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ALLELOCHEMICALS AS BIO-HERBICIDES FOR WEED MANAGEMENT IN WHEAT

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ABSTRACT

Allelochemicals used as natural herbicides offer an environmentally safe alternative with minimal harmful effects on agricultural products. Therefore, allelopathic approaches have gained attention for weed suppression in agricultural systems. Field experiments were conducted during 2021–2022 at the Agricultural Research Institute, Tarnab, Peshawar, Pakistan. Treatments were applied as post-emergence sprays, and an untreated weedy check was maintained as a control for comparison. Statistical analysis revealed that the application of plant water extracts in combination with reduced doses of herbicides significantly influenced grain yield, biological yield, harvest index, cost-benefit ratio (CBR), and proximate composition of wheat. The highest grain yield (5716 kg ha⁻¹) and harvest index (53.77%) were recorded in plots treated with *Phragmites australis* + ½ dose of Puma Super 750EW. In contrast, the lowest grain yield (3788 kg ha⁻¹) and harvest index (41.75%) were observed in untreated control plots. Similarly, the highest biological yield, cost-benefit ratio (CBR = 1:7.1), protein content (67.92%), and starch content (12.13%) were observed in plots treated with *Phragmites australis* + ½ P. Super 750EW, followed closely by *Phragmites australis* + ½ Buctril Super, with no statistically significant difference between the two. Biological treatments involving highly allelopathic plants such as *Phragmites australis*, *Parthenium hysterophorus*, and *Datura alba* appear to be both environmentally friendly and economically viable. These approaches not only aid in weed management but may also serve as bio-fertilizers, as some allelopathic plants positively influence crop growth, yield, and quality in wheat.

Keywords: Allelochemicals, CBR, integrated application, proximate analysis.

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INTRODUCTION

Wheat remains the most significant cereal crop in Pakistan, cultivated annually and forming the backbone of national food security. In Khyber Pakhtunkhwa, wheat production is challenged by a wide range of weeds such as *Avena fatua*, *Phalaris minor*, *Poa annua*, *Cirsium arvense*, *Convolvulus*

arvensis, *Chenopodium album*, *Fumaria indica*, *Carthamus oxyacantha*, *Cynodon dactylon*, and *Euphorbia helioscopia* (Arif et al., 2015). Traditional mechanical methods of weed control are often labor-intensive and inefficient, while chemical herbicides raise concerns about environmental safety, food quality, and human health (Scavo et al., 2021).

Moreover, the repeated use of synthetic herbicides has accelerated the emergence of resistant weed biotypes, driving up production costs and complicating management strategies. Consequently, researchers are increasingly exploring alternative approaches such as allelopathy for sustainable weed suppression (Gurmani et al., 2021).

Allelopathy refers to the biochemical interactions among plants, where certain species release allelochemicals that inhibit the growth of neighboring plants. This natural mechanism can be integrated into weed management systems to reduce reliance on synthetic inputs. Effective weed suppression often requires reductions of 70–80% depending on weed type and infestation levels (Khan et al., 2016). While herbicides have historically boosted yields, their overuse has caused soil and water contamination, ecological imbalance, and widespread resistance among weed species. The International Herbicide-Resistant Weed Database now reports over 539 unique cases of resistance across 273 weed species worldwide, underscoring the urgency of eco-friendly alternatives. Allelopathy has thus emerged as a promising tool for sustainable agriculture, aligning with growing public demand for organic and environmentally safe practices (Scavo et al., 2021).

Allelopathic interactions can suppress seed germination, root elongation, and shoot growth, though distinguishing these effects from other biotic or abiotic stresses remains challenging. In farming systems, allelopathic crops act as natural weed suppressants by releasing allelochemicals through leaching, root exudation, residue decomposition, and volatilization. These compounds include phenolics, flavonoids, terpenoids, tannins, and alkaloids. At low concentrations, some phenolics may stimulate plant growth, but higher levels typically inhibit development (Gurmani et al., 2021). Interestingly, certain weeds themselves exhibit allelopathic properties, releasing toxic metabolites into the rhizosphere that negatively affect crop growth.

Recent studies highlight the potential of combining allelopathic plant extracts with reduced herbicide doses to achieve effective weed control in wheat fields. Foliar application of extracts from species such as *Oryza sativa*, *Parthenium hysterophorus*, *Phragmites australis*, and *Datura alba* has been shown to significantly reduce weed density and biomass while enhancing wheat yield within 30 days of sowing. This study highlighted the integrated approach not only minimizes reliance on synthetic chemicals but also supports sustainable crop production under the agro-climatic conditions of Peshawara (Arif et al., 2015).

MATERIALS AND METHODS

Field experiments were conducted at the experimental farm of

the Agricultural Research Institute, Tarnab, Peshawar, Pakistan, located between 33°44' and 34°15' N latitude and 71°22' and 71°42' E longitude. The wheat variety "Pirsabak-08," which is widely cultivated in the region, was sown in rows spaced 25 cm apart using a single-row hand drill on November 15th, 2020, and the experiment was repeated on the same date in 2021. A recommended seed rate of 120 kg ha⁻¹ was used. The experiment was sown in plot with eight (8) rows. Each row was 3m long and 2.4m wide. Row to row distance was kept 30cm. The experimental plot area was 7.20m². Fertilizer was applied at the recommended rate of 120:90 kg ha⁻¹ of nitrogen (N) and phosphorus (P). Half of the nitrogen and the full dose of phosphorus were applied at sowing, while the remaining nitrogen was applied at the time of the second irrigation. Urea and di-ammonium phosphate (DAP) were used as the sources of nitrogen and phosphorus, respectively. These fertilizer practices are standard for wheat cultivation in the region. Irrigation was applied as needed based on crop requirements. The experiment was laid out in a Randomized Complete Block Design (RCBD) with sixteen treatments, each replicated four times.

Meteorological data

The experimental area experiences hot summers and mild winters. During summer, the mean maximum temperature exceeds 40 °C, with a mean minimum of 25 °C. In winter, temperatures range from an average minimum of 4 °C to a maximum of 18.35 °C. Winter rainfall is generally higher than that of summer. Based on a 30-year climatic record, the average annual precipitation is approximately 400 mm. Wind speeds fluctuate throughout the year, ranging from 5 knots in December to 24 knots in June. Relative humidity also varies seasonally, from 46% in June to a peak of 76% in August.

Physicochemical Properties of the Experimental Field

Soil samples were collected from the experimental plots a few days prior to wheat sowing. Samples were taken to a depth of 10 cm and analyzed for various physicochemical properties at the Soil Science Laboratory, Agricultural Research Institute Tarnab, Peshawar, Pakistan. The proportions of clay, silt, and sand were determined using the hydrometer method, and the soil textural class was classified based on the International Textural Triangle.

The soil was categorized as silty clay loam, containing 37% clay, 60% silt, 3% sand, 18.50% calcium carbonate (CaCO₃), and 0.41% organic matter. The nitrogen, phosphorus, and potassium contents were 0.02%, 7.1 mg kg⁻¹, and 300 mg kg⁻¹, respectively. The soil had an electrical conductivity of 0.17 dS m⁻¹ and a pH of 8.2.

Collection of allelopathic plants for extracts

Mature plants of *Oryza sativa* L., *Parthenium hysterophorus*

L., *Phragmites australis* Cav., and *Datura alba* L. were collected from fields in Peshawar, Pakistan. The plants were harvested at the base above ground level using a sickle. After collection, they were manually cleaned by shaking off dust and other particles.

Among these species, *Parthenium hysterophorus* and *Phragmites australis* have been declared invasive weeds in Pakistan. *P. hysterophorus* is a major troublesome weed commonly found in wastelands, along roadsides, canal banks, and in vegetable fields. *P. australis* has become a dominant weed in canal systems and wetlands. In the study area, it has largely replaced *Typha latifolia* in aquatic bodies, making it a relevant species for inclusion in this study.

Extract preparation

The allelopathic plants were chopped into small pieces (approximately 3 cm) using an electric fodder cutter. The

chopped plant materials were then oven-dried (Kenton; KH-120AS) at 65 °C for 72 hours. After drying, the plant material was soaked in distilled water at a concentration of 150 g L⁻¹ for 48 hours, while volume of aqueous extracts for *Oryza sativa* L., *Parthenium hysterophorus*, *Phragmites australis* and *Datura alba* L. @ 500 kg ha⁻¹ has been used in the instant study respectively, followed by filtration to obtain the respective aqueous extracts.

These extracts were applied as post-emergence sprays using a knapsack sprayer equipped with a flat-fan nozzle, 30 days after sowing, according to the treatment plan. Although hand weeding was practiced, it was not possible to keep the plots completely weed-free due to frequent rainfall during March and April each year. A weedy check (un-weeded control) was maintained for comparison. Details of the treatments applied are illustrated in Table 1.

Table 1: List of treatments and application status.

Treatments No.	Treatments	Applied as
T1	<i>Oryza sativa</i> L. extract @ 500 kg ha ⁻¹	Alone
T2	<i>Parthenium hysterophorus</i> L. extract @ 500 kg ha ⁻¹	Alone
T3	<i>Phragmites australis</i> Cav. extract @ 500 kg ha ⁻¹	Alone
T4	<i>Datura alba</i> L. extract @ 500 kg ha ⁻¹	Alone
T5	<i>Oryza sativa</i> L. extract + ½ Puma super 750EW	Combined
T6	<i>Oryza sativa</i> L. extract + ½ Buctril super 600 EC	Combined
T7	<i>Parthenium hysterophorus</i> L. extract + ½ Puma super 750EW	Combined
T8	<i>Parthenium hysterophorus</i> L. extract + ½ Buctril super 600EC	Combined
T9	<i>Phragmites australis</i> Cav. extract + ½ Puma super 750EW	Combined
T10	<i>Phragmites australis</i> Cav. extract + ½ Buctril super 600EC	Combined
T11	<i>Datura alba</i> L. extract + ½ Puma super 750EW	Combined
T12	<i>Datura alba</i> L. extract + ½ Buctril super 600EC	Combined
T13	½ Puma super 750EW (Grassy killer) @ 625 ml ha ⁻¹	Alone
T14	½ Buctril super 600 EC (Broad leaf killer) @ 375 ml ha ⁻¹	Alone
T15	Hand weeding	-----
T16	Control (weedy check)	-----

EW: Emulsion, Oil-in-Water; EC: Emulsifiable Concentrate

Parameters studied

Grain yield (kg ha⁻¹)

To record grain yield data, three central rows from each subplot were harvested using a sickle. The harvested samples were dried, threshed, weighed, and then converted to kilograms per hectare (kg ha⁻¹) using the following formula:

$$\text{Grain yield (kg/ha)} = \frac{\text{Grain weight of three central rows}}{\text{Row length (m)} \times \text{R-R distance (m)} \times \text{no. of rows}} \times 100$$

Biological yield (kg ha⁻¹)

For recording biological yield, six central rows were

harvested from each treatment and bundles were tied. The weight (kg) was taken after sun drying with the help of spring balance and subsequently was converted into kg ha⁻¹.

Harvest index (%)

The harvest index (%) was recorded using the following formula:

$$\text{Harvest Index (\%)} = \frac{\text{Grain yield} \left(\frac{\text{kg}}{\text{ha}} \right)}{\text{Biological yield} \left(\frac{\text{kg}}{\text{ha}} \right)} \times 100$$

Cost-benefit ratio

To calculate the cost of weed control, the cost of each treatment was determined and compared based on the

prevailing market price of wheat grain. The cost-benefit ratio (CBR) was calculated by dividing the added income by the added cost. The added income was derived from the increase in yield resulting from weed control treatments compared to the weedy check. The added cost referred to the expenses incurred for the control measures applied. The cost-benefit ratio was calculated using the following formula:

$$\text{Cost – benefit ratio (CBR)} = \frac{\text{Added income (Rs)}}{\text{Added Cost (Rs)}} \times 100$$

Proximate analysis of wheat

The proximate analysis of wheat was conducted for each treatment and the results were compared accordingly.

Statistical analysis

The collected data were analyzed using the appropriate procedures for a Randomized Complete Block Design (RCBD). Means were compared using the Least Significant Difference (LSD) test when the F-values were significant (Steel and Torrie, 1984).

RESULTS AND DISCUSSION

Weed density (m⁻²)

Weed density, species composition, and dry biomass are critical indicators of crop yield reduction. Any decline in these parameters through weed management practices directly contributes to improved crop productivity. Statistical analysis revealed that allelopathic extracts, either alone or combined with reduced herbicide doses, significantly ($p < 0.05$) influenced weed density at 45 and 75 days after sowing (DAS). At 45 DAS, the lowest weed density (43.0 m⁻²) was recorded in plots treated with *Parthenium hysterophorus* extract combined with half-dose Puma Super, closely followed by *P. hysterophorus* + half-dose Buctril Super (43.5 m⁻²). Similarly, *Datura alba* extracts in combination with reduced herbicide doses effectively suppressed weeds compared to control or herbicide alone.

Other treatments also reduced weed density, though *P. hysterophorus* and *D. alba* consistently showed stronger suppression. For instance, *Phragmites australis* combined with half-dose herbicides resulted in weed densities of 63.25 and 67.00 m⁻² at 45 DAS, and 152.00 and 159.00 m⁻² at 75 DAS, respectively, compared to untreated plots. Half-dose herbicides alone suppressed weeds moderately (121.38–216.33 m⁻²), but extracts applied independently also demonstrated notable control. Importantly, combined use of extracts and herbicides was more effective than either treatment alone, highlighting the synergistic potential of allelopathy in weed management (Khamare et al., 2022).

The trend of weed density across treatments indicated a

general increase beyond 45 DAS, yet suppression by promising treatments remained consistent throughout the season. The experimental site was heavily infested, explaining the relatively high weed densities overall. Modern studies confirm that allelopathic plants release diverse bioactive compounds—phenolics, alkaloids, terpenoids, flavonoids, and fatty acids—that inhibit weed germination and growth through multiple mechanisms, including disruption of photosynthesis, mitochondrial function, phytohormone regulation, ion uptake, and water balance.

Recent findings emphasize that *P. hysterophorus* extracts, rich in allelochemicals such as parthenin and caffeic acid, can effectively inhibit mitotic activity, enzyme function, and chlorophyll synthesis in weeds (Bashar et al., 2023). When combined with herbicides, these extracts enhance weed suppression and allow reduction of chemical doses, thereby minimizing environmental and health risks (Khamare et al., 2022). Field studies in wheat have shown that allelopathic water extracts of *Oryza sativa*, *P. hysterophorus*, *P. australis*, and *D. alba* combined with reduced herbicide doses significantly lowered weed density while improving yield attributes.

Furthermore, allelopathy is increasingly recognized as a sustainable tool for integrated weed management, offering eco-friendly alternatives to synthetic herbicides (Ihsan et al., 2024). Application timing is crucial; extracts applied at the 2–3 leaf stage of weeds yield better suppression, while late applications may be less effective due to limited soil activity. Overall, the results support the feasibility of using allelochemicals as natural herbicides and growth regulators, contributing to sustainable agriculture.

Grain yield (kg ha⁻¹)

Grain yield was significantly ($p \leq 0.05$) enhanced through effective weed suppression achieved by post-emergence herbicide application, either alone or in combination with allelopathic plant water extracts (Table 3). The integration of allelopathic extracts with half doses of herbicides consistently produced the highest yields, with *Phragmites australis* + ½ Puma Super and *P. australis* + ½ Buctril Super yielding 5,716.4 and 5,655.2 kg ha⁻¹, respectively. These were closely followed by *Parthenium hysterophorus* + ½ Puma Super (5,533.0 kg ha⁻¹) and *P. hysterophorus* + ½ Buctril Super (5,505.2 kg ha⁻¹). Comparable yields were also observed for *Datura alba* + ½ Puma Super (5,410.8 kg ha⁻¹) and *D. alba* + ½ Buctril Super (5,255.2 kg ha⁻¹), while *Oryza sativa* extracts combined with herbicides produced moderate yield increases (5,055.2 and 4,610.8 kg ha⁻¹).

Table 2: Effect of allelopathic plant water extracts in combination with low dose of herbicide on weed density at 45 and 75 days after sowing (DAS).

Extracts/Herbicides	Rate (kg ha ⁻¹)	Weed density (m ⁻²) 45 DAS	Weed density (m ⁻²) 75 DAS
<i>O.sativa</i> (alone)	500	140.88 c	229.88 b
<i>P.hysterophorus</i> (alone)	500	87.00 g	176.00 f
<i>P.australis</i> (alone)	500	127.25 d	216.25 c
<i>D.alba</i> (alone)	500	115.25 f	204.25 e
<i>O.sativa</i> + ½ P. Super 750 EW	500 +500 ml	75.75 h	163.13 g
<i>O.sativa</i> + ½ B. Super 600 EC	500 +300 ml	78.00 h	165.38 g
<i>P.hysterophorus</i> + ½ P. super 750EW	500 +500 ml	43.00 l	145.00 k
<i>P.hysterophorus</i> + ½ B. super 600EC	500 +300 ml	43.50 l	132.75 k
<i>P.australis</i> + ½ P. super 750EW	500 +500 ml	63.25 j	152.00 hi
<i>P.australis</i> + ½ B. super 600EC	500 +300 ml	67.00 i	159.00 gh
<i>D. alba</i> + ½ P. super 750EW	500 +500 ml	52.00 k	141.60 jk
<i>D. alba</i> + ½ B. super 600EC	500 +300 ml	54.75 k	145.25 ij
½ P. Super 750EW	500 ml	121.38 e	210.67 d
½ B. super 600 EC	300 ml	127.75 d	216.33 c
Hand weeding	-	154.13 b	203.13 de
Control (weedy check)	-	178.75 a	267.75 a
Means		95.61	184.40

LSD_(0.05) for weed density (m⁻²) 45 DAS = 2.79; LSD_(0.05) for weed density (m⁻²) 75 DAS = 2.81

The yield improvement was attributed not only to weed suppression but also to the growth-promoting allelopathic effects of plant extracts, including enhanced nutrient mineralization, stimulation of soil microbial activity, and improved root development. These mechanisms ultimately contributed to better crop vigor and grain production. Recent studies confirm that allelopathic extracts can act as bio-stimulants, improving soil microbial health and enzyme activity while simultaneously reducing weed pressure (Khamare et al., 2022; Bashar et al., 2023). The synergistic effect of combining allelopathic extracts with reduced herbicide doses has been highlighted as a sustainable strategy, lowering chemical inputs while maintaining high yield levels (Scavo and Mauromicale., 2021; Kostina-Bednarz et al., 2023).

Consistent with earlier findings, integrated treatments outperformed herbicides or extracts applied alone, demonstrating that allelopathic plants such as *P. australis* and *P. hysterothorus* are particularly effective when combined with synthetic herbicides at reduced rates. This approach not only maximizes yield but also reduces production costs and environmental risks associated with excessive herbicide use. Recent trials in wheat and canola confirm that allelopathic-herbicide combinations improve yield components such as spike number, grain weight, and harvest index, while minimizing ecological impact (Ihsan et

al., 2024).

Biological yield (kg ha⁻¹)

Statistical evaluation revealed that the application of allelopathic plant aqueous extracts, reduced doses of synthetic herbicides, and their integrated treatments exerted a significant influence ($p \leq 0.05$) on the biological yield of wheat (Table 3). The highest yields were obtained in plots treated with *Phragmites australis* combined with half doses of Puma Super (10,878 kg ha⁻¹) and Buctril Super (10,843 kg ha⁻¹). Comparable biological yields were also recorded with *Parthenium hysterothorus* + ½ Puma Super (10,722 kg ha⁻¹) and *P. hysterothorus* + ½ Buctril Super (10,703 kg ha⁻¹). In contrast, untreated control plots produced the lowest biological yield.

The variation in yield among integrated treatments can be attributed to their enhanced weed suppression efficiency, which directly improved crop growth and resource utilization. Recent studies confirm that combining allelopathic extracts with reduced herbicide doses not only suppresses weed density but also sustains crop productivity without yield penalties. For instance, Kundra et al., (2023) demonstrated that allelopathic water extracts integrated with cultural practices significantly improved organic wheat performance. while Jatoi et al., (2022) highlighted the synergistic role of sunflower extract with herbicides in boosting wheat yield.

Beyond weed suppression, allelopathic extracts may exert direct stimulatory effects on crop physiology, enhancing attributes such as plant height, tiller number, and grain yield. Hussain et al. (2023) reported that aqueous wheat extracts themselves can act as biological weed control agents, while Dar et al., (2024) emphasized bacterial allelopathy as a promising eco-friendly alternative for sustainable weed management. These findings align with earlier evidence that integrated treatments improve morpho-physiological traits and biomass accumulation, ultimately increasing fertile tillers, spikelets per spike, and grains per spike.

The growing recognition of allelopathy in agriculture underscores its potential as a biological weed control strategy that reduces reliance on synthetic herbicides and mitigates environmental risks. In conclusion, combining allelopathic plant water extracts with half doses of herbicides maximized reductions in weed density, fresh and dry biomass, while simultaneously enhancing grain yield and net economic returns. This integrated approach offers farmers a viable pathway to achieve higher productivity with reduced chemical inputs. However, widespread adoption will require targeted training and extension services to popularize allelopathic practices among farming communities.

Harvest index (%)

Data analysis indicated that the application of allelopathic

plant water extracts, either alone or in combination with reduced herbicide doses, significantly ($p \leq 0.05$) enhanced the harvest index of wheat (Table 3). Treatments integrating allelopathic extracts with half doses of herbicides consistently produced higher harvest index values compared to single applications of either component. The maximum harvest indices (53.77% and 53.33%) were observed in plots treated with *Phragmites australis* combined with $\frac{1}{2}$ dose of Puma Super and *P. australis* combined with $\frac{1}{2}$ dose of Buctril Super, respectively. These were closely followed by *Parthenium hysterophorus* combined with $\frac{1}{2}$ dose of Puma Super (52.70%) and *P. hysterophorus* combined with $\frac{1}{2}$ dose of Buctril Super (52.62%). In contrast, untreated control plots recorded the lowest harvest index (41.75%).

The inhibitory action of decomposing allelopathic plant residues including roots, stems, leaves, and oily secretions on weed seed germination and seedling growth likely reduced weed competition, thereby improving both grain and biological yields of wheat (Fig. 1). This synergistic effect of bioactive compounds combined with low herbicide doses on yield-related variables is further illustrated in Figure 2, highlighting the potential of integrated allelopathic-herbicide strategies for sustainable crop production.

Table 3: Effect of allelopathic plant water extracts in combination with a low dose of herbicide on yield variables of wheat crop.

Extracts/Herbicides	Grain yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)	Harvest index (%)
<i>O. sativa</i> (alone)	4472 cd	10134 e	45.8 bcdef
<i>P. hysterophorus</i> (alone)	4294 de	10038 efg	44.6 def
<i>P. australis</i> (alone)	4455 cde	10079 ef	45.3 cdef
<i>D. alba</i> (alone)	4278 de	10002 efg	43.8 def
<i>O. sativa</i> + $\frac{1}{2}$ P. super 750 EW	5055 abc	10460 d	49.0 abcde
<i>O. sativa</i> + $\frac{1}{2}$ B. super 600 EC	4611 bcd	10442 d	45.4 cdef
<i>P. hysterophorus</i> + $\frac{1}{2}$ P. super 750EW	5533 a	10722 ab	52.7 ab
<i>P. hysterophorus</i> + $\frac{1}{2}$ B. super 600EC	5505 a	10703 abc	52.6 ab
<i>P. australis</i> + $\frac{1}{2}$ P. super 750EW	5716 a	10878 a	53.8 a
<i>P. australis</i> + $\frac{1}{2}$ B. super 600EC	5655 a	10843 a	53.3 a
<i>D. alba</i> + $\frac{1}{2}$ P. super 750EW	5411 a	10526 cd	52.5 abc
<i>D. alba</i> + $\frac{1}{2}$ B. super 600EC	5255 ab	10564 bcd	50.7 abcd
$\frac{1}{2}$ P. super 750EW	4322 de	9933 fg	45.2 def
$\frac{1}{2}$ B. super 600 EC	4289 de	9880 g	45.0 def
Hand weeding	4278 de	9247 h	43.1 ef
Control	3789 e	8869 i	41.8 f
LSD _(0.05)	681	179	7.2



Figure 1: Weeds density difference between control and treated wheat.

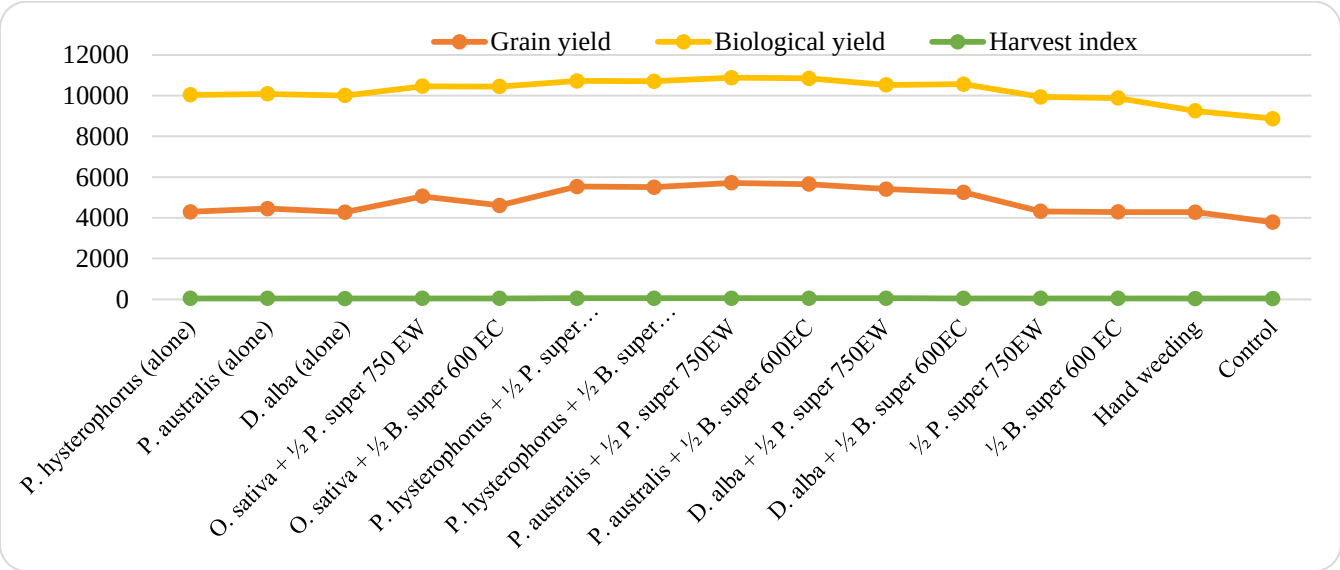


Figure 2: The combined effect of bio-chemicals with low dose of herbicide on yield variables of wheat crop.

Harvest index is determined by the balance between crop productivity and the competitive pressure exerted by weed species. Recent studies confirm that integrating allelopathic plant water extracts with reduced herbicide doses enhances harvest index more effectively than either treatment alone. For example, Hickman et al., (2023) emphasized that cropping system redesign incorporating allelopathy can significantly improve yield efficiency while reducing chemical inputs. Similarly, Kostina-Bednarz et al., (2023) highlighted that allelopathic bioherbicides contribute to sustainable crop growth by suppressing weed interference and improving resource allocation.

The positive influence of allelopathic extracts on crop growth and yield components is largely attributed to their ability to reduce weed competition. Mandviwala., (2025) reported that allelochemicals disrupt weed germination and physiological processes, thereby enhancing crop harvest index and biomass accumulation. Consistent with these findings, Motta Dolianitis et al., (2025) demonstrated that plant-based bioherbicides improved growth parameters and yield stability in organic cropping systems, underscoring their eco-friendly potential. Furthermore, allelopathic residues and powders have been shown to exert species- and dose-specific effects, improving

physiological traits such as chlorophyll content and nutrient uptake. These bioactive compounds act synergistically with low herbicide doses, functioning as bio-herbicides that suppress weed growth while minimizing environmental risks. Variation in weed suppression among plant species is explained by differences in the type and concentration of allelochemicals secreted, reinforcing the importance of species selection in allelopathic weed management. Thus, integrating allelopathic plant water extracts with reduced herbicide doses offers a sustainable pathway to enhance harvest index, reduce chemical dependency, and mitigate ecological harm.

Cost benefit ratio (CBR)

Significant differences ($p \leq 0.05$) were observed for the cost-benefit ratio (CBR). The analysis revealed that all combined treatments of allelopathic plant aqueous extracts with reduced herbicide doses were more economical compared to treatments where allelopathic extracts or reduced herbicide doses were applied alone, including hand-weeded and untreated plots (Table 4). The integrated treatments produced higher net returns, with CBR values of 1:7.1, 1:6.7, 1:5.5, 1:5.0, 1:4.8, and 1:4.3 recorded for *Phragmites australis* + ½ Puma Super, *P. australis* + ½ Buctril Super, *Datura alba* + ½ Puma Super, *D. alba* + ½ Buctril Super, *Parthenium hysterophorus* + ½ Puma Super, and *P. hysterophorus* + ½ Buctril Super, respectively.

Treatments with allelopathic extracts or reduced herbicide doses alone resulted in comparatively lower CBR values. The superior CBR observed in combined applications was primarily due to reduced input costs and enhanced weed suppression. These findings align with recent studies, such as Hussain et al., (2023), who demonstrated that wheat aqueous extracts used in combination with herbicides improved weed control efficiency and profitability. Similarly, Kundra et al., (2023) reported that allelopathic water extracts integrated with cultural practices enhanced economic returns in organic wheat systems.

Earlier evidence also supports this trend. Akbar et al., (2011) found that atrazine alone or in combination with allelopathic extracts increased grain yield through effective weed management. More recent work by Dar et al., (2024) emphasized bacterial allelopathy as a sustainable bioherbicidal approach, reducing reliance on synthetic herbicides while maintaining profitability. Motta Dolianitis et al., (2025) further highlighted that plant-based bioherbicides, when integrated with reduced herbicide doses, improved yield stability and economic efficiency in organic farming systems.

Although herbicide use is globally discouraged due to

environmental and health concerns, their application remains economically significant for immediate weed control. However, herbicide doses can be strategically reduced when combined with allelopathic plant water extracts, offering a more sustainable and cost-effective weed management approach.

Proximate analysis of wheat

The combined treatments of *Phragmites australis* with half doses of Puma Super and Buctril Super exhibited a modest but positive effect on the starch and protein content of wheat grain compared to the control (Table 5). The highest starch (67.92%) and protein (12.13%) levels were recorded in plots treated with *P. australis* + ½ Puma Super, followed closely by *P. australis* + ½ Buctril Super (67.89% starch and 12.10% protein), both exceeding control values. Enhanced wheat growth resulting from effective weed suppression likely improved photosynthetic efficiency, leading to greater carbohydrate and protein accumulation in the grain.

Recent studies confirm that allelopathic extracts and bioactive compounds such as phenolics and amino acids can improve crop quality traits. For instance, Hussain et al., (2023) demonstrated that wheat aqueous extracts reduced weed competition and enhanced grain nutritional quality, while Motta Dolianitis et al. (2025) reported that plant-based bioherbicides improved protein and oil content in organic farming systems. Similarly, Kostina-Bednarz et al. (2023) highlighted the role of allelopathic bioherbicides in regulating crop biochemical processes, including starch and protein synthesis.

Allelopathic plants are known to contain diverse allelochemicals—phenolics, alkaloids, fatty acids, terpenoids, and flavonoids—that influence both crop yield and quality. Phenolic acids such as ferulic, vanillic, and p-hydroxybenzoic have been identified in aqueous extracts and are implicated in modifying plant physiological responses. Mandviwala., (2025) emphasized that phenolic compounds act as bio-regulators, enhancing nutrient uptake and metabolic activity. Amino acids also play critical roles in synthesizing proteins, enzymes, vitamins, and secondary metabolites, thereby contributing to improved grain quality. Overall, phenolics, salicylic acid, fatty acids, and amino acids exert bio-regulatory effects on ion uptake, protein and starch synthesis, and photosynthetic activity. Given that wheat is a staple food for resource-limited farmers in the study area, improvements in grain nutrient content are vital for dietary security. Further research on allelopathic plants and their allelochemicals is warranted to validate these findings and explore their potential in enhancing wheat grain quality under diverse agro-ecological conditions.

Table 4: Cost-benefit ratio (CBR) of allelopathic plant water extracts in combination with a low dose of herbicides for weed control in wheat crop.

Treatments	Yield (kg ha ⁻¹)	Yield increased over control (kg ha ⁻¹)	Additional income (Rs. ha ⁻¹)	Additional expenditure (Rs. ha ⁻¹)	Net income (Rs. ha ⁻¹)	Cost Benefit Ratio
<i>O. sativa</i> (alone)	4471.9	683.3	13666.00	2985.8	10680.20	1:3.6
<i>P. hysterophorus</i> (alone)	4294.1	505.5	10110.00	2985.8	7124.20	1:2.4
<i>P. australis</i> (alone)	4455.2	666.7	13332.00	2985.8	10346.20	1:3.5
<i>D. alba</i> (alone)	4277.5	488.9	9778.00	2985.8	6792.20	1:2.3
<i>O. sativa</i> + ½ P. super 750 EW	5055.2	1266.7	25332.00	4583.3	20748.70	1:4.5
<i>O. sativa</i> + ½ B. super 600 EC	4610.8	822.2	16444.00	3009.8	13434.20	1:4.5
<i>P. hysterophorus</i> + ½ P. super 750EW	5533	1744.4	34888.00	5983.3	28904.70	1:4.8
<i>P. hysterophorus</i> + ½ B. super 600EC	5505.2	1716.7	34332.00	6519.8	27812.20	1:4.3
<i>P. australis</i> + ½ P. super 750EW	5716.4	1927.8	38556.00	4783.3	33772.70	1:7.1
<i>P. australis</i> + ½ B. super 600EC	5655.2	1866.7	37332.00	4819.8	32512.20	1:6.7
<i>D. alba</i> + ½ P. super 750EW	5410.8	1622.2	32444.00	5013.3	27430.70	1:5.5
<i>D. alba</i> + ½ B. super 600EC	5255.2	1466.7	29332.00	4919.8	24412.20	1:5.0
½ P. Super 750EW	4321.9	533.3	10666.00	2320.5	8345.50	1:3.6
½ B. Super 600 EC	4288.6	500.0	10000.00	2334	7666.00	1:3.3
Hand weeding	4277.5	488.9	9778.00	4034	5744.00	1:1.4
Control	3788.6	-	-	-	-	-

Table 5: Effect of allelopathic plant water extracts in combination with a low dose of herbicides on proximate analysis of wheat crop.

Treatments	Starch %	Protein %
<i>O. sativa</i> (alone)	67.79	11.81
<i>P. hysterophorus</i> (alone)	67.77	11.78
<i>P. australis</i> (alone)	67.80	11.82
<i>D. alba</i> (alone)	67.81	11.79
<i>O. sativa</i> + ½ P. Super 750 EW	67.81	11.86
<i>O. sativa</i> + ½ B. super 600 EC	67.84	11.89
<i>P. hysterophorus</i> + ½ P. super 750EW	67.88	11.88
<i>P. hysterophorus</i> + ½ B. super 600EC	67.85	11.91
<i>P. australis</i> + ½ P. super 750EW	67.92	12.13
<i>P. australis</i> + ½ B. super 600EC	67.89	12.10
<i>D. alba</i> + ½ P. super 750EW	67.92	11.97
<i>D. alba</i> + ½ B. Super 600EC	67.97	11.98
½ P. Super 750EW	67.79	11.83
½ B. Super 600 EC	67.81	11.80
Hand weeding	67.34	11.77
Control	67.17	11.72

CONCLUSION

Weed management through physical, mechanical, and cultural practices is generally safer but often less cost-effective. In contrast, synthetic herbicides provide rapid and efficient weed control, though their widespread use raises concern about human health and environmental sustainability. Recent research highlights biological approaches utilizing highly allelopathic plants such as *Phragmites australis*, *Parthenium hysterophorus*, *Datura*

alba, and *Oryza sativa* as promising eco-friendly and economically viable alternatives. These species not only suppress weed populations in field crops but also act as bio-fertilizers, enhancing vegetative growth, yield, and yield components through the release of bioactive compounds. Importantly, *P. hysterophorus* and *P. australis*—both major invasive weeds in many agro-ecosystems—can be repurposed as bio-herbicides. Their use not only reduces the competitive pressure of other weed species but also

contributes to lowering the abundance of these invasive plants themselves, thereby offering a dual benefit of weed suppression and ecological restoration. This integrated approach aligns with sustainable agriculture goals by reducing reliance on chemical herbicides while improving crop productivity and soil health.

RECOMMENDATIONS

Oryza sativa L., *Parthenium hysterophorus* L., *Phragmites australis* Cav., and *Datura alba* L. are widely available plant species that hold considerable potential for use in crop production systems. Although organic food production may be less economically accessible in developing countries, the growing demand in international markets presents significant opportunities for export. Current findings suggest that integrating low doses of herbicides with allelopathic plants represents a promising and sustainable strategy for weed management and crop productivity.

The effectiveness of allelopathic plants depends on their developmental stage, as the concentration and activity of allelochemicals fluctuate with plant maturity and environmental conditions. Therefore, systematic collection and evaluation at different growth stages are essential. Future research should prioritize the recognition, classification, isolation, and synthesis of active allelochemicals from these plants to better understand their mechanisms of action. Moreover, testing low concentrations of allelochemicals is necessary to explore hormesis effects, where sub-lethal doses stimulate plant growth and yield, thereby optimizing their application in sustainable weed management.

AUTHOR'S CONTRIBUTION

Riaz Ahmad Afridi and Muhammad Azim Khan: Conceptualization, Writing – Writing – original draft, Visualization, Validation, Methodology, Data recording and analysis, field work. Muhammad Khalid and Farhanullah: data recording, analysis, review & editing. Syed Asghar, Basit Ali Afridi, Aamir Iqbal, Munsif ur Rahman, Hanif Raza, Akhtar Ali, Farmanullah Khan, Shah Fahad, Qamar Zeb and Albrr Afridi review and formatting.

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