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### Research Article

## ALLELOPATHIC EFFECTS OF DRYLAND PLANT EXTRACTS ON THE SPROUTING OF PURPLE NUTSEDEGE (*CYPERUS ROTUNDUS* L.)

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### ABSTRACT

This study explores the potential of ten arid dryland plant species as novel bioherbicides for the sustainable suppression of purple nutsedge (*Cyperus rotundus* L.), a troublesome weed in many ecosystems. We investigated the allelopathic effects of *Calotropis procera*, *Alhagi maurorum*, *Tamarix aphylla*, *Aerva javanica*, *Capparis decidua*, *Withania coagulans*, *Leptadenia pyrotechnica*, *Haloxylon salicornicum*, *Fagonia indica*, and *Rhazya stricta* using a factorial experiment arranged in a completely randomized design with four replications. Three treatments were compared: a control (C1), a crude aqueous extract (C2), and a 20-fold concentrated extract (C3). The concentrated extracts (C3) of all species completely inhibited the sprouting and growth of purple nutsedge. Notably, *F. indica* (P9 × C2) achieved 100% suppression even at the crude extract level, performing comparably to the concentrated extracts of the other species. *H. salicornicum* (P8 × C2) and *L. pyrotechnica* (P7 × C2) showed statistically similar suppression to *F. indica*. Other crude extracts significantly reduced sprouting percentage, sprouting energy, vigor index, shoot and root length, biomass, and chlorophyll index compared to the control, except for *A. maurorum* and *W. coagulans*. These findings underscore the potential of dryland plant extracts, especially *F. indica*, as promising natural herbicide sources for managing purple nutsedge. Incorporating these bioherbicides into integrated weed management strategies offers a sustainable and eco-friendly alternative to synthetic herbicides, reducing their usage and enhancing ecological health.

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### INTRODUCTION

The escalating global demand for food necessitates the development of sustainable agricultural practices that minimize environmental impact while maximizing crop yields (Getahun et al., 2024). Conventional weed management, which heavily relies on synthetic herbicides, poses significant challenges, including the emergence of

herbicide-resistant weeds (Ofosu et al., 2023), soil and water contamination (Stefanski et al., 2020), and adverse effects on human health (Parven et al., 2024). This dependence on synthetic chemicals contradicts the growing global push for sustainable agriculture, prompting the search for environmentally friendly alternatives (Muhie, 2022). Allelopathy, the chemical

interaction between plants, offers a promising avenue for sustainable weed management (Ain et al., 2023). This phenomenon involves the release of allelochemicals by certain plants, which can inhibit the germination, growth, and development of neighboring plants, including weeds (Akhtar et al., 2024). The use of allelopathic plant extracts as bioherbicides presents a compelling strategy to reduce dependence on synthetic herbicides, thereby contributing to a more environmentally sustainable agricultural system (Islam et al., 2024).

The study aimed to investigate the allelopathic potential of dryland plant extracts as a sustainable strategy for controlling purple nutsedge (*Cyperus rotundus*), a globally significant and notoriously difficult-to-manage weed (Ameena et al., 2024). The adaptability and resilience of purple nutsedge to diverse environmental conditions, along with its ability to reproduce both sexually and asexually, make it a major threat to crop productivity worldwide (Babiaka et al., 2024). Its aggressive growth habit necessitates the development of effective and sustainable control measures to significantly reduce crop losses and minimize the environmental and economic impacts associated with conventional weed management strategies (Gao and Su, 2024; Kumar and Kaur, 2024).

Plants that thrive in desert conditions have evolved sophisticated mechanisms to cope with water scarcity and nutrient limitations. These adaptations often include the production of secondary metabolites that serve multiple functions, such as defense against herbivores and competition with neighboring plants (Ali et al., 2024). Some of these secondary metabolites, which are central to allelopathy research, have shown promise as natural herbicides (Islam et al., 2024; Nath et al., 2024). Plant extracts may delay seed germination, inhibit plant growth, or cause other adverse effects due to the presence of allelochemicals (Li et al., 2024; Wang et al., 2024). Numerous studies have examined the allelopathic behavior and extract potential of certain graminoid species for weed control (Khamare et al., 2022; Mohamed Salman et al., 2024).

The herbicidal potential of semi-arid plants such as *Rhazya stricta*, *Citrullus colocynthis*, *Crotalaria burhia*, and *Calligonum polygonoides* against *Lathyrus aphaca*, a common weed in wheat fields, has shown suppression rates ranging from 9% to 91% across various growth parameters, offering a sustainable alternative to synthetic herbicides (Iqbal et al., 2020). Aqueous

extracts from some tropical plants have also been found to delay and reduce nutsedge sprouting, with complete suppression observed at higher concentrations (Iqbal et al., 2018). Several studies have confirmed the strong allelopathic and herbicidal potential of tropical plants such as *R. stricta* (Al-Mutlaq, 2001; Khan et al., 2011; Musharaf Khan et al., 2011; Anwar et al., 2018).

This study aims to evaluate the allelopathic potential of dryland plant extracts for the sustainable management of *C. rotundus* L., thereby reducing reliance on synthetic herbicides. Specifically, it investigates the allelopathic efficacy of desert plants. Although existing research on allelopathy has primarily focused on weed control using monocotyledonous wild plants, limited attention has been given to the allelopathic potential of dicot species grown under stressful conditions. This study addresses this gap by evaluating the allelopathic effects of ten dicotyledonous wild plants viz. *Calotropis procera*, *Alhagi maurorum*, *Tamarix aphylla*, *Aerva javanica*, *Capparis decidua*, *Withania coagulans*, *Leptadenia pyrotechnica*, *Haloxylon salicornicum*, *Fagonia indica*, and *R. stricta* on the sprouting and growth of purple nutsedge. The research aims to identify potent plant-based bioherbicides that can be integrated into weed management strategies, ensuring effective control while minimizing environmental and health risks.

## MATERIAL AND METHODS

### Experiment site and plant collection

To evaluate the weedicide potential of ten selected dryland plants against the troublesome purple nutsedge (*Cyperus rotundus* L.), a Petri dish experiment was meticulously conducted in the Botany Laboratory of Ghazi University, Dera Ghazi Khan. Mature plant specimens were collected from the arid regions of Dera Ghazi Khan (30.03°N, 70.38°E; 129 meters above sea level), characterized by dryland conditions.

### Experimental layout and extract preparation

The allelopathic potential of ten dryland plants, *Calotropis procera*, *Alhagi maurorum*, *Tamarix aphylla*, *Aerva javanica*, *Capparis decidua*, *Withania coagulans*, *Leptadenia pyrotechnica*, *Haloxylon salicornicum*, *Fagonia indica*, and *Rhazya stricta*, was evaluated using a completely randomized design (CRD) with four replications. The experiment comprised two factors: Factor A included the ten plant species, while Factor B consisted of three extract concentrations, including a control.

Plant extract preparation involved several steps. First, the collected plant material was shade-dried at a temperature of  $35^{\circ}\text{C} \pm 2^{\circ}\text{C}$  and then chopped into approximately 2 cm pieces. These pieces were soaked in distilled water at room temperature (approximately  $35^{\circ}\text{C} \pm 2^{\circ}\text{C}$ ) for 24 h at a 1:10 (w/v) ratio, following the method of Iqbal et al. (2018). The resulting mixture was filtered through sieves with mesh sizes of 10 and 60.

Two types of extracts were prepared, considering that allelopathic effects are concentration-dependent. The crude aqueous extract (C2) was obtained by soaking the dried plant material in distilled water for 24 h, while the concentrated extract (C3) was prepared by boiling the crude extract to reduce its volume to one-twentieth of the original. A control treatment (C1), consisting of distilled water, was included for comparison.

Five *C. rotundus* tubers were placed in each Petri dish

corresponding to the treatment. Each Petri dish received 6 ml of the respective plant extract after placing the tubers. The experiment was replicated four times using the same Petri dish protocol. Germination data were recorded daily.

#### Parameters studied

The following parameters were assessed during the experiment:

#### Time to start sprouting

Sprouting of each tuber per treatment and replication was recorded daily. The day on which sprouting began in each treatment was noted.

#### Sprouting percentage

Sprouting data were recorded daily throughout the experiment. Only tubers with radicles at least 2 mm in length were considered sprouted. The total percentage of sprouted tubers on the final day of the experiment was calculated using the following formula:

$$\text{Sprouting percentage} = \frac{\text{Number of tubers Sprouted}}{\text{Total tubers in particular petri dish}} \times 100$$

#### Mean sprouting time (M.S.T)

Mean sprouting time (M.S.T) refers to the average duration required for tubers to begin sprouting, with an emphasis on identifying the day when the majority of tubers have initiated sprouting. To calculate the mean germination time (MGT) for the tested tubers, the formula proposed by Ellis et al., 1981 was used.

$$\text{Mean sprouting time} = \frac{\sum Dn}{\sum n}$$

The formula for calculating MGT involves using the

variable "D" to represent the number of days counted from the start of the sprouting process, and "n" is the number of tubers that have sprouted on the day "D".

#### Sprouting index (S.I)

The sprouting index is a parameter that combines both the percentage of sprouting and the time taken for sprouting. To calculate the sprouting index for purple nutsedge, the formula was used based on the guidelines provided by the Association of Official Seed Analysts (AOSA, 1983).

$$\text{GI} = \frac{\text{Number of seed germinated} + \dots + \text{Number of seed germinated}}{\text{First day count} \quad \quad \quad \text{Final day count}}$$

#### Root and shoot length

Root and shoot lengths were measured using a measuring scale. The average length (cm) was calculated for both roots and shoots.

#### Root and shoot fresh weight

Roots and shoots were separated at the base, and their fresh weights (mg) were measured for each treatment using a digital electronic balance. The average fresh weight per plant was then calculated.

#### Root and shoot dry weight

Fresh plant materials from each treatment were oven-dried at  $70^{\circ}\text{C}$  for 48 h until a constant weight was achieved. The dry biomass was recorded using a digital electronic balance, and the mean dry weight per treatment was calculated.

#### Chlorophyll content (SPAD)

Chlorophyll content was measured on purple nutsedge leaves using a plant chlorophyll meter (SPAD meter), and the average SPAD value was recorded.

#### Data analysis

All data were analyzed using analysis of variance (ANOVA) under a factorial arrangement in a CRD. Treatment means were separated using the Least Significant Difference (LSD) test at a 1% level of significance, using STATISTIX 8.1 software.

## RESULTS

Significant effects were observed for plant extracts, concentration levels, and their interaction ( $p \leq 0.01$ ) (Table 1). The results in Table 2 demonstrated the

individual effect of plants and extract concentration level. concentrated water extracts (C3: 100%) of all dryland plants completely inhibited sprouting, resulting in a 0% sprouting rate across all measured parameters as presented in Table 2. Interaction analysis between plant extract and concentration level is presented in Table 3. Notably, *F. indica* (P9 × C2) achieved 100% suppression of tuber sprouting at the crude extract concentration, showing results comparable to the concentrated extracts of all plant species. Among the crude extract treatments (C2), *F. indica* (P9 × C2) and *H. salicornicum* (P8 × C2) performed similarly to the concentrated extracts of other plants. However, all crude extract treatments (C2) significantly reduced sprouting rate index, sprouting percentage, sprouting energy, vigor index, shoot and root length, fresh and dry biomass, and chlorophyll content compared to the control, except for

*T. aphylla* (P4 × C2), followed by *W. coagulans* and *A. maurorum*. Following *F. indica* (P9 × C2), the C2 treatments of *H. salicornicum* (P8) and *L. pyrotechnica* (P7) exhibited the highest allelopathic potential against purple nutsedge sprouting, closely followed by *R. stricta* and *C. deciddua*.

Among the tested plant crude extract treatments (C2), *H. salicornicum* exhibited the most pronounced inhibitory effect on sprouting parameters, significantly delaying sprouting with a mean sprouting time of 6.53 days. It also recorded the lowest sprouting rate index (0.17) and a final sprouting percentage of just 5.00%, indicating strong suppression of purple nutsedge emergence. Similarly, *L. pyrotechnica* showed substantial inhibitory potential, with a mean sprouting time of 6.31 days, a sprouting rate index of 0.43, and a final sprouting percentage of 10.00% as shown in Figure 1 and Table 3.

Table 1. Analysis of variance for Mean sprouting time, sprouting rate index, Final sprouting percentage, and Vigor index of purple nutsedge as influenced by various plants extract with LSD

Source	DF	Mean sum of squares				
		Mean sprouting time	Sprouting rate index	Final sprouting percentage	Sprouting energy	Vigor index
Concentrations (C)	2	410.52***	132.62***	48543***	2919***	932888***
Plants (P)	9	4.84***	5.23***	1348***	751.5***	30620**
Concentrations×Plants	18	4.95***	1.58**	447***	393.7***	81900***
Error	90	0.49	0.60	118.2	118.9	33936

\*\*\* = Significant at p ≤ 0.01, \*\* = Significant at p ≤ 0.05, ns = non-significant at p > 0.05

Table 2. Effect of selected dryland plant extracts on the sprouting parameter of purple nutsedge (individual comparisons of plant extracts and concentrations).

Treatments/Plant extract	Mean sprouting	Sprouting rate index	Final sprouting	Sprouting energy	Vigor index
P1: <i>Calotropis procera</i>	3.87a	1.76bcd	38.33abc	33.33ab	391.83cd
P2: <i>Alhagi maurorum</i>	3.80a	2.53ab	45.00a	35.00ab	631.33ab
P3: <i>Aerva javavica</i>	3.94a	1.53cde	31.66bcd	26.66bc	379.33cde
P4: <i>Tamarix aphylla</i>	3.85a	1.85bcd	38.33abc	26.66bc	433.33bcd
P5: <i>Cappris deciddua</i>	3.81a	2.29abc	41.66ab	26.66bc	505.83bc
P6: <i>Withania coagulans</i>	3.54a	2.86a	48.33a	40.00a	710.33a
P7: <i>Leptadenia pyrotechnica</i>	4.05a	1.22de	23.33de	16.66c	310.17cde
P8: <i>Haloxylon salicornicum</i>	4.21a	1.05de	20.00de	16.66c	270.08de
P9: <i>Fagonia indica</i>	1.95b	0.83e	18.33e	18.33c	193.50e
P10: <i>Rhazya stricta</i>	3.88a	1.43de	28.33cde	25.00bc	349.83cde
LSD at p≤0.01	0.75	0.83	11.68	11.72	198.06
<b>Concentrations</b>					
C1: Control	5.75 a	3.63 a	69.50 a	54.0 a	946.42 a
C2: Crude extract	4.82 b	1.57 b	30.50 b	25.50 b	284.35 b
C3: 100% Concentrated extract	0.00 c	0.00 c	0.00 c	0.00 c	0.00 c
LSD at p≤0.01	0.53	0.46	6.50	6.53	109.18

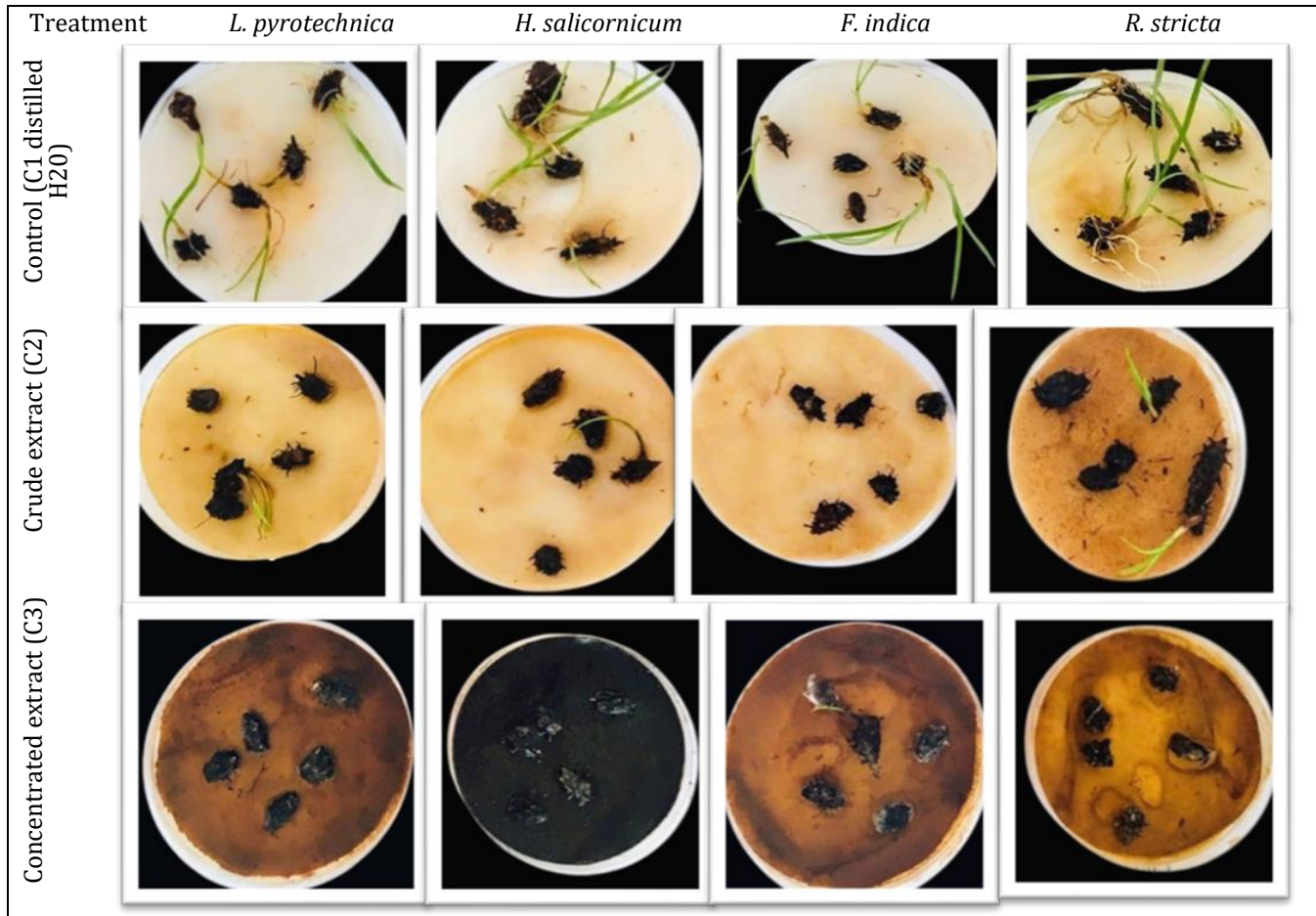


Figure 1. Comparative effects of the most effective plant treatments on purple nutsedge sprouting.

Analysis of variance revealed highly significant effects ( $p \leq 0.01$ ) for plant extracts, concentration levels, and their interaction (Table 4) on growth parameters. The individual effects of plant extracts showed a significant reduction in shoot and root length, as well as in fresh and dry weight. *F. indica* (P9) exhibited the lowest growth, biomass, and chlorophyll content, and its performance was statistically similar to that of *H. salicornicum*. *L. pyrotechnica* also caused a significant reduction in growth parameters and was statistically comparable to *R. stricta*. In contrast, *W. coagulans* (P6) had a promotive effect, showing the highest shoot and root lengths. Its fresh and dry weight and SPAD value were statistically at par with *A. maurorum* as presented in Table 5.

However, the 100% concentration (C3) of all plant extracts completely inhibited shoot and root growth, with all growth parameters recorded as zero. This pattern indicates that C3 was the most effective in suppressing purple nutsedge sprouting.

A more detailed interaction analysis (Table 6) revealed that the combined effects of different plant extracts and concentrations on purple nutsedge growth, biomass, and

chlorophyll index were complex and variable. Specifically, all ten dryland plant extracts at their highest concentration (100%, C3) completely suppressed tuber sprouting, resulting in zero shoot and root length, fresh and dry weight, and chlorophyll index. Among the crude extract treatments (C2), *F. indica* (P9  $\times$  C2) completely inhibited tuber sprouting. Similarly, *H. salicornicum* (P8  $\times$  C2) and *L. pyrotechnica* (P7  $\times$  C2) showed comparable effectiveness, resulting in minimal shoot and root length, fresh and dry weight, and chlorophyll index. Crude water extracts from other plants also reduced these parameters compared to the control, except for *A. maurorum*, *W. coagulans*, and *C. decidua* at the C2 concentration.

Moderate suppression was observed with the extracts of *R. stricta* (P10  $\times$  C2) and *C. decidua* (P5  $\times$  C2). The crude extract of *R. stricta* extended the mean sprouting time to 6.06 days, reduced the sprouting rate index to 1.05, and limited the final sprouting percentage to 20.00%. *C. decidua* followed, with a mean sprouting time of 5.83 days, a sprouting rate index of 2.58, and a final sprouting percentage of 45.00%, both showing significant reductions compared to the control.

Table 3. Effect of selected dryland plant extracts on the sprouting parameters of purple nutsedge (interaction between plant extracts x concentration).

Treatments/ Plant extract	Mean sprouting time	Sprouting rate index	Final sprouting percentage	Sprouting energy	Vigor index
P1 × C1	5.67 ab	3.45 b-e	75 abc	65 ab	921.5 b-e
P1 × C2	5.95 ab	1.85 f-i	40 efg	35 cde	254 hij
P1 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P2 × C1	5.87 ab	4.68 ab	80 ab	65 ab	1256.5 ab
P2 × C2	5.53 ab	2.91 c-f	55 cde	40 cde	637.5 d-g
P2 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P3 × C1	5.81 ab	3.40 b-e	65 abcd	55 abc	887 cde
P3 × C2	6.02 ab	1.17 ghij	30 fgh	35 cde	251 hij
P3 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P4 × C1	5.62 ab	3.49 b-e	75 abc	55 abc	940 bcd
P4 × C2	5.93 ab	2.06 e-h	40 efg	35 cde	360 ghi
P4 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P5 × C1	5.58 ab	4.28 abc	80 ab	50 abcd	1036.50 bc
P5 × C2	5.83 ab	2.58 d-g	45 def	35 cde	481 fgh
P5 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P6 × C1	5.50 ab	5.04 a	85 a	70 a	1425 a
P6 × C2	5.13 b	3.56 bcd	60 bcde	50 abcd	706 c-f
P6 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P7 × C1	5.83 ab	3.23 b-f	60 bcde	45 bcd	810 c-f
P7 × C2	6.31 ab	0.43 ij	10h i	5 f	120.5 ij
P7 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P8 × C1	6.10 ab	2.97 c-f	55 cde	45 bcd	795.25 c-f
P8 × C2	6.53 a	0.17 j	5.00 i	5 f	15.03 ij
P8 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P9 × C1	5.85 ab	2.50 d-g	55 cde	55 abc	580.5 e-h
P9 × C2	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P9 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
P10 × C1	5.58 ab	3.24 b-f	65 abcd	55 abc	812 c-f
P10 × C2	6.06 ab	1.05 hij	20 ghi	20 ef	237.5 hij
P10 × C3	0.00 c	0.00 j	0.00 i	0.00 f	0.00 j
LSD at p≤0.01	1.31	1.44	20.24	20.31	343.05

Means not sharing a letter in common in column differ significantly at a 1% probability level by the LSD test.

Table 4. Analysis of variance for shoot length, Root length, Root fresh weight, and shoot fresh weight weight, shoot dry weight and chlorophyll index of purple nutsedge as influenced by selected dryland plant extracts with LSD.

Source	DF	Mean Sum of Squares						
		Shoot length (cm)	Root length (cm)	Root fresh weight	Root dry weight (mg)	Shoot fresh weight	Shoot dry weight (mg)	Chlorophyll index
Concentrations(C)	2	750.22**	255.70***	11785***	55.06***	280888***	3308***	15528***
Plants (P)	9	17.84***	11.21***	333***	1.35***	6816***	194.69***	370***
Concentrations×Pla	18	6.90***	2.97***	120***	0.55***	3853***	57.82***	237***
Error	90	1.41	0.44	3.00	0.03	288	6.34	14.30

\*\*\* = Significant at p ≤ 0.01, \*\* = Significant at p ≤ 0.05, ns = non-significant at p > 0.05.

Table 5. Effect of selected dryland plant extracts on the germination parameter of purple nutsedge (individual comparisons of plant extracts and concentrations).

Treatments/Plant extract	Shoot length (cm)	Root length (cm)	Root fresh weight (mg)	Root dry weight (mg)	Shoot fresh weight (mg)	Shoot dry weight (mg)	Chlorophyll index
P1: <i>Calotropis procera</i>	4.67 bcd	2.79 bc	16.55 cd	1.26 bcd	86.57 b	8.54 cd	17.11 bc
P2: <i>Alhagi maururum</i>	5.85 ab	3.50 ab	19.84 b	1.39 ab	118.00 a	11.94 b	26.37 a
P3: <i>Aerva javavica</i>	4.40 cd	2.56 cd	16.32 cd	1.20 cd	84.37 b	8.03 cd	16.76 bc
P4: <i>Tamarix aphylla</i>	5.05 4abc	2.96abc	17.96 bc	1.18 cd	87.15 b	8.63 cd	18.83 b
P5: <i>Cappris decidua</i>	5.375 abc	3.23abc	19.16 b	1.33 abc	91.43 b	9.43 bc	24.76 a
P6: <i>Withania coagulans</i>	5.98 a	3.59 a	26.14 a	1.47 a	120.71 a	18.92 a	28.76 a
P7: <i>Leptadenia pyrotechnica</i>	3.47 de	1.63 e	11.75 e	0.75 e	65.75 cd	6.56 de	16.02 bcd
P8: <i>Haloxylon salicornicum</i>	2.76 e	1.25 ef	9.76 f	0.73 e	54.17 d	5.93 de	14.15 cd
P9: <i>Fagonia indica</i>	2.47 e	0.86 f	8.167 f	0.45 f	47.92 d	4.67 e	12.13 d
P10: <i>Rhazya stricta</i>	4.12 cd	1.86 de	15.82 d	1.08 d	80.37 bc	7.15 cde	16.46 bc
LSD at p≤0.01	1.28	0.71	1.87	0.17	18.23	2.71	4.06
Concentrations							
C1: Control	8.65 a	5.04 a	34.72 a	2.34 a	167.60 a	18.18 a	39.160 a
C2: Crude extract	4.59 b	2.22 b	14.26 b	0.91 b	83.41 b	8.75 b	18.045 b
C3: 100% Concentrated	0.00c	0.00 c	0.00 c	0.00 c	0.00 c	0.00 c	0.00c
LSD at p≤0.01	0.70	0.39	0.96	0.09	10.08	1.49	2.20

The maximum reduction in vigor index was observed with the crude extract of *H. salicornicum*, which lowered the vigor index to 15.03, representing a 98.5% decrease compared to the control (1036.5). *L. pyrotechnica* also exhibited strong suppressive effects, with a vigor index of 120.5. These findings indicate that, among the C2 treatments, *H. salicornicum* and *L. pyrotechnica* were the most effective in reducing sprouting rates and vigor index, following *F. indica*, which demonstrated the strongest allelopathic potential as demonstrated in Figure 1 and Table 6.

Regarding the concentration effects, the concentrated water extracts exhibited the strongest inhibitory effect on growth, biomass, and chlorophyll content, followed by crude extracts. Both concentrations (C2 and C3) were significantly more inhibitory than the control (Table 6).

## DISCUSSION

The allelopathic potential of ten above-mentioned dryland plant species was evaluated for their effects on the sprouting and growth attributes of purple nutsedge. Two extract concentrations were tested, based on the principle that allelopathic effects are often concentration-dependent: a crude aqueous extract

(C2), prepared by soaking plant material in distilled water for 24 h, and a concentrated extract (C3), obtained by boiling the crude extract to reduce its volume twentyfold. A control treatment (C1) was included for comparison. This methodological approach aimed to assess the potential of these plant extracts as a sustainable strategy for suppressing purple nutsedge sprouting.

Among the crude extract treatments (C2), *F. indica* (P9 × C2) and *H. salicornicum* (P8 × C2) performed comparably to the concentrated extracts (C3) of the other species. Except for *W. coagulans* (P6) and *A. maurorum* (P2), which showed a promotive effect, all crude extracts significantly reduced sprouting compared to the control. These findings are consistent with the well-established understanding that allelopathic effects are concentration-dependent, with stronger inhibitory effects observed at higher concentrations.

This study highlights the effectiveness of bioactive compounds such as phenolics and alkaloids in suppressing germination and growth by disrupting the metabolic activities of weeds (Alqarawi et al., 2018; Shirgapure and Ghosh, 2020; Anwar et al., 2021a, b;

Fangue-Yapseu et al., 2021; Alemayehu et al., 2024). A comparative analysis of the plant extracts revealed significant variations in their allelopathic potential against *C. rotundus*. *F. indica* demonstrated the highest efficacy, exhibiting the greatest reduction in sprouting, growth, and chlorophyll index. Notably, its allelopathic potential was statistically similar to that of *H. salicornicum*, *L. pyrotechnica*, and *R. stricta*, identifying these four species as the most potent.

This remarkable finding underscores the potential of *F. indica* as a natural herbicide alternative and aligns with studies such as Iqbal et al. (2018), who reported complete suppression of tuber sprouting at 100% extract concentration. Similar results have been reported by other researchers (Dastagir and Hussain, 2013; Iqbal et al., 2018; Khan et al., 2018), who also observed significant phytotoxic effects of *Fagonia* species against common weeds and crops.

Table 6. Effect of selected dryland plant extracts on the germination parameter of purple nutsedge (interaction between plant extracts x concentration).

Treatments/ Plant extract	Shoot length (cm)	Root length (cm)	Root fresh weight (mg)	Root dry weight (mg)	Shoot fresh weight (mg)	Shoot dry weight (mg)	Chlorophyll index
P1 × C1	8.50 abc	5.63 ab	33.75 cde	2.55 ab	173.65 ab	17.40 cd	38.83 abc
P1 × C2	5.50 def	2.75 fg	15.90 j	1.22 e	86.06 c	8.23 fg	12.50 d
P1 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P2 × C1	10.18 a	6.50 de	38.01 b	2.65 a	178.75 a	19.325 c	42.87 ab
P2 × C2	7.38 bcd	4.00 de	21.50 gh	1.53 d	175.25 ab	16.50 cd	36.25 bc
P2 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P3 × C1	8.43 abc	5.32 bc	33.57 de	2.39 abc	173.56 ab	17.16 cd	38.45 abc
P3 × C2	4.78 ef	2.37 gh	15.37 j	1.21 ef	79.55 c	6.93 fgh	11.83 de
P3 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P4 × C1	9.16 ab	5.87 ab	36.90 bc	2.25 bc	173.75 ab	17.63 cd	39.67 abc
P4 × C2	6.04 def	3.00 efg	16.98 ij	1.30 de	87.69 c	8.25 fg	16.80 d
P4 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P5 × C1	9.55 ab	5.87 ab	37.87 b	2.65 a	177.50 a	17.77 cd	40.47 abc
P5 × C2	6.58 cde	3.83 def	19.63 hi	1.33 de	96.8 c	10.50 ef	33.82 c
P5 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P6 × C1	10.40 a	6.73 a	43.30 a	2.68 a	184.20 a	32.5 a	43.77 a
P6 × C2	7.55 bcd	7.05 de	35.13 bcd	1.54 d	178.13 a	24.25 b	42.50 ab
P6 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P7 × C1	8.25 abc	4.25 cd	31.50 ef	2.25 c	157.25 ab	15.17 cde	37.80 abc
P7 × C2	2.15 gh	0.625 ij	3.75 k	0.00 g	40.0 d	4.50 ghi	10.25 de
P7 × C3	0.00 h	3.37 d-g	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P8 × C1	6.31 cde	0.00 j	29.27 f	2.17 c	144.25 b	15.13 cde	37.45 abc
P8 × C2	2.02 gh	0.37 ij	0.00 l	0.00 g	18.25 de	2.67 hi	5.00 ef
P8 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P9 × C1	7.43 bcd	2.57 g	24.50 g	1.34 de	143.75 b	14d e	36.37 bc
P9 × C2	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P9 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
P10 × C1	8.38 abc	4.33 cd	33.05 de	2.34 bc	169.5 ab	15.75 cd	37.90 abc
P10 × C2	3.98 fg	1.25 hi	14.41 j	0.92 f	71.63 c	5.713 gh	11.50 de
P10 × C3	0.00 h	0.00 j	0.00 l	0.00 g	0.00 e	0.00 i	0.00 f
LSD at p≤0.01	2.21	1.24	3.24	0.29	31.58	4.69	7.03

Means not sharing a letter in common in column differ significantly at a 1% probability level by the LSD test.

Although limited literature exists on the allelopathic properties of *F. indica* against weeds, its phytochemical and medicinal properties have been extensively studied (Farheen et al., 2017; Ali and Khan, 2021; Sulieman et al., 2023). The complete inhibition observed in the present study might be attributed to bioactive compounds identified in *F. indica*, such as flavonoids, alkaloids, saponins, terpenoids, coumarins, and tannins, which are known to inhibit weed germination and growth (Anwar et al., 2021a, b; Serag et al., 2020).

Similarly, *H. salicornicum* contains several phytochemicals including alkaloids, tannins, saponins, and glycosides, which may contribute to its allelopathic potential (Al-Saeed et al., 2023; Otmani et al., 2023). *L. pyrotechnica*, rich in phenolic acids and flavonoids, also reduced germination parameters at higher concentrations, supporting its proposed use as a natural herbicide (Hassan and Mohammed, 2020). These compounds have been shown to adversely affect seed germination and plant growth across multiple species (Kumari et al., 2024), further validating the potential of *L. pyrotechnica* in sustainable weed management.

Moreover, *R. stricta* demonstrated strong allelopathic activity against purple nutsedge, consistent with previous studies that reported its inhibitory effects on the germination and growth of weeds, with efficacy increasing proportionally to extract concentration (Alqarawi et al., 2018; Khan et al., 2011; Anwar et al., 2021a, b; Zamanipour et al., 2024). These findings are further supported by studies showing that allelochemicals can significantly reduce final germination percentage, mean germination time, and germination rate index in various weed species (Othman et al., 2023).

The significant suppression of *C. rotundus* tuber sprouting observed with extracts of *F. indica*, *H. salicornicum*, *L. pyrotechnica*, and *R. stricta* likely involves a complex interplay of allelopathic mechanisms. Allelopathic compounds can disrupt the initial stages of tuber sprouting by interfering with water uptake (imbibition), hormonal regulation, and enzymatic activity (Hsueh et al., 2020). For instance, stress-adapted plants release various phenolic compounds, a common class of allelochemicals (Einhellig, 1995), which have been shown to inhibit the activity of the enzyme  $\lambda$ -phosphorylase involved in seed germination. This enzyme may be suppressed by chlorogenic acid, caffeic acid, and catechol (Rice, 1985; Einhellig, 1995), which are essential for the breakdown of storage reserves in

tubers, thereby supplying energy for sprouting (Rice, 1985). The biochemical pathways through which allelochemicals inhibit sprouting include cell destruction, disruption of oxidative homeostasis, and photoinhibition, all of which negatively impact seed germination and overall plant growth and development (Cheng et al., 2024). Further research is required to elucidate these pathways in greater detail.

All plant extracts, except those from *A. maurorum* and *W. coagulans*, significantly reduced *C. rotundus* seedling vigor (as indicated by root and shoot length, fresh and dry biomass, and vigor index) compared to the control, demonstrating strong allelopathic effects consistent with the findings of Waris et al. (2024). These reductions suggest the presence of bioactive compounds capable of disrupting hormonal balance, particularly the auxin-to-cytokinin ratio, thereby interfering with cell division and differentiation. This ultimately inhibits germination and early seedling growth, as supported by Staszek et al. (2021) and Yan et al. (2022). In contrast to the more effective extracts, *W. coagulans* showed minimal allelopathic inhibition, with effects statistically similar to *A. maurorum*, followed by *C. decidua*, *T. aphylla*, and *C. procera*. This variability is likely due to differences in their phytochemical profiles, including alkaloids, phenolics, and flavonoids, which are known to affect *C. rotundus* (Carvalho et al., 2023). Particularly, *A. maurorum* and *W. coagulans* exhibited no inhibitory effects at low concentrations (C2), in contrast to findings by Khalil et al. (2020). However, complete inhibition of sprouting was observed at the highest concentration (C3), supporting the concentration-dependent nature of allelopathy (Mota et al., 2020).

Crude extracts of most dryland plants, except *A. maurorum* and *W. coagulans*, reduced the chlorophyll index of *C. rotundus*, consistent with the known allelopathic potential of plant extracts. Concentrated extracts (C3) of all tested species, as well as the crude extract (C2) of *F. indica*, completely inhibited sprouting and eliminated chlorophyll. Consistent with previous studies (Ye et al., 2006; Yang et al., 2004), high concentrations of bioactive compounds can impair photosynthesis by inhibiting antioxidant enzymes, leading to the accumulation of harmful reactive oxygen species (ROS). Moreover, allelochemicals are known to damage the photosynthetic apparatus.

A proportional decrease in chlorophyll and porphyrin content was observed following the application of specific

allelochemicals, including o-hydroxyphenylacetic acid, ferulic acid, and p-coumaric acid, as reported by Huang et al. (2023). This supports the disruptive impact of allelochemicals in concentrated extracts on chlorophyll synthesis and overall plant health (Souza et al., 2020; Janusauskaite, 2023; Akter et al., 2024). However, *W. coagulans* and *A. maurorum* extracts promoted higher chlorophyll indices, in contrast to earlier findings that reported moderate inhibitory effects from these species (Khalil et al., 2017; Khalil et al., 2020; Islam et al., 2024). This discrepancy may be attributed to differences in extraction methods, plant developmental stages, or environmental factors affecting allelochemical activity (Ahmed et al., 2025).

### CONCLUSION

The findings of this study hold considerable promise for advancing sustainable weed management practices. The strong inhibitory effects of *Fagonia indica*, *Haloxylon salicornicum*, *Leptadenia pyrotechnica*, and *Rhazya stricta* on purple nutsedge suggest that these species could serve as environmentally friendly and effective alternatives to synthetic herbicides, thereby reducing dependence on chemical weed control.

With herbicide-resistant weeds posing a growing threat to global agricultural productivity, effective alternative strategies are essential. The practical implications of this research extend to the development of natural herbicide formulations based on these potent plant extracts. Such products could provide farmers with sustainable options for weed management, minimizing chemical inputs while ensuring effective weed suppression. This aligns with global efforts to adopt more sustainable agricultural practices that safeguard both environmental and human health.

Furthermore, integrating these findings into an overall weed management strategy could help mitigate the adverse effects of excessive herbicide use, such as soil fertility loss, soil structure degradation, and water contamination. Future research should focus on optimizing extraction techniques and concentrations and identifying the specific phytochemicals responsible for the observed allelopathic effects to enhance the efficacy and commercial potential of these bio-herbicides.

### AUTHORS' CONTRIBUTIONS

SA and JI designed the study, formulated the experiments, and executed them; SA collected and

organized the data, analyzed the results, and wrote the manuscript; JI and AA assisted in writing the manuscript and proofreading the paper.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### SUSTAINABLE DEVELOPMENT GOALS TARGETED

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

SDG 15: Life on Land

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