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Weed control through allelopathic crop water extracts and S-metolachlor in cotton

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Weeds are one of the most important biological constraint to cotton production, and resulting in a yield losses of up to 90%. The evolution of hundreds of resistant weed species, the lack of new herbicide chemistries, and the increase in weed management costs are all making weed management more arduous for the growers. Hence, a field experiment was conducted to investigate the efficacy of allelopathic crop water extracts (ACWEs) alone and in combination with one third rate of S-metolachlor (717 g a.i. ha^{-1}) for effective weed management in cotton. The treatments investigated were; weedy check, sorghum + brassica water extract (WE) at 1.5 L ha^{-1}, sorghum + sunflower WE at 1.5 L ha^{-1}, sorghum + brassica + sunflower WE at 1.5 L ha^{-1}, sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, sorghum + brassica WE + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, and S-metolachlor at recommended rate of 2.15 kg a.i. ha^{-1}. Results revealed that pre-emergent application of sorghum + brassica water extract (WE) at 1.5 L ha^{-1} was the best treatment in terms of effective dry biomass reduction (40%) of *Trianthema portulacastrum* and *Cyperus rotundus*, and increase in seed cotton yield (12%). The second best treatment was sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1} with yield increase of 11% over the weedy control. In comparison, S-metolachlor at recommended rate 2.15 kg a.i. ha^{-1} recorded only 4% decrease in weeds dry biomass reduction and 8% increase in seed cotton yield. Hence, it can be predicted that binary combination of sorghum and brassica WE at 1.5 L ha^{-1} or binary combination of sorghum + sunflower WE at 1.5 L ha^{-1} with one third dose of S-metolachlor (717 g a.i. ha^{-1}) can be used for effective weed management and increase in seed cotton yield. Furthermore, adoption of this technique will also reduce the herbicide application, which is not only beneficial for the ecosystem but, also minimize the evolution of herbicide-resistant weed species.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is an important summer annual crop of warm temperate regions, being grown in more than 70 countries around the globe crop and has a share of

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around 31% in the world fiber market [1]. Cotton is also an important crop for the textile industry and contributes directly towards world's economy. In Pakistan, cotton is also a major crop with 10% contribution to the agriculture gross domestic product and 55% earning as a foreign reserve [2]. Weeds are a major biotic constraint to successful production of cotton resulting in a yield loss of up to 90% [1]. Weeds impact cotton crop both directly and indirectly by reducing lint yield and lint quality, increasing production cost and serving as alternative hosts for insect pests, disease pathogens, rodents, and nematodes [3].

Since their launch in 1940, dependency of herbicides increased gradually and replaced all other methods of weed control like manual, cultural and mechanical [4]. Herbicides can provide adequate and cost-effective weed management in the cotton crop [5]. The situation is worsening in Pakistan due to unavailability of no selective post-emergence (POST) herbicide and no release of genetically modified crops. Dinitroaniline herbicide like S-metolachlor is readily available and used by the cotton growers on large scale for controlling all types of grassy and broadleaf weeds particularly black pigweed (*Trianthema portulacastrum* L.) and purple nutsedge (*Cyperus rotundus* L.) [6,7,8]. However, it has not been tested under Faisalabad conditions yet.

Despite the tremendous success and large-scale adaptation by the growers, the continuous and heavy applications of herbicide are not only deteriorating the ecosystem but also posing severe health risks and evolution of herbicide-resistant weed populations [9,10]. As of today, 255 weeds (including 107 monocots and 148 dicots) from 92 crops have developed resistance to 163 herbicides around the world [9]. Furthermore, serious concerns are rising globally on the potential toxicological and carcinogenic repercussions of herbicides especially glyphosate that is widely used in glyphosate-tolerant cotton [11]. Due to frequent and heavy applications, residues of glyphosate and its primary metabolic product, aminomethylphosphonic acid (AMPA) are accumulating in the environment and entering the food chain, thus contamination of soil and water bodies is becoming a possibility, and a threat to human and animal health [10]. The current situation demands to evolve new strategies providing solutions to these chronic problems.

Allelopathy is a multi-dimensional science and one aspect of allelopathy is utilizing natural allelochemicals for weed management [12]. Unlike synthetic herbicides, such compounds are produced naturally in the plants and used directly as herbicides [13–16]. These allelochemicals are effective, economically viable and environmental friendly [17]. Such phytotoxic natural products could be used in several ways for effective weed suppression like cover crops or mulches or directly sprayed as organic herbicide [18,19].

The allelopathic potential of several crop plants like sorghum (*Sorghum bicolor* L.), sunflower (*Helianthus annus* L.) and brassica (*Brassica campestris* L.) has been reported in the previous studies [20,21]. Naturally occurring allelochemicals from these crops can be easily extracted and sprayed just like herbicides [22]. Previous study reported that two POST applications of sorghum water extract (WE) provided total weed biomass reduction of 35% and increased lint yield by 59% [6]. Generally, ACWEs of sorghum, brassica or sunflower reduce weed biomass in the range of 40 to 50% with the two to three applications which sometimes is neither practicable nor desirable [23]. Hence, reduced rates of herbicide is necessary to achieve the effective weed control [24]. In a previous study, mixing sorghum WE (1 L ha^{-1}) with one third rate of pendimethalin (667 g a.i. ha^{-1}) reduced the total weed biomass by 50–74% and increased lint yield by 25% [25].

Allelopathic substances from different crops may have synergistic effects and can be applied in the mixture [26]. In the previous research, several crop plants have been identified as phytotoxic against various weeds like sorghum [27], brassica [28], and sunflower [29]. However, the effect of their tank mixture with each other was never studied in cotton before. Furthermore, it was not sure before this study whether the allelochemicals present in these crops *viz*. sorghum, sunflower and brassica can have synergistic or additive effects when applied in combination.

Therefore, the present study was conducted to determine the synergistic or additive phytotoxic effects of different ACWEs of sorghum, sunflower and brassica either tank mixed or mixed with reduced rates of S-metolachlor for effective weed management in cotton.

2. Material and method

2.1. Experimental site

The study was conducted at the Agronomic Research Area of the University of Agriculture, Faisalabad-Pakistan (N 31°26′13.965″, E 73°4′20.277″) during the summer season of 2003. The soil type for the experimental field was loam, having moderate fertility.

2.2. Experimental design

The experimental design was a randomized complete block design (RCBD), with eight treatments, four replicates, and a plot size of 7 × 4 m. Measurements were taken from the central 4 × 4 m of each plot, allowing for a buffer zone between each experimental unit. Two permanent quadrats (50 × 50 cm) were randomly positioned in the middle portion of each plot. The quadrats were maintained in the same position for the duration of the experiment. The weed control treatments, herbicides and ACWEs application rates illustrated in Table 1.

2.3. Preparation of ACWEs

Allelopathic crop water extracts were prepared by following the previous procedure [30]. Crop herbage (sorghum, sunflower, and brassica) was harvested at maturity, dried under shade and then chopped into 2 cm pieces with the help of fodder cutter. This chopped material was soaked in the distilled water in a tub in a ratio of 1: 10 (w/v) for 24 h. Water extracts were collected by passing through sieves (10 and 80 mesh). The filtrate was boiled at 100 °C for a considerable period of time so as to reduce its volume by 20 times. The concentrated extract was stored at room temperature for overnight and then used for spray.

Table 1 – Allelopathic crop water extracts and herbicides treatments, rates and timings used in the experiments undertaken in 2003.

Treatment	Application rate of herbicide and ACWEs[y]	Time of application of herbicides and ACWEs
Weedy check	–	–
Sorghum + brassica WE[y]	1.5[z]	PRE[y]
Sorghum + sunflower WE	1.5 + 1.5	PRE
Sorghum + brassica + sunflower WE	1.5 + 1.5 + 1.5	PRE
Sorghum + brassica WE + S-metolachlor	1.5 + 1.5 + [0.72][z]	PRE
Sorghum + sunflower WE + S-metolachlor	1.5 + 1.5 + [0.72]	PRE
Sorghum + brassica + sunflower WE + S-metolachlor	1.5 + 1.5 + 1.5 + [0.72]	PRE
S-metolachlor at recommended rate	[2.15]	PRE

y A bbreviations: WE, water extract; PRE, pre-emergence; ACWEs, allelopathic crop water extracts.
z Application rates enclosed in [ ] are given in g a.i. ha^{-1}; rates not enclosed in brackets expressed as L ha^{-1}.

2.4. *Experimental procedure*

The seedbed was prepared by cultivating the land thrice with a tractor mounted rotary to a depth of 8 cm. The field was fertilized with nitrogen (N) and phosphorus (P) at the rate of 115 and 57 kg ha^{-1}, respectively in the form of urea and diammonium phosphate. Both fertilizers *viz.* urea and diammonimum phosphate were purchased from Engro Fertilizers Ltd with the brand name of Engro Urea and Engro DAP, respectively. Engro Urea contained 46% N content, while Engro DAP contained 18% N and 46% P contents. Full dose of DAP (124 kg ha^{-1}) was applied at the time of sowing, while 50 kg ha^{-1} Urea was applied at sowing and remaining 130 kg ha^{-1} was applied at 45 days after sowing (DAS) to fertilize the soil with the required N and P contents.

Cotton *cv.* FH-1000 was sown with a single row hand drill, using a seed rate of 20 kg ha^{-1} and maintaining a density of 111,111 plants ha^{-1} on 16th May 2003 at 75 cm apart rows and 12 cm plant to plant distance. The volume of spray (330 L ha^{-1}) was determined by calibration. The treatments investigated were; weedy check, sorghum + brassica water extract (WE) at 1.5 L ha^{-1}, sorghum + sunflower WE at 1.5 L ha^{-1}, sorghum + brassica + sunflower WE at 1.5 L ha^{-1}, sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, sorghum + brassica WE + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i.ha^{-1}, and S-metolachlor at recommended rate of 2.15 kg a.i. ha^{-1}. All the treatments were sprayed as PRE except the weedy control where no spray was done (Table 1). Throughout the experiment, flat fan nozzles were used at a pressure of 200 kPa, with an output of 100 L ha^{-1}.

First irrigation was applied at 45 DAS and subsequent 8 irrigations were adjusted according to the climatic conditions and need of the crop. Total water applied was 760 mm. Generally, water requirement of cotton grown in the Indus basin areas like Faisalabad varies from 627 mm to 1,000 mm [36]. The monthly rainfall for cotton growing seasons 2003 is given in Table 2. Insects like jassids (*Amrasca biguttula* Ishida), thrips (*Thrips tabaci* Lindeman), silverleaf whitefly (*Bemisia argentifolii* Bellows and Perring), and aphid (*Aphis gossypii* Glover) were controlled by using recommended insecticides, chlorfenapyr at 180 g a.i. ha^{-1} from planting up to harvest. Additionally, lambda-cyhalothrin at 15 g a.i. ha^{-1} was applied to control cotton bollworms like cotton bollworm (*Helicoverpa armigera* Hübner), native budworm (*Helicoverpa punctigera* Wallengren), and pinkspotted bollworm (*Pectinophora scutigera* Holdaway). No spray was done for the disease.

Weed density was measured at 15 and 40 DAS and above ground dry biomass was determined at 40 DAS from two randomly selected, centrally placed permanent quadrats (50 × 50 cm), in each plot. Weed samples were oven dried before weighing at 70 °C till constant weight was achieved. The seed cotton yield was recorded from each individual plot after manual hand picking. The harvested produce was weighed and then converted into yield per hectare.

2.5. *Statistical analyses*

All the results pertaining to weed density, weed biomass and seed cotton yield were analyzed statistically using Statistix 8.1 software and differences among the treatment means was compared by using a least significant test (LSD) at 5% probability. Analysis of variance (ANOVA) indicated significant differences in data of weed density, weed biomass and seed cotton yield. To achieve the uniform distribution of weed density, data was subjected to square-root $\sqrt{(x + 0.5)}$ transformation before analysis.

3. Results and discussion

Two major weeds in the experimental plots were *T. portulacastrum* and *C. rotundus*. The infestation of *T. portulacastrum* was more as compared to *C. rotundus*. Some other weeds were also present at the experimental site, but in low numbers *viz.* lawn grass [*Cynodon dactylon* (L.) Pers], field bind weed (*Convolvulus arvensis* L.), common lambsquarters (*Chenopodium album* L.), and carpet weed (*Portulaca oleraceae* L.).

3.1. *Weed density*

Total weed count was significantly influenced by all the treatments at 15 and 40 DAS (Table 3). The weed density was generally low at 15 DAS and increased at 40 DAS in all the treatments due to rain. Amongst the APCWs combinations, binary combination of sorghum + brassica WE at 1.5 L ha^{-1}

Table 2 – Total monthly rainfall data for the complete growing cotton season from May to October in 2003 at Experimental Research Farm, University of Agriculture, Faisalabad, Pakistan [Source: 36].

Months	Rainfall (mm)
May	13.0
June	44.1
July	47.0
August	135.0
September	33.0
October	6.0

suppressed weed population by 51 and 34% at 15 and 40 DAS, respectively as compared to the weedy control, which was statistically at par with sorghum + brassica WE at 1.5 L ha^{-1} + one-third dose of S-metolachlor (717 g a.i. ha^{-1}) (Table 3). Similarly, a binary combination of sorghum + sunflower WE at 1.5 L ha^{-1} recorded weed suppression of 51 and 43% at 15 and 40 DAS, respectively, while sorghum + sunflower WE at 1.5 L ha^{-1} + one-third dose of S-metolachlor at 717 g a.i. ha^{-1} recorded weed suppression of 31 and 61%, respectively. The tertiary combination of sorghum + brassica + sunflower WE at 1.5 L ha^{-1} was not effective in weed suppression and recorded only 37 and 35% reduction at 15 and 40 DAS, respectively. The weed control with recommended dose of S-metolachlor (2.15 kg a.i. ha^{-1}) at 15 DAS was lesser (43%) and statistically equal to binary combination of sorghum + brassica WE at 1.5 L ha^{-1} (51%), sorghum + sunflower WE 1.5 L ha^{-1} (51%) and sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1} (51%). At 40 DAS, recommended dose of S-metolachlor (2.15 kg a.i. ha^{-1}) recorded greater weed suppression of 80%, followed by sorghum + brassica WE + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha-1 (64%) and sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1} (61%). A similar trend was observed in the individual weed density suppression of *T. portulacastrum* and *C. rotundus* (Table 4).

The results suggested that binary (sorghum + brassica or sorghum + sunflower WE at 1.5 L ha^{-1}) or tertiary (sorghum + brassica + sunflower WE at 1.5 L ha^{-1}) combination of ACWEs whether applied alone or reduced rate of S-metolachlor (717 g a.i. ha^{-1}) provided effective suppression of *T. portulacastrum* and *C. rotundus* at 15 and 40 DAS (Tables 3 and 4). These results conur to the previous studies where tank mixing of sorghum at 1.2 L ha^{-1} with reduced rate of pendimethalin (500 g a.i. ha^{-1}) and S-metolachlor (1000 g a.i. ha^{-1}) provided highest weed suppression [24,25]. Furthermore, binary combination of ACWEs (sorghum + brassica or sorghum + sunflower WE) recorded maximum weed suppression at 15 DAS, while their efficiency decreased at 40 DAS as compared to recommended rate of S-metolachlor (2.15 kg a.i. ha^{-1}) (Table 4). The decrease in efficacy of ACWEs with the passage of time could be due to the dilution of the natural chemical effect in the soil [25]. The improved effiency of S-metolachlor with the increased duration is due to its residual herbicidal characteristcs [8]. It can be predicted that ACWEs could provide better weed suppression for early seasonal weeds which are very critical for the initial crop-weed interference and determining potential lint yield [31]. Furthermore, ACWEs can also combined with the reduced rate of herbicide for best management of late emerging weeds throughout the crop season [16].

3.2. Weed biomass

The total weed biomass was significantly affected by all the treatments (Table 5). The binary combination of sorghum + brassica WE at 1.5 L ha^{-1} recorded weed suppression of 41%, which was statistically at par with sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at a reduced rate of 717 g a.i. ha^{-1}. It was followed by tertiary combination of sorghum + brassica + sunflower WE with 25% weed biomass suppression. All other treatments including the recommended dose of S-metolachlor (2.15 kg a.i. ha^{-1}) recorded less biomass reduction in the range of 1–4%. These results concur to the previous studies [6,15,25,32].

Table 3 – Effect of allelopathic crop water extracts alone and in combination with reduced rates of S-metolachlor on total weed density.

Treatments	Total weed density (plants m^{-2})		% reduction	
	15 DAS[y]	40 DAS	15 DAS	40 DAS
Weedy check	6 a[z] (35)[x]	19 a (348)	–	–
Sorghum + brassica WE[y] at 1.5 L ha^{-1}	4 ef (17)	15 b (231)	51	34
Sorghum + sunflower WE at 1.5 L ha^{-1}	4 f (17)	14 c (204)	51	41
Sorghum + brassica + sunflower WE at 1.5 L ha^{-1}	5 cd (22)	15 b (227)	37	35
Sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	4 ef (17)	16 b (243)	51	30
Sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	5 bc (24)	12 d (135)	31	61
Sorghum + brassica WE + sunflower WE 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	5 b (26)	11 d (126)	26	64
S-metolachlor at recommended rate of 2.15 kg a.i. ha^{-1}	4 bc (20)	8 e (70)	43	80
LSD at 5%	0.35	0.60		

x Values given in parenthesis show actual data.
y Abbreviations: DAS, days after sowing; WE, water extract.
z Means within a column followed by the same letter are not different according to LSD Test at $p = 0.05$.

Table 4 – Effect of allelopathic crop water extracts alone and in combination with reduced rates of S-metolachlor on individual weed densitites of *T. portulacastrum* and *C. rotundus*.

Treatments	*Trianthema portulacastrum* (plants m^{-2})		*Cyperus rotundus* (plants m^{-2})	
	15 DAS[y]	40 DAS	15 DAS	40 DAS
Weedy check	4 a[z] (20)[x]	18 a (333)	4 a (12)	3 a (8)
Sorghum + brassica WE[y] at 1.5 L ha^{-1}	3 d (11)	15 bc (216)	2 bc (4)	3 abc (6)
Sorghum + sunflower WE at 1.5 L ha^{-1}	4 c (13)	14 d (184)	1 c (2)	3 ab (7)
Sorghum + brassica + sunflower WE at 1.5 L ha^{-1}	4 ab (18)	15 c (213)	1 c (2)	3 abc (6)
Sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	3 d (10)	15 b (229)	3 b (6)	2 c (4)
Sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	4 ab (18)	11 e (126)	2 c (3)	2 bc (5)
Sorghum + brassica WE + sunflower WE 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	4 ab (17)	11 e (118)	3 (6)	2 abc (6)
S-metolachlor at recommended rate of 2.15 kg a.i. ha^{-1}	4 bc (15)	8 f (62)	2 bc (4)	2 bc (5)
LSD at 5%	0.37	0.47	0.70	0.57

x Values given in parenthesis show actual data.
y Abbreviations: DAS, days after sowing; WE, water extract.
z Means within a column followed by the same letter are not different according to LSD Test at $p = 0.05$.

Table 5 – Effect of allelopathic crop water extracts alone and in combination with reduced rates of S-metolachlor on total weed dry biomass recorded at 40 DAS[y].

Treatments	Total weed biomass (g m^{-2})	% reduction
Weedy check	177 a[z]	–
Sorghum + brassica WE[y] at 1.5 L ha^{-1}	104 d	41
Sorghum + sunflower WE at 1.5 L ha^{-1}	176 a	1
Sorghum + brassica + sunflower WE at 1.5 L ha^{-1}	132 c	25
Sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	100 d	44
Sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	175 a	1
Sorghum + brassica WE + sunflower WE 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	174 ab	2
S-metolachlor at recommended rate of 2.15 kg a.i. ha^{-1}	170 b	4
LSD at 5%	5.42	

y Abbreviations: DAS, days after sowing; WE, water extract.
z Means within a column followed by the same letter are not different according to LSD Test at $p = 0.05$.

Table 6 – Effect of allelopathic crop water extracts alone and in combination with reduced rates of S-metolachlor on seed cotton yield.

Treatments	Number of bolls $plant^{-1}$	Boll weight (g)	Seed cotton yield (kg ha^{-1})	% increase in seed cotton yield
Weedy check	13 b[z]	4	1023 h	–
Sorghum + brassica WE[y] at 1.5 L ha^{-1}	14 b	4	1150 a	12
Sorghum + sunflower WE at 1.5 L ha^{-1}	13 b	4	1043 f	2
Sorghum + brassica + sunflower WE at 1.5 L ha^{-1}	14 b	4	1037 g	1
Sorghum + brassica WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	17 a	4	1047 e	2
Sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	16 a	4	1132 b	11
Sorghum + brassica WE + sunflower WE 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1}	14 b	4	1098 d	7
S-metolachlor at recommended rate of 2.15 kg a.i. ha-1	16 a	4	1107 c	8
LSD at 5%	1.65	ns[y]	3.08	

y Abbreviations: WE, water extract; ns, non-significant.
z Means within a column followed by the same letter are not different according to LSD Test at $p = 0.05$.

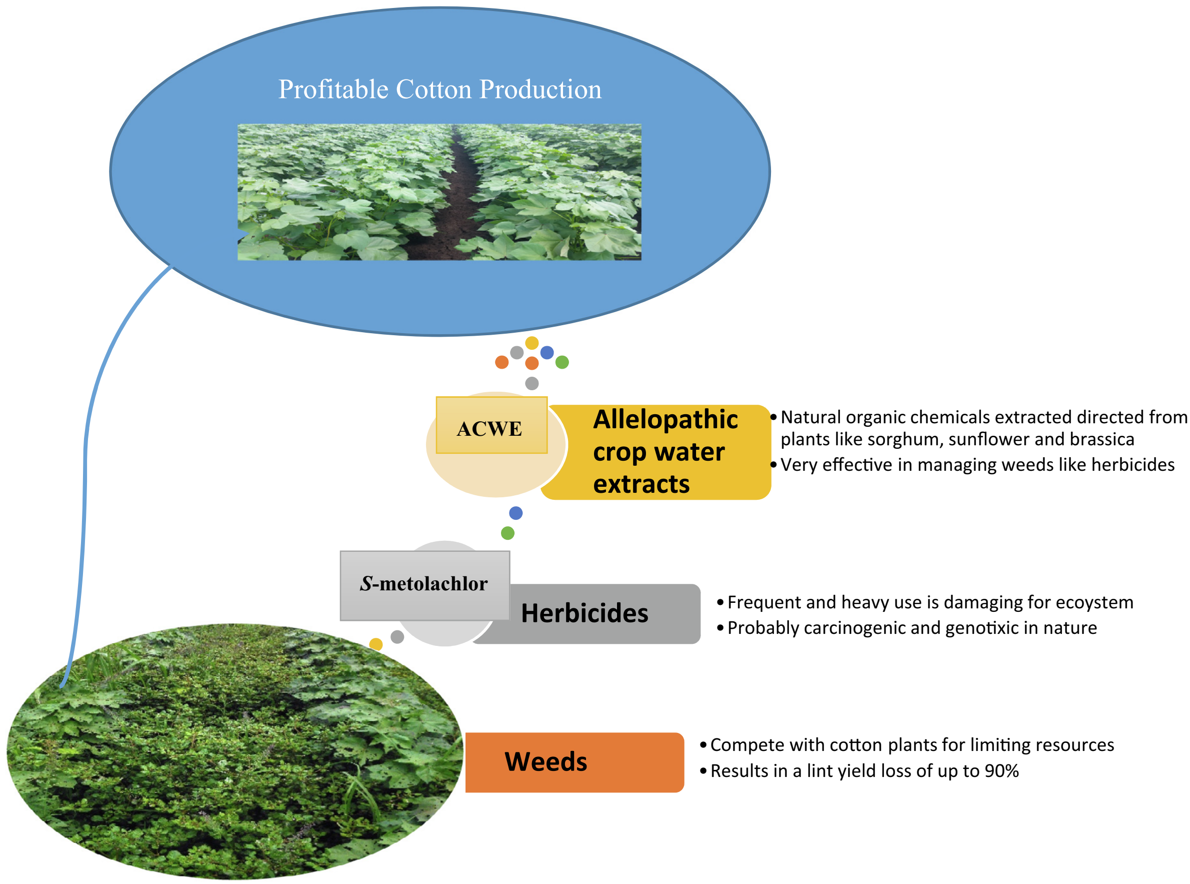

Fig. 1 – Flow diagram of weeds and their management in cotton through allelopathic crop water extracts.

The less biomass reduction with the full dose of S-metolachlor (2.15 kg a.i. ha^{-1}) might be due to less soil moisture contents at the time of spray which affected its efficacy adversely [8,33]. However, it can be concluded from this study that ACWEs could provid significant biomass reduction and therefore, possibilities exist for its tank mixing with lower herbicide rates [21,24].

Herbicide-resistant weeds are the biggest concern for all cotton stakeholders worldwide [34]. Currently, 78 herbicide-resistant cases of 17 noxious weeds have been reported in cotton crop worldwide and this number is increasing at an alarming rate [9]. Hence, inclusion of ACWEs (sorghum, brassica and sunflower) in the weed management program of cotton will be highly beneficial for growers as it will not not only give effective control of early season weeds, but also reduce the application of herbicides as happened in this study, which in turn slow down the evolution of future herbicide-resistant weeds.

3.3. *Seed cotton yield*

The seed cotton yield was significantly affected by all the treatments with an increase ranging from 1 to 12% (Table 6). The highest yield of 1,150 kg ha^{-1} was recorded in a binary combination of sorghum + brassica WE at 1.5 L ha^{-1} which showed an increase of 12% over the weedy control. The second best treatment was sorghum + sunflower WE at 1.5 L ha^{-1} + S-metolachlor at 717 g a.i. ha^{-1} which recorded a yield increase of 11%. Comparatively, S-metolachlor at the label rate (2.15 kg a.i. ha^{-1}) recorded an increase of only 8% in seed cotton yield.

Final yield is the outcome of all the agronomic factors, in which effective weed management play an important role. The higher seed cotton yield in a binary combination of sorghum + brassica WE at 1.5 L ha^{-1} could possibly be due to relatively higher weed suppression and seed cotton yield contributing parameters like a number of bolls plant^{-1} and boll weight [6,25]. The effects of different combinations of ACWEs *viz.* sorghum, sunflower and brassica on seed cotton yield varied greatly due to complex interaction of various allelopathic crop water extracts [16], herbicidal doses [6], edaphic and moisture contents [33,35] and weed spectrum [8].

4. Conclusion

The study predicted that ACWEs of sorghum and brassica at 1.5 L ha^{-1} could be tank mixed and applied as a pre-emergent natural herbicide for early season suppression of most common and troublesome cotton weeds like *T. portula-*

castrum and *C. rotundus* (Fig. 1). Furthermore, sorghum + sunflower WE at 1.5 L ha^{-1} with one third-dose of S-metolachlor (717 g a.i. ha^{-1}) could also be used for effective weed management and increase in seed cotton yield, which in turn reduce the herbicide application by 67%. Reduced herbicide dosage is very beneficial for environmental safety, mitigating human health risks and minimizing the expansion of herbicide-tolerant weed biotypes. The results of this study will be useful to all cotton industry stakeholders like researchers, industrialists, extension agents and growers for developing environmental benign effective weed management strategies with less dependency on herbicides. The current study was conducted at one geographic location involving one cotton variety. Further trials should be conducted at different agro-ecological zones involving different genetically modified cotton varieties like glyphosate-resistant cotton, glufosinate-resistant cotton, and dicamba-resistant cotton. Moreover, it could be important to see effectiveness of ACWES on different weed spectrum and soil types.

Conflicts of interest

The authors declare no conflicts of interest in publication of this manuscript.

REFERENCES

[1] Doğan M, Jabran K, Unay A. Integrated weed management in cotton. In: Chauhan B, Mahajan G, editors. Recent Advances in Weed Management. USA: Springer; 2014. p. 197–222.

[2] Pakistan Government. Economic Survey of Pakistan 2016/17. Link: http://www.finance.gov.pk/survey_1617.html. 2017

[3] Cortés JA, Mendiola MA, Castejón M. Competition of velvetleaf (*Abutilon theophrasti* M.) weed with cotton (*Gossypium hirsutum* L.). Economic damage threshold. Spanish J Agric Res 2010;8(2):391–9.

[4] Matthews G. Pesticides: health, safety and the environment. UK: John Wiley & Sons; 2015. p. 9–11.

[5] Richardson RJ, Wilson HP, Hines TE. Preemergence herbicides followed by trifloxysulfuron postemergence in cotton. Weed Technol 2007;21:1–6.

[6] Cheema ZA, Khaliq A, Tariq M. Evaluation of concentrated sorghum alone and in combination with reduced rates of 3-pre-emergence herbicides for weed control in cotton. Int J Agric Bio 2002;4:549–52.

[7] Iqbal J, Cheema ZA. Purple nutsedge (*Cyperus rotundus* L.) management in cotton with combined application of sorgaab and S-metolachlor. Pak J Bot 2008;40(6):2383–91.

[8] O'Connell PJ, Harms CT, Allen JR. Metolachlor, S-metolachlor and their role within sustainable weed-management. Crop Prot 1998;17(3):207–12.

[9] Heap I. International survey of herbicide-resistant weeds. Link: http://www.weedscience.org/. 2019.

[10] Van Bruggen AHC, He MM, Shin K, Mai V, Jeong KC, Finckh MR, et al. Environmental and health effects of the herbicide glyphosate. Sci Total Environ 2018;616–617:255–68.

[11] Guyton KZ, Loomis D, Grosse Y, El Ghissassi F, Benbrahim-Tallaa L, Guha N, et al. Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. Lancet Oncol 2015;16(5):490–1.

[12] Jabran K, Farooq M. Implications of potential allelopathic crops in agricultural systems. In: Cheema Z, Farooq M, Wahid A, editors. Allelopathy: Current trends and future applications. UK: Springer; 2013. p. 349–85.

[13] Duke SO. Proving allelopathy in crop–weed interactions. Weed Sci 2015;63(SP1):121–32.

[14] Jabran K, Farooq M, Hussain M, Ali M. Wild oat (*Avena fatua* L.) and canary grass (*Phalaris minor* Ritz.) management through allelopathy. J Plant Prot Res 2010;50(1):41–4.

[15] Khaliq A, Matloob A, Tanweer A, Khan MB. Naturally occurring phytotoxins in allelopathic plants help reduce herbicide dose in wheat. Nat Prod Res 2012;26(12):1156–60.

[16] Razzaq A, Cheema Z, Jabran K, Hussain M, Farooq M, Zafar M. Reduced herbicide doses used together with allelopathic sorghum and sunflower water extracts for weed control in wheat. J Plant Prot Res 2012;52(2):281–5.

[17] Jabran K, Mahajan G, Sardana V, Chauhan BS. Allelopathy for weed control in agricultural systems. Crop Prot. 2015;72:57–65.

[18] Farooq M, Jabran K, Cheema ZA, Wahid A, Siddique KH. The role of allelopathy in agricultural pest management. Pest Manage Sci 2011;67(5):493–506.

[19] Sturm DJ, Kunz C, Gerhards R. Inhibitory effects of cover crop mulch on germination and growth of *Stellaria media* (L.) Vill., *Chenopodium album* L. and *Matricaria chamomilla* L. Crop Prot 2016;90:125–31.

[20] Farooq M, Bajwa AA, Cheema SA, Cheema ZA. Application of allelopathy in crop production. Int J Agric Biol 2013;15(6):1367–78.

[21] Iqbal J, Cheema ZA, Mushtaq MN. Allelopathic crop water extracts reduce the herbicide dose for weed control in cotton (*Gossypium hirsutum*). Int J Agric Biol 2009;11(4):360–6.

[22] Razzaq A, Cheema ZA, Jabran K, Farooq M, Khaliq A, Haider G, et al. Weed management in wheat through combination of allelopathic water extract with reduced doses of herbicides. Pak J Weed Sci Res 2010;16(3):247–56.

[23] Khan MB, Ahmad M, Hussain M, Jabran K, Farooq S, Waqas-Ul-Haq M. Allelopathic plant water extracts tank mixed with reduced doses of atrazine efficiently control *Trianthema portulacastrum* L. Zea mays. J Animal Plant Sci 2012;22(2):339–46.

[24] Cheema ZA, Khaliq A, Iqbal N. Use of allelopathy in field crops in Pakistan. In: Proc. WC '2005 Proceedings of the 2007 4th World Congress on Allelopathy: Establishing the scientific base, Wagga Wagga, Australia; 2005. p. 550-553.

[25] Cheema ZA, Khaliq A, Hussain RI. Reducing herbicide rate in combination with allelopathic sorgaab for weed control in cotton. Int J Agric Biol 2003;5(1):1–6.

[26] Einhellig FA. Interactions involving allelopathy in cropping systems. Agron J 1996;88(6):886–93.

[27] Uddin MR, Park KW, Kim YK, Park SU, Pyon JY. Enhancing sorgoleone levels in grain sorghum root exudates. J Chem Ecol 2010;36(8):914–22.

[28] Al-Sherif E, Hegazy AK, Gomaa NH, Hassan MO. Allelopathic effect of black mustard tissues and root exudates on some crops and weeds. Planta Daninha 2013;31(1):11–9.

[29] El Marsni Z, Torres A, Varela RM, Molinillo JM, Casas L, Mantell C, et al. Isolation of bioactive compounds from sunflower leaves (*Helianthus annuus* L.) extracted with supercritical carbon dioxide. J Agric Food Chem 2015;63(28):6410–21.

[30] Cheema ZA. Sorghum allelopathy, a new weed control technology for enhancing wheat productivity. J Animal Plant Sci 1998;8:19–21.

[31] Papamichail D, Eleftherohorinos I, Froud-Williams R, Gravanis F. Critical periods of weed competition in cotton in Greece. Phytoparasitica 2002;30(1):105–11.

[32] Cheema ZA, Khaliq A, Saeed S. Weed control in maize (*Zea mays* L.) through sorghum allelopathy. J Sustain Agric 2004;23:73–86.

[33] Rice PJ, Anderson TA, Coats JR. Degradation and persistence of metolachlor in soil: effects of concentration, soil moisture, soil depth, and sterilization. Environ Toxicol Chem 2002;21 (12):2640–8.
[34] Iqbal N, Manalil S, Chauhan BS, Adkins SW. Investigation of alternate herbicides for effective weed management in glyphosate-tolerant cotton. Arch Agron Soil Sci 2019. https://doi.org/10.1080/03650340.2019.1579904.
[35] Stewart CL, Nurse RE, Hamill AS, Sikkema PH. Environment and soil conditions influence pre-and postemergence herbicide efficacy in soybean. Weed Tech. 2010;24(3):234–43.
[36] Pakistan Meterological Department. Link: http://www.pmd.gov.pk/g/. 2003.