusion of summer crops in wheat-based crop rotations. Similarly, a 23–99% reduction in the density of black grass was noted through rotating the mode of action of herbicides. Likewise, false seedbed was capable of causing a 70% reduction in blackgrass density. Hence, not only crop rotation, but rotation of herbicides could also lower the density of a particular weed. This was not investigated in the study; therefore, inferring the impact of herbicide rotation on weed density on overall productivity of a crop rotation and weed suppression is recommended for future studies. Maize-winter wheat rotation has also been reported to suppress weed density in wheat crop [47]. Crop rotation combined with half of the recommended dose of herbicides provided 99% control over weeds in maize crop [47]. MacLaren et al. [48] reported that crop rotation with reduced tillage lowered weed infestation, whereas crop interaction by zero tillage interaction was unable to reduce weed density.

The current study indicated that while the sorghum-wheat rotation reduced weed infestation to some extent compared to weedy-check treatment, it exerted negative impacts on growth and yield related parameters of the wheat crop. Economic analysis indicated that the lowest productivity was recorded for fallow-wheat with weedy-check followed by sorghum-wheat rotation with allelopathic crop water extracts. This can be owed to allelopathic activity of the sorghum, although there was no evidence to support this claim. Sorghum possesses a high concentration of allelochemicals and its allelopathic potential has been intensively reported [43,44,62,63]. Sorgoleone is an allelochemical that is produced in roots of the sorghum plants and exuded to the soil [38]. A high activity of this allelochemical has been reported against weeds [64,65]. In the present study, we supposed that sorghum produced alleleochemicals that were excluded to the soil and played a role in suppressing weeds in the wheat crop. However, this inference warrants further investigation.

Mungbean-wheat rotation improved growth traits, whereas sorghum-wheat rotation suppressed these traits. Soil physical and chemical properties are significantly affected by crop rotation [60], which ultimately affected the crop productivity. Introducing legumes in crop rotation lowers soil compaction, while induction of allelopathic crops increases it [29,60]. Previous studies indicated that addition of sesbania (*Sesbania rostrata* L.) and mungbean (*Vigna radiata* L. Wilczek) biomass into the soil reduced the bulk density, increased porosity and available soil moisture [60,66,67]. Therefore, growing mungbean in rotation with wheat improved soil fertility with better soil physical properties. Compaction decreases the soil porosity and alters pore connectivity which directly affect the soil aeration, plant water availability and drainage [68,69]. Addition of sorghum in the rotation might have adversely affected wheat germination, which reduced growth traits.

Improved wheat yield in this study can be attributed to improved yield-related parameters (grain per spike and 1000-grain weight) by the adoption of various weed management strategies [8,60]. On the other hand, the absence of weeds (weed-free plots) or low weed infestation improved wheat yield due to absence of weed-crop competition [17,70]. The enhanced leaf area index and crop growth rate might resulted in more dry matter production [5].

Regarding economic feasibility of the opted rotations and weed management strategies, rice-wheat rotation with chemical control proved the highest income generating interaction. Fallow-wheat with weedy-check treatment was the lowest income generating interaction of the study. The higher productivity of rice-wheat cropping rotation can be owed to nature of both crops and timely weed control provided by the chemical control. Although higher yield and related traits were observed for mungbean-wheat rotation, economic analysis indicated that it was not the highest income generating interaction of the study. This can be explained with lower yield of mungbean compared to rice. However, for soil health, mungbean-wheat rotation is better than other rotations included in the study.

5. Conclusions

Non-chemical weed control methods such as false seedbed proved helpful in managing weeds. Mungbean-wheat crop rotation improved wheat performance probably by fixing atmospheric nitrogen, whereas sorghum-wheat rotation reduced weed infestation. Mungbean likely improved the soil fertility which (along with other benefits) also helped to improve the competitiveness of wheat crop plants against the weeds. Three different conclusions can be made from the results depending on particular targets. Sorghum-wheat rotation can be recommended for lowering weed infestation. Rice-wheat crop rotation with chemical control or weeds managed successfully by alternative weed management approach is recommended for higher economic returns. Mungbean wheat rotation combined with false seedbed is recommended for improving soil health. Future studies must test the changes in soil microorganisms in different rotations and weed management strategies. Nonetheless, the residual effects of sorghum and chemical mechanisms behind suppressed wheat growth must be tested.

Since the rotations were studied for a shorter time span, these should be investigated for their long-term impacts on weed suppression and growth and productivity of the crops being rotated. Since weeds provide significant ecosystem services and each weed species has a specific function associated to it, these services should also be considered in the future studies.

Author Contributions: Conceptualization, K.J., M.F. and S.F.; Data curation, M.S. and M.H.; Formal analysis, K.J.; Funding acquisition, K.G., M.B., B.S.A., A.T.K.Z. and A.M.E.-S.; Investigation, M.S.; Methodology, M.H., M.F. and S.F.; Project administration, M.H.; Software, S.F.; Supervision, M.H. and M.F.; Writing—original draft, M.S.; Writing—review & editing, M.H., K.J., M.F., S.F., K.G., M.B., B.S.A., A.T.K.Z. and A.M.E.-S. All authors have read and agreed to the published version of the manuscript.

Funding: The current work was funded by Taif University Researchers Supporting Project number (TURSP-2020/245), Taif University, Taif, Saudi Arabia. The present work was carried out with the support of the project EPPN2020-OPVaI-VA-ITMS313011T813.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All relevant data are within the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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