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Screening of herbicides for weed management in quinoa (*Chenopodium quinoa* Willd.) - The first report from India

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Abstract

Weed management without herbicide poses a significant challenge in crop production, especially for emerging crops like quinoa, which are highly sensitive to many herbicides. Identifying suitable herbicides and determining their optimal doses are critical steps for enhancing quinoa cultivation. To address this, two screening experiments followed by a conformity study were conducted in pots at Tamil Nadu Agricultural University, Coimbatore in 2024. The study evaluated eight pre-emergence, six early post-emergence and three post-emergence herbicides, each applied at 100 % and 75 % of the recommended dose (a total of 34 treatments) and compared their effects against a non-treated control (no herbicide). The experiments were carried out in a completely randomized design. Screening results indicated that pre-emergence applications of pretilachlor, butachlor, bensulfuron methyl + pretilachlor and pyrazosulfuron ethyl at 100 % recommended doses significantly reduced total weed density and dry weight while enhancing quinoa growth parameters, with minimal phytotoxic effects. In the conformity study, only the full recommended doses of pretilachlor (750 g ha^{-1}), butachlor (1000 g ha^{-1}) and bensulfuron methyl + pretilachlor (660 g ha^{-1}) consistently reduced weed density and dry weight effectively. However, phytotoxicity evaluations revealed that both the 100 and 75 % doses of atrazine, metribuzin, oxyfluorfen, tembotrione, topramezone, pendimethalin, imazethapyr, triafamone + ethoxysulfuron, penoxsulam + cyhalofop butyl, pyrazosulfuron ethyl, bispyribac sodium, fomesafen + fluzifop-p-butyl, quizalofop ethyl and pyrithiobac sodium were unsuitable for quinoa due to their high phytotoxicity.

Keywords

bensulfuron methyl + pretilachlor; butachlor; phytotoxicity; pretilachlor; quinoa; suitable herbicides

Introduction

Quinoa is an annual herbaceous plant classified as a pseudo-cereal, originating from the Andean region of South America (1). In recognition of the Andean people's long-standing tradition of preserving quinoa for future generations, the UN General Assembly declared 2013 as "The International Year of Quinoa" (2). Quinoa is a protein-rich grain, with protein content ranging from 13.8 to 21.9 % depending on its variety. It is naturally gluten-free and contains higher levels of essential amino acids compared to conventional cereals (3). The grains are particularly rich in lysine and methionine and comprise 67-74 % carbohydrates and 2-10 % of fat. Quinoa's oil content varies between 1.8 % and 9.5 % and it is a significant source of essential fatty acids (4).

Quinoa is a resilient crop capable of thriving under extreme climatic conditions. Its ability to withstand drought is attributed to several mechanisms, including drought escape, tolerance and avoidance, which enable the plant to adapt to diverse environmental challenges (5). Drought escape in quinoa is primarily achieved through early maturity, either at the beginning or end of the growing season. Drought tolerance mechanisms include growth plasticity, tissue elasticity and maintaining low osmotic potential. Additionally, quinoa avoids the adverse effects of drought through features such as a deep root system, leaf shedding to reduce leaf area, specialized vesicular glands and small, thick-walled cells that can endure significant water loss while retaining turgor. Stomatal regulation also plays a key role in minimizing water loss (5).

The ideal temperature range for quinoa cultivation is between 15°C and 30°C, though it can endure temperatures from -4°C to +50°C. Quinoa grows well on a wide variety of soil types, including marginal soils with a broad pH range (6). However, fertile soils significantly enhance its productivity (7). Additionally, quinoa exhibits resistance to drought salinity, pests and diseases, earning it the nickname 'golden grain' due to its resistance to cold, salt and drought, as well as its high nutritional value (8, 9).

Indian farmers have been growing quinoa for the past decade with minimum or no use of scientific methods or standardized agricultural practices. To enhance productivity, it is crucial to identify and implement optimal agronomic practices. Several factors affect productivity, including improved seed varieties, land preparation and sowing techniques, water management, nutrient application, weed control and pest and disease management. Among these, weed management is particularly critical in quinoa cultivation, as quinoa typically grows during a season when its wild relatives, such as *Chenopodium album* and *Chenopodium murale*, also thrive. These weeds compete with quinoa for essential resources like light, water, nutrients and space.

Farmers often face challenges in distinguishing quinoa seedlings from weed species during the early stages of growth making weed management a significant concern. Effective weed control has more pronounced effects on the growth and yield of quinoa than other crops. It is essential to identify and manage weeds before the critical weed-free period, which occurs 16 days after seedling emergence (10). Failure to implement proper weed management strategies can substantially reduce quinoa seed yield (11).

The development of effective weed control strategies and the identification of suitable herbicides are critical for advancing quinoa cultivation practices. Existing literature highlights that weed management in quinoa has primarily relied on manual methods or the use of hand tools, with no established chemical weed management protocols in India due to quinoa's sensitivity to herbicides. In other countries, some herbicides were tested that caused phytotoxicity to quinoa plants (12). For instance, post-emergence (PoE) application of herbicides such as atrazine, metribuzin, clethodim, quizalofop tefuryl, clodinafop, haloxyfop methyl, sethoxydim, pendimethalin, oxyfluorfen, bentazon and oxadiazone as well as benoxacor and pendimethalin, have been reported to be toxic to quinoa (13, 14).

While a few herbicides have been tested alongside manual weeding for managing weeds in quinoa, these studies primarily focused on limited weed parameters (15, 16). However, no comprehensive research has been conducted to screen pre-emergence (PE), early post-emergence (EPoE) and PoE herbicides in quinoa, particularly under tropical conditions like those in India. The current study aims to address this gap by identifying effective PE, EPoE and PoE herbicides for quinoa cultivation while minimizing phytotoxic effects on the crop.

Materials and Methods

Screening experiment

The screening experiment was conducted twice using pots at the Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, in 2024. Coimbatore, located in the western agroclimatic zone of Tamil Nadu, is positioned at 11°N latitude, 77°E longitude and an altitude of 426.7 m above mean sea level. The soil used in pots was sandy clay loam in texture, with low organic carbon (4.54 g kg^{-1}) and available nitrogen (174.5 kg ha^{-1}). However, it was high in available phosphorus (17.40 kg ha^{-1}) and potassium (560.2 kg ha^{-1}) and had a pH of 8.17. During the study, the maximum and minimum temperatures recorded were 34.10°C and 22.76°C, respectively. The crop was exposed to an average evaporation rate of 6.83 mm, 8.77 hr of bright sunshine daily and mean solar radiation of 405.2 Cal cm^{-2} per day. No rainfall was recorded during the pot culture experiment.

The experiment followed a completely randomized design with two replications and involved the screening of 34 treatments. These treatments included addition of herbicides during the pre-emergence (PE), early post-emergence (EPoE) and post-emergence (PoE) stages, each herbicide applied at two different doses (100% and 75% of the recommended dose). The results were compared with a control group that received no herbicide application. Detailed treatment details are presented in Table 1.

Note: EC - emulsifiable concentrate, WP - wettable powder, EW - emulsion-in-water, GR - granules, SC - suspension concentrate, W/W - weight per weight, SL - soluble liquid, PE - pre-emergence, EPoE - early post-emergence, PoE - post-emergence, a.i. - active ingredient

Quinoa seeds (local variety) were procured from the Agricultural Research Station, Mandor, Jodhpur, Rajasthan. Pots were filled with five kilograms of soil and twenty seeds were sown in each pot. According to the treatment schedule, PE herbicides were applied three days after sowing (DAS), EPoE herbicides at 15 DAS and PoE herbicides at 25 DAS using a 50 mL hand sprayer. Irrigation was provided as needed based on the moisture content of the soil.

Observation made

The number of germinated seeds was recorded on the 10th DAS and the germination percentage was calculated based on the total number of seeds sown (Eqn. 1).

$$\text{Germination percentage (GP)} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds own}} \times 100 \quad \text{(Eqn. 1)}$$

Table 1. Treatment details of the screening experiment

Treatment	Herbicide	Formulation	Application rate (g a.i. ha^{-1})	Application
T_1	Pendimethalin	30% EC	1000	PE
T_2	Pendimethalin	30% EC	750	PE
T_3	Atrazine	50% WP	1000	PE
T_4	Atrazine	50% WP	750	PE
T_5	Butachlor	50% EW	1000	PE
T_6	Butachlor	50% EW	750	PE
T_7	Metribuzin	70% WP	500	PE
T_8	Metribuzin	70% WP	375	PE
T_9	Pretilachlor	50% EC	750	PE
T_{10}	Pretilachlor	50% EC	560	PE
T_{11}	Oxyfluorfen	23.5% EC	250	PE
T_{12}	Oxyfluorfen	23.5% EC	187.5	PE
T_{13}	Pyrazosulfuron ethyl	10% WP	30	PE
T_{14}	Pyrazosulfuron ethyl	10% WP	22.5	PE
T_{15}	Bensulfuron methyl + pretilachlor	0.6% + 6% GR	660	PE
T_{16}	Bensulfuron methyl + pretilachlor	0.6% + 6% GR	500	PE
T_{17}	Penoxsulam + cyhalofop butyl	1.02% + 5.1% W/W	135	EPoE
T_{18}	Penoxsulam + cyhalofop butyl	1.02% + 5.1% W/W	101.25	EPoE
T_{19}	Imazethapyr	10% SL	100	EPoE
T_{20}	Imazethapyr	10% SL	75	EPoE
T_{21}	Bispyribac sodium	10% SC	25	EPoE
T_{22}	Bispyribac sodium	10% SC	18.75	EPoE
T_{23}	Tembotrione	34.4% SC	120	EPoE
T_{24}	Tembotrione	34.4% SC	90	EPoE
T_{25}	Topramezone	33.6% SC	25	EPoE
T_{26}	Topramezone	33.6% SC	18.75	EPoE
T_{27}	Triafamone + ethoxysulfuron	30% WP	60	EPoE
T_{28}	Triafamone + ethoxysulfuron	30% WP	45	EPoE
T_{29}	Fomesafen + fluzifop-p-butyl	11.1% + 11.1% W/W SL	250	PoE
T_{30}	Fomesafen + fluzifop-p-butyl	11.1% + 11.1% W/W SL	187.5	PoE
T_{31}	Quizalofop ethyl	5 % EC	50	PoE
T_{32}	Quizalofop ethyl	5 % EC	37.5	PoE
T_{33}	Pyrithiobac sodium ethyl	10% EC	62.5	PoE
T_{34}	Pyrithiobac sodium ethyl	10% EC	46.9	PoE
T_{35}	Control (no herbicide)	-	-	-

Phytotoxicity in quinoa was evaluated at 30 DAS following herbicide treatment, as per the guidelines recommended by the European Weed Research Council (17). A rating system was used to assess crop phytotoxicity (Table 2).

Table 2. Phytotoxicity scoring chart

Rating	Crop phytotoxicity (%)	Visual description
1	0	No reduction or no injury
2	1.0-3.5	Very slight discoloration
3	3.5-7.0	More severe but not lasting
4	7.0-12.5	Moderate and lasting
5	12.5-20.0	Medium and lasting
6	20.0-30.0	Heavy
7	30.0-50.0	Very heavy
8	50.0-90.0	Nearly destroyed
9	100	Completely destroyed

The density and dry weight of weeds were recorded at 30 DAS and the weed control efficiency (WCE) was calculated as:

$$WCE\ (\%) = \frac{DMc - DMt}{DMc} \times 100 \qquad \text{(Eqn. 2)}$$

Where, WCE - Weed Control Efficiency (%); DMc - Dry matter of weeds in the control (no herbicide) and DMt - Dry matter of weeds in the treated plot.

The growth parameters of quinoa, such as plant height (cm), leaf area (cm^2), number of leaves per plant and dry matter accumulation (g per plant) were recorded at 15 and 30 DAS.

Conformity experiment

After two rounds of screening experiments, the most effective treatments were identified based on their weed control efficiency and impact on quinoa. A conformity pot trial was subsequently conducted using a completely randomized design with nine treatments and three replications (Table 3).

All cultivation practices followed the procedures used in the previous screening experiments and the same soil was used for the conformity trail. Twenty seeds were sown in each pot and the PE herbicides were applied at 3 DAS (as per the treatment). Growth and weed parameters were recorded in the same manner as in the screening experiment.

Statistical Analysis

The original data on weed and plant growth parameters were square root transformed ($\sqrt{X} + 0.5$) and subjected to statistical analysis. Statistical significance was determined using the F-test at a 0.05 probability level. For parameters that showed significant effects ($p \leq 0.05$), critical differences (CD) were calculated to compare the impacts of different treatments (18).

Table 3. Treatment details of the conformity experiment

Treatment	Herbicide	Formulation	Application rate (g a.i. ha^{-1})	Application
T_1	Pretilachlor	50% EC	750	PE
T_2	Pretilachlor	50% EC	560	PE
T_3	Butachlor	50% EW	1000	PE
T_4	Butachlor	50% EW	750	PE
T_5	Bensulfuron methyl + pretilachlor	0.6% + 6% GR	660	PE
T_6	Bensulfuron methyl + pretilachlor	0.6% + 6% GR	500	PE
T_7	Pyrazosulfuron ethyl	10% WP	30	PE
T_8	Pyrazosulfuron ethyl	10% WP	22.5	PE
T_9	Control (no herbicide)	-	-	-

Results and Discussion

Weeds flora

The experimental pots were infested with a variety of weeds, including broad-leaved weeds, grasses and sedge weeds. Grassy weeds observed included crabgrass [*Digitaria sanguinalis*], Egyptian crowfoot grass [*Dactylactenium aegeptium*], purple top chloris [*Chloris barbata*], wild foxtail [*Setaria viridis*] and viper grass [*Dinebra retroflexa*]. Sedge weed such as nutgrass [*Cyperus rotundus*] and broad-leaved weeds like black pigweed [*Trianthema portuacastrum*], congress grass [*Parthenium hysterophorus*], common purslane [*Protulaca oleracea*], erect spiderling [*Boerhavia erecta*], prostrate sand mat [*Euphorbia prostrata*], fire plant [*Euphorbia geniculata*] and wild jute [*Corchorus olitoris*] were all observed at 30 DAS.

Germination percentage

Based on the observation made at 10 DAS in the screening experiments, only the PE herbicide treatments (T_1 to T_{16}) showed variation in germination percentage, ranging from 0.00 to 93.75% (Table 4). When atrazine (1000 g ha^{-1}, T_3) and (750 g ha^{-1}, T_4), metribuzin (500 g ha^{-1}, T_7) and (375 g ha^{-1}, T_8) and oxyfluorfen (250 g ha^{-1}, T_{11}) and (187.5 g ha^{-1}, T_{12}) were sprayed as PE treatments at 3 DAS, quinoa germination failed completely (0.00%). However, the highest germination rate (93.75 %) was observed with bensulfuron methyl + pretilachlor (500 g ha^{-1}, T_{16}), followed closely by butachlor (T_5 and T_6), pretilachlor (T_9 and T_{10}), pyrazosulfuron (T_{13} and T_{14}) and bensulfuron methyl + pretilachlor (660 g ha^{-1}, T_{15}), with germination ranging from 70 % to 75 %. Pendimethalin (T_1 and T_2) treatments resulted in the lowest germination percentages (27.50 % and 35.00 %, respectively) among the PE herbicides. Pretilachlor, butachlor and bensulfuron methyl + pretilachlor are selective herbicides that target specific weed species without adversely affecting quinoa. The variation in germination percentage was due to the phytotoxicity of the individual herbicides. These herbicides exhibit lower phytotoxic effects on quinoa compared to others. Herbicides with higher toxicity can hinder seed germination and seedling vigor, whereas pretilachlor, butachlor and bensulfuron methyl + pretilachlor are less likely to cause damage, leading to better germination rates. The mode of action of these herbicides appears to be more compatible with the quinoa growth cycle, especially during the early stages of germination and establishment, promoting better seedling emergence and growth. Additionally, these herbicides may have a favourable residual effect in the soil, maintaining weed control during the critical early growth stages, ensuring optimal conditions for quinoa germination without harmful residues that could inhibit seedling development. In this study, an inverse relationship was observed between the phytotoxicity of PE herbicides and quinoa germination percentage, i.e., the higher the phytotoxicity of the herbicide, the lower the germination percentage. Previous scientific evidence on the variation in germination percentage due to their toxicity supports these findings (19). All other treatments (T_{17} to T_{34}), where herbicides were applied post the 10 DAS observation, recorded 100% germination. The control pot (T_{35}), with no herbicide application, also achieved full germination (100 %) of quinoa.

Effect of herbicides on phytotoxicity of quinoa

The phytotoxic effects of herbicides on quinoa were evaluated through visual observation at 30 DAS (Table 2). Phytotoxicity was characterized by stunted growth, wilting and a decrease in plant height, leaf area and dry matter production, as well as leaf discolouration in quinoa (Fig. 1). Based on visual observation using a 1-9 point scale, all the treatments exhibited a varying degree of phytotoxicity, with scores ranging from 4 to 9 (Table 4).

Fig. 1. Overall view of the screening experiment (30 DAS).

Table 4. Effect of herbicides on germination percentage, phytotoxicity rating and weed parameters in quinoa (mean of two screening experiments)

	Treatments	Germination percentage	Phyto-toxicity rating	Weed density (No. pot^{-1})	Weed dry weight (g pot^{1})	WCE (%)
T_1	Pendimethalin @ 1000 g ha^{-1}	27.50	8	3.35 (10.75)	0.92 (0.35)	73.47
T_2	Pendimethalin @ 750 kg ha^{-1}	35.00	8	3.61 (12.5)	0.93 (0.37)	71.95
T_3	Atrazine @ 1000 g ha^{-1}	0.00	9	3.50 (11.75)	0.86 (0.24)	81.87
T_4	Atrazine @ 750 g ha^{-1}	0.00	9	3.61 (12.50)	0.87 (0.26)	80.15
T_5	Butachlor @ 1000 g ha^{-1}	73.75	4	1.75 (2.58)	0.76 (0.09)	93.51
T_6	Butachlor @ 750 g ha^{-1}	75.00	4	3.08 (9.00)	0.82 (0.17)	87.40
T_7	Metribuzin @ 500 g ha^{-1}	0.00	9	0.71 (0.00)	0.71 (0.00)	100.00
T_8	Metribuzin @ 375 g ha^{-1}	0.00	9	0.71 (0.00)	0.71 (0.00)	100.00
T_9	Pretilachlor @ 750 g ha^{-1}	75.25	4	1.66 (2.25)	0.75 (0.07)	95.04
T_{10}	Pretilachlor @ 560 g ha^{-1}	73.75	4	2.96 (8.25)	0.82 (0.17)	87.02
T_{11}	Oxyfluorfen @ 250 g ha^{-1}	0.00	9	0.71 (0.00)	0.71 (0.00)	100.00
T_{12}	Oxyfluorfen @ 187.5 g ha^{-1}	0.00	9	0.71 (0.00)	0.71 (0.00)	100.00
T_{13}	Pyrazosulfuron ethyl @ 30 g ha^{-1}	71.75	7	1.87 (3.00)	0.77 (0.10)	92.56
T_{14}	Pyrazosulfuron ethyl @ 22.5 g ha^{-1}	71.25	6	3.16 (9.50)	0.83 (0.19)	85.50
T_{15}	Bensulfuron methyl + pretilachlor @ 660 g ha^{-1}	73.25	5	1.84 (2.90)	0.77 (0.09)	93.32
T_{16}	Bensulfuron methyl + pretilachlor @ 500 g ha^{-1}	93.75	4	3.12 (9.25)	0.82 (0.17)	87.21
T_{17}	Penoxsulam + cyhalofop butyl @ 135 g ha^{-1}	100.00	8	3.46 (11.50)	1.12 (0.75)	42.56
T_{18}	Penoxsulam + cyhalofop butyl @ 101.25 g ha^{-1}	100.00	8	3.57 (12.25)	1.14 (0.80)	39.12
T_{19}	Imazethapyr @ 100 g ha^{-1}	100.00	8	3.67 (13.00)	1.15 (0.83)	36.64
T_{20}	Imazethapyr @ 75 g ha^{-1}	100.00	6	3.87 (14.50)	1.17 (0.88)	33.21
T_{21}	Bispyribac sodium @ 25 g ha^{-1}	100.00	7	3.60 (12.50)	1.17 (0.86)	34.35
T_{22}	Bispyribac sodium @ 18.75 g ha^{-1}	100.00	6	4.12 (16.50)	1.18 (0.90)	31.49
T_{23}	Tembotrione @ 120 g ha^{-1}	100.00	9	3.50 (11.75)	1.03 (0.57)	56.49
T_{24}	Tembotrione @ 90 g ha^{-1}	100.00	9	3.74 (13.50)	1.07 (0.65)	50.76
T_{25}	Topramezone @ 25 g ha^{-1}	100.00	9	3.50 (11.75)	1.08 (0.67)	49.05
T_{26}	Topramezone @ 18.75 g ha^{-1}	100.00	9	3.74 (13.5)	1.11 (0.73)	44.08
T_{27}	Triafamone + ethoxysulfuron @ 60 g ha^{-1}	100.00	8	3.61 (12.50)	1.12 (0.75)	42.75
T_{28}	Triafamone + ethoxysulfuron @ 45 g ha^{-1}	100.00	8	3.77 (13.75)	1.13 (0.78)	40.84
T_{29}	Fomesafen + fluzifop-p-butyl @ 250 g ha^{-1}	100.00	7	3.74 (13.50)	1.10 (0.72)	45.23
T_{30}	Fomesafen + fluzifop-p-butyl @ 187.5 g ha^{-1}	100.00	7	4.06 (16.00)	1.16 (0.84)	35.69
T_{31}	Quizalofop ethyl @ 50 g ha^{-1}	100.00	6	3.81 (14.00)	1.04 (0.58)	55.73
T_{32}	Quizalofop ethyl @ 37.5 g ha^{-1}	100.00	6	4.00 (15.50)	1.08 (0.66)	50.00
T_{33}	Pyrithiobac sodium @ 62.5 g ha^{-1}	100.00	6	3.67 (13.00)	1.17 (0.86)	34.35
T_{34}	Pyrithiobac sodium @ 47 g ha^{-1}	100.00	6	3.87 (14.50)	1.18 (0.88)	32.63
T_{35}	Control (no herbicide)	100.00	-	5.83 (33.50)	1.35 (1.31)	0.00
	SEd	-	-	0.11	0.01	-
	CD (p=0.05)	-	-	0.22	0.02	-

Figures in parenthesis are original values which were transformed into ($\sqrt{X}$ + 0.5).

Complete destruction (100 % injury; score 9) of quinoa was observed with the PE application of atrazine at 1000 g ha^{-1} (T_3) and 750 g ha^{-1} (T_4), metribuzin at 500 g ha^{-1} (T_7) and 375 g ha^{-1} (T_8) and oxyfluorfen at 250 g ha^{-1} (T_{11}) and 187.5 g ha^{-1} (T_{12}). Similarly, the EPoE application of tembotrione at 120 g ha^{-1} (T_{23}) and 90 g ha^{-1} (T_{24}), as well as topramezone at 25 g ha^{-1} (T_{25}) and 18.75 g ha^{-1} (T_{26}), also resulted in 100% injury (Fig. 2).

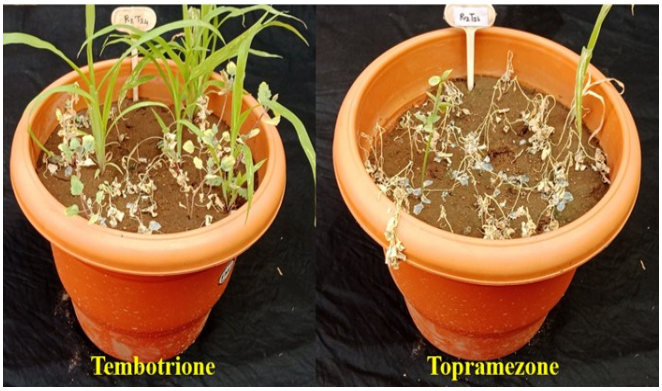

Fig. 2. Phytotoxicity in quinoa plants.

Triazine herbicides, such as atrazine and metribuzin, block electron transport in photosynthesis, hindering seedling growth (20). The herbicide exposure can cause chlorosis due to the disruption of chlorophyll production and the degradation of existing chlorophyll, which may progress to necrosis, particularly in sensitive plants like quinoa (21). These herbicides also cause oxidative stress by promoting the accumulation of reactive oxygen species (ROS), leading to cell membrane damage, lipid peroxidation and reduced cellular function in quinoa (22). Oxyfluorfen inhibits protoporphyrinogen oxidase (PPO), inducing necrosis and eventually plant death (23). This inhibition results in the accumulation of toxic intermediates that cause oxidative stress and damage plant tissues. A similar toxicity effect was observed in quinoa with the application of atrazine, metribuzin and oxyfluorfen, emphasizing the need for careful herbicide selection (13).

Topramezone and tembotrione caused complete plant death by inhibiting the 4-hydroxyphenyl-pyruvate dioxygenase (HPPD) enzyme, which plays a crucial role in carotenoid biosynthesis. Carotenoids protect chlorophyll from photooxidation and are involved in light absorption for photosynthesis. Inhibition of HPPD disrupts carotenoid production, leading to chlorophyll degradation and oxidative stress, which causes significant phytotoxicity in quinoa plants (24, 25). This damage includes chlorosis, necrosis, impaired water regulation and stunted growth. Similar findings on the phytotoxicity of tembotrione in sorghum and topramezone in finger millet support the results of the current study (26, 27).

A phytotoxicity score of 8 (nearly destroyed; 50-90%) was observed in quinoa due to the application of PE herbicide such as pendimethalin at 1000 g ha^{-1} (T_1) and 750 g ha^{-1} (T_2); early post-emergence (EPoE) herbicides such as penoxsulam + cyhalofop butyl 135 g ha^{-1} (T_{17}) and 101.25 g ha^{-1} (T_{18}), imazethapyr 100 g ha^{-1} (T_{19}) and triafamone + ethoxysulfuron 60 g ha^{-1} (T_{27}) and 45 g ha^{-1} (T_{28}). Pendimethalin inhibits mitotic cell division, blocks root extension and finally stunts growth (28), leading to reduced growth in emerging quinoa seedlings. Penoxsulam, a selective acetolactate synthase (ALS) inhibitor, disrupts the synthesis of essential branched-chain amino acids (leucine, isoleucine and valine), impairing protein synthesis and causing the accumulation of toxic metabolites. Cyhalofop-butyl inhibits acetyl-CoA carboxylase (ACCase), an enzyme crucial for fatty acid biosynthesis, disrupting membrane integrity and inhibiting cell growth and division (29). The combined effects of both herbicides can severely impact quinoa's growth and development, resulting in stunted root and shoot development. Quinoa plants exposed to these herbicides exhibit reduced height, smaller leaves and poor overall biomass accumulation. Imazethapyr impedes acetohydroxy acid synthase enzyme activity, disrupting protein synthesis, slowing cell division and eventually leading to cell death (30). Triafamone + ethoxysulfuron inhibits ALS enzyme activity in meristematic tissues, causing plant death (31). Previous toxicity reports on the application of pendimethalin and imazethapyr in quinoa support the findings of this study (13, 14, 16).

Herbicides such as pyrazosulfuron ethyl at 30 g ha^{-1} (T_{13}) as PE, bispyribac sodium at 25 g ha^{-1} (T_{21}) as EPoE and fomesafen + fluzifop-p-butyl at 250 g ha^{-1} (T_{29}) and 187.5 g ha^{-1} (T_{30}) as PoE resulted in a toxicity score of 7 (30-50 % injury; very heavy) on quinoa. Pyrazosulfuron and bispyribac sodium interfere with ALS enzyme activity, hindering plant growth (32). This disruption leads to impaired protein synthesis, reduced growth and increased oxidative stress, causing chlorosis, stunted growth and necrosis in quinoa plants. Bispyribac sodium has been reported to have slight phytotoxic effects on rice, supporting the present study's findings (33). Fomesafen inhibits chlorophyll production by blocking the PPO enzyme, while fluazifop-p-butyl inhibits the ACCase enzyme, contributing to phytotoxicity in quinoa (34). Minor phytotoxic effects of fomesafen + fluazifop-p-butyl in soybeans have been noted, further supporting the present study's results (35).

The PE herbicide pyrazosulfuron ethyl 22.5 g ha^{-1} (T_{14}); EPoE herbicides like Imazethapyr 75 g ha^{-1} (T_{20}) and bispyribac sodium at 18.75 g ha^{-1} (T_{22}) and PoE herbicides like quizalofop ethyl 50 g ha^{-1} (T_{31}) and 37.5 g ha^{-1} (T_{32}), as well as pyrithiobac sodium at 62.5 g ha^{-1} (T_{33}) and 47 g ha^{-1} (T_{34}), all exhibited a toxicity score of 6 (Heavy; 20-30 %). These herbicides caused a reduction in plant growth parameters, including plant height, number of leaves, leaf area and plant dry matter, observed 10 days after application. Quizalofop ethyl inhibits the ACCase enzyme in susceptible species while pyrithiobac sodium impairs plant development by inhibiting the ALS enzyme (29, 36). The current results are supported by the findings of a previous study, which reported that pyrithiobac sodium and quizalofop ethyl were phytotoxic to cotton (37).

Other PE herbicides, such as pretilachlor at 750 g ha^{-1} (T_9) and 560 g ha^{-1} (T_{10}), butachlor at 1000 g ha^{-1} (T^5) and 750 g ha^{-1} (T_6) and bensulfuron methyl + pretilachlor at 500 g ha^{-1} (T_{16}), exhibited moderate and lasting toxicity (7.0-12.5 %; score 4). Butachlor and pretilachlor (anilides) are surface-active PE herbicides that interfere with the synthesis of proteins, nucleic acids and long-chain fatty acids, leading to lower phytotoxicity in plants (38). These herbicides are more toxic to weeds than to quinoa due to the physiological differences in metabolism and enzyme pathways between quinoa and the target weeds. Earlier studies have demonstrated slight phytotoxicity of pretilachlor and butachlor in rice and wheat, respectively, which supports the

findings of this study (39, 40) . Bensulfuron methyl (an ALS inhibitor) and pretilachlor, which inhibits cell division and elongation, affect specific biochemical pathways more crucial for weeds, leading to their death, while quinoa plants are less affected or can compensate for the inhibition. Quinoa plants have a strong ability to activate detoxifying enzymes, such as cytochrome P450s and glutathione S-transferases, which help break down and metabolize herbicides like pretilachlor, butachlor and bensulfuron methyl before they can cause significant damage. Quinoa's thick-walled cells and tissue elasticity allow it to better withstand osmotic stress, minimizing the negative impact of herbicides on cell division and growth. Additionally, quinoa's special vesicular glands help the plant cope with herbicides in the soil, reducing the likelihood of herbicide uptake and translocation to sensitive tissues. Previous reports on the application of bensulfuron methyl + pretilachlor on finger millet showed reduced phytotoxicity further supporting the current findings (41). Although the PE herbicides like pretilachlor, butachlor and bensulfuron methyl + pretilachlor caused moderate to medium toxicity, quinoa recovered after two weeks and appeared normal, similar to the control.

Effect of herbicides on weed parameters

Based on the screening experiment (mean of two trials), herbicide application resulted in significant variations in weed density and dry weight at 30 DAS (Table 4). Among the herbicides tested, pretilachlor at 750 g ha^{-1} (T_9) recorded the lowest weed density (2.25 pot^{-1}) and dry weight (0.07 g pot^{-1}) compared to all other treatments. Other treatments like butachlor at 1000 g ha^{-1} (T_5) (2.58 pot^{-1} and 0.09 g pot^{-1}, respectively), bensulfuron methyl + pretilachlor at 660 g ha^{-1} (T_{15}) (2.90 pot^{-1} and 0.09 g pot^{-1}, respectively) and pyrazosulfuron ethyl at 30 g ha^{-1} (T_{13}) (3.00 pot^{-1} and 0.10 g pot^{-1}, respectively) showed comparatively low weed density and dry weight. In the conformity trial, the lowest weed density (2.83 pot^{-1}) and dry weight (0.07 g pot^{-1}) were observed with the application of pretilachlor at 750 g ha^{-1} (T_1) at 30 DAS (Table 5). This was statistically similar to butachlor at 1000 g ha^{-1} (T_3) (3.23 pot^{-1} and 0.09 g pot^{-1}, respectively) and bensulfuron methyl + pretilachlor at 660 g ha^{-1} (T_5) (3.27 pot^{-1} and 0.09 g pot^{-1}, respectively). This may be attributed to the superior weed control efficacy of these herbicides compared to others. Pretilachlor and butachlor inhibit cell division by blocking the synthesis of proteins, nucleic acids and gibberellic acid, thereby suppressing weed growth (42). These herbicides primarily target the growing shoots, making them effective against both broadleaf weeds and grasses. Similarly, bensulfuron methyl, which interferes with ALS, inhibits cell division and disrupts the synthesis of branched-chain amino acids in weeds, stunting their growth. The combination of bensulfuron methyl + pretilachlor utilizes different mechanisms of action to control a broader spectrum of weeds. Pretilachlor mainly targets grasses, while bensulfuron methyl is more effective against broadleaf weeds and sedges. This complementary action results in more comprehensive weed control compared to a single herbicide. These herbicides are typically applied in the PE stage, targeting weeds before they can compete with the crop. The gradual reduction in weed density and dry weight, observed in previous studies due to the application of pretilachlor butachlor (45) and bensulfuron methyl + pretilachlor (46), strongly supports the conclusions of the present study (43-46). Pretilachlor 50 % EC was found to be more effective at reducing weed biomass than other herbicidal treatments, including butachlor (47). Notably, the control (no herbicide) demonstrated the highest weed density (33.50 and 31.00 pot^{-1} in the screening and conformity experiments, respectively) and dry weight (1.31 and 0.99 g pot^{-1}, respectively). The maximum weed density and dry weight in the control were due to the absence of herbicide application, which allowed for the unchecked growth of weeds.

The application of different herbicides to quinoa significantly influenced the WCE (Table 4). Based on the screening experiments, a higher WCE was found at the 100 % dose compared to the 75 % dose. The maximum WCE (100 %) was recorded with metribuzin at 500 g ha^{-1} (T_7) and 375 g ha^{-1} (T_8) and oxyfluorfen 250 g ha^{-1} (T_{11}) and 187.5 g ha^{-1} (T_{12}), although these treatments resulted in the death of quinoa plants. This was followed by pretilachlor at 750 g ha^{-1} (95.04 %; T_9), butachlor at 1000 g ha^{-1} (93.51 %; T_3), bensulfuron methyl + pretilachlor at 660 g ha^{-1} (93.32 %; T_{15}) and pyrazosulfuron ethyl at 30 g ha^{-1} (92.56 %; T_{13}). In the conformity experiment (Table 5), the highest WCE (92.50 %) was recorded with pretilachlor at 750 g ha^{-1} (T_1), followed by butachlor at 1000 g ha^{-1} (90.91 %; T_3) and bensulfuron methyl + pretilachlor at 660 g ha^{-1} (90.91 %; T_5) (Fig. 3). The lower dry weight of weeds in these treatments contributed to the higher WCE. Additionally, the mode of action of these herbicides effectively controlled weed flora in quinoa by inhibiting development and cell division, which further contributed to the high WCE observed with pretilachlor 50% EC in the current experiment. These results are in agreement with previous studies that documented better WCE with pretilachlor in rice butachlor in rice and bensulfuron methyl + pretilachlor in finger millet (41, 48).

Effect of herbicides on the growth of quinoa

The application of herbicides significantly affected the plant height, number of leaves per plant, leaf area and dry matter production of quinoa (Table 6; Fig. 4). Based on the mean results from both screening experiments, the application of pretilachlor 750 g ha^{-1} (T_9) recorded the higher plant height (9.89 and 21.20 cm), number of leaves per plant (13.78 and 31.20), leaf area (20.59 and 79.00 cm^2) and dry matter accumulation per plant (0.21 and 0.67 g per plant) at 15 and 30 DAS, respectively compared to other herbicides. However, herbicides such as butachlor 1000 g ha^{-1} (T_5), bensulfuron methyl + pretilachlor 660 g ha^{-1} (T_{15}) and pyrazosulfuron ethyl 30 g ha^{-1} (T_{13}) showed similar results to pretilachlor (T_9) in terms of quinoa growth parameters. In the conformity experiment (Table 7), pretilachlor at 750 g ha^{-1} (T_1) as a PE application also demonstrated superior performance with respect to plant height (9.93 and 21.23 cm), number of leaves per plant (14.83 and 30.60), leaf area (20.99 and 72.39 cm^2) and dry matter production (0.21 and 0.65 g per plant) at 15 and 30 DAS, respectively, than control. However, it was comparable to butachlor at 1000 g ha^{-1} (T_3) and bensulfuron methyl + pretilachlor at 660 g ha^{-1} (T_5). The improvement in growth parameters for these treatments was attributed to effective weed control, as evidenced by lower weed density, reduced dry weight and enhanced WCE (Table 4 & 5; Fig. 1 & 3), which minimized competition for resource in quinoa. Reduced weed growth likely enhanced the availability of nutrient, light and

Table 5. Effect of herbicides on weed parameters in quinoa at 30 DAS (Conformity trial)

	Treatments	Weed density (No. pot^{-1})	Weed dry weight (g pot^{-1})	WCE (%)
T_1	Pretilachlor @ 750 g ha^{-1}	1.82 (2.83)	0.76 (0.07)	92.50
T_2	Pretilachlor @ 560 g ha^{-1}	3.03 (8.67)	0.83 (0.18)	81.82
T_3	Butachlor @ 1000 g ha^{-1}	1.93 (3.23)	0.77 (0.09)	90.91
T_4	Butachlor @ 750 g ha^{-1}	3.14 (9.33)	0.81 (0.16)	83.50
T_5	Bensulfuron methyl + pretilachlor @ 660 g ha^{-1}	1.94 (3.27)	0.77 (0.09)	90.91
T_6	Bensulfuron methyl + pretilachlor @ 500 g ha^{-1}	3.29 (10.33)	0.83 (0.19)	81.14
T_7	Pyrazosulfuron ethyl @ 30 g ha^{-1}	2.21 (4.40)	0.80 (0.14)	86.20
T_8	Pyrazosulfuron ethyl @ 22.5 g ha^{-1}	3.57 (12.33)	0.87 (0.25)	74.75
T_9	Control (no herbicide)	5.61 (31.00)	1.22 (0.99)	0.00
	SEd	0.13	0.02	-
	CD (p=0.05)	0.27	0.03	-

Figures in parenthesis are original values which were transformed into (√X + 0.5).

Fig. 3. Overall view of the conformity experiment (30 DAS).

Fig. 4. Effect of herbicides on weeds and quinoa plants (30 DAS).

Table 6. Effect of herbicide treatments on growth parameters in quinoa (mean of two screening experiments)

Treatment	Plant height (cm)		Number of leaves plant^{-1}		Leaf area (cm^2)		Plant dry matter (g plant^{-1})	
	15 DAS	30 DAS	15 DAS	30 DAS	15 DAS	30 DAS	15 DAS	30 DAS
T_1	0.89 (0.29)	1.08 (0.67)	1.13 (0.85)	1.79 (2.70)	0.72 (0.02)	1.08 (0.68)	0.72 (0.02)	0.73 (0.04)
T_2	0.85 (0.23)	0.80 (0.14)	1.79 (2.75)	1.12 (0.78)	0.83 (0.19)	0.75 (0.06)	0.73 (0.03)	0.73 (0.03)
T_3	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_4	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_5	3.20 (9.72)	4.62 (20.89)	3.75 (13.60)	5.61 (30.95)	4.55 (20.22)	8.73 (75.72)	0.84 (0.20)	1.05 (0.60)
T_6	2.96 (8.29)	4.37 (18.57)	3.54 (12.00)	4.75 (22.05)	4.34 (18.37)	8.16 (66.14)	0.81 (0.16)	1.03 (0.56)
T_7	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_8	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_9	3.22 (9.89)	4.66 (21.20)	3.78 (13.78)	5.63 (31.20)	4.59 (20.59)	8.92 (79.00)	0.84 (0.21)	1.08 (0.67)
T_{10}	2.99 (8.41)	4.39 (18.78)	3.55 (12.08)	5.10 (25.50)	4.35 (18.45)	8.07 (64.69)	0.81 (0.16)	1.03 (0.57)
T_{11}	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_{12}	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
T_{13}	3.15 (9.42)	4.62 (20.81)	3.62 (12.58)	5.54 (30.25)	4.54 (20.15)	8.60 (72.72)	0.82 (0.18)	1.05 (0.60)
T_{14}	2.85 (7.61)	4.24 (17.47)	3.46 (11.45)	4.33 (18.25)	4.24 (17.48)	6.69 (44.54)	0.81 (0.16)	0.97 (0.45)
T_{15}	3.18 (9.60)	4.62 (20.81)	3.75 (13.53)	5.56 (30.40)	4.56 (20.28)	8.61 (73.58)	0.84 (0.20)	1.07 (0.64)
T_{16}	2.96 (8.26)	4.37 (18.62)	3.49 (11.68)	5.02 (24.75)	4.35 (18.40)	8.05 (64.27)	0.81 (0.16)	1.01 (0.53)
T_{17}	2.62 (6.38)	2.89 (7.85)	3.16 (9.50)	3.33 (10.58)	3.31 (10.44)	3.52 (11.91)	0.75 (0.07)	0.97 (0.45)
T_{18}	2.70 (6.80)	4.18 (16.94)	3.17 (9.55)	3.32 (10.53)	3.79 (13.82)	3.29 (10.30)	0.76 (0.08)	0.83 (0.19)
T_{19}	2.48 (5.65)	3.39 (10.97)	3.28 (10.23)	3.61 (12.53)	3.83 (14.15)	3.73 (13.44)	0.80 (0.15)	0.96 (0.41)
T_{20}	2.55 (5.99)	3.30 (10.42)	3.11 (9.15)	3.71 (13.28)	3.77 (13.68)	4.00 (15.47)	0.81 (0.15)	0.97 (0.43)
T_{21}	2.42 (5.35)	3.37 (10.84)	3.16 (9.50)	4.19 (17.05)	3.91 (14.82)	4.72 (21.76)	0.80 (0.14)	0.96 (0.42)
T_{22}	2.44 (5.46)	2.69 (6.71)	3.31 (10.45)	2.89 (7.85)	3.98 (15.32)	2.68 (6.69)	0.78 (0.11)	0.80 (0.14)
T_{23}	2.37 (5.10)	0.71 (0.00)	3.27 (10.20)	0.71 (0.00)	3.78 (13.82)	0.71 (0.00)	0.81 (0.15)	0.71 (0.00)
T_{24}	2.71 (6.83)	0.71 (0.00)	3.19 (9.70)	0.71 (0.00)	3.75 (13.60)	0.71 (0.00)	0.77 (0.10)	0.71 (0.00)
T_{25}	2.70 (6.81)	0.71 (0.00)	3.29 (10.35)	0.71 (0.00)	3.76 (13.61)	0.71 (0.00)	0.79 (0.13)	0.71 (0.00)
T_{26}	2.71 (6.86)	0.71 (0.00)	3.36 (10.78)	0.71 (0.00)	4.11 (16.43)	0.71 (0.00)	0.81 (0.15)	0.71 (0.00)
T_{27}	2.66 (6.59)	3.03 (8.66)	3.22 (9.88)	3.00 (8.53)	4.04 (15.85)	2.94 (8.15)	0.81 (0.15)	0.86 (0.25)
T_{28}	2.59 (6.23)	3.00 (8.51)	3.11 (9.15)	2.85 (7.60)	3.29 (10.30)	2.75 (7.04)	0.78 (0.11)	0.79 (0.13)
T_{29}	2.64 (6.49)	3.71 (13.27)	3.19 (9.65)	3.04 (8.75)	3.66 (12.89)	3.46 (11.47)	0.76 (0.08)	0.87 (0.25)
T_{30}	2.71 (6.83)	3.76 (13.63)	3.29 (10.30)	3.32 (10.50)	3.51 (11.81)	4.24 (17.51)	0.79 (0.12)	0.93 (0.37)
T_{31}	2.81 (7.40)	4.17 (16.87)	3.29 (10.33)	4.27 (17.70)	4.15 (16.70)	5.35 (28.22)	0.78 (0.12)	0.96 (0.42)
T_{32}	2.69 (6.76)	3.91 (14.80)	3.35 (10.70)	3.32 (10.55)	3.86 (14.37)	3.94 (15.05)	0.77 (0.09)	0.94 (0.38)
T_{33}	2.70 (6.80)	3.79 (13.88)	3.30 (10.40)	3.15 (9.45)	3.89 (14.60)	3.86 (14.40)	0.77 (0.09)	0.93 (0.36)
T_{34}	2.73 (6.97)	3.91 (14.81)	3.38 (10.95)	3.26 (10.10)	4.05 (15.88)	4.52 (19.93)	0.77 (0.09)	0.96 (0.43)
T_{35}	2.70 (6.79)	3.81 (14.03)	3.27 (10.23)	3.09 (9.05)	3.54 (12.01)	3.77 (13.75)	0.78 (0.11)	0.92 (0.35)
SEd	0.05	0.02	0.10	0.07	0.02	0.16	0.01	0.02
CD (p=0.05)	0.08	0.05	0.20	0.14	0.05	0.32	0.02	0.03

Figures in parenthesis are original values which were transformed into (√X + 0.5). T_1 - Pendimethalin 1000 g ha^{-1}, T_2 - Pendimethalin 750 g ha^{-1}, T_3 - Atrazine 1000 g ha^{-1}, T_4 - Atrazine 750 g ha^{-1}, T_5 - Butachlor 1000 g ha^{-1}, T_6 - Butachlor 750 g ha^{-1}, T_7 - Metribuzin 500 g ha^{-1}, T_8 - Metribuzin 375 g ha^{-1}, T_9 - Pretilachlor 750 g ha^{-1}, T_{10} - Pretilachlor 560 g ha^{-1}, T_{11} - Oxyfluorfen 250 g ha^{-1}, T_{12} - Oxyfluorfen 187.5 g ha^{-1}, T_{13} - Pyrazosulfuron ethyl 30 g ha^{-1}, T_{14} - Pyrazosulfuron ethyl 22.5 g ha^{-1}, T_{15} - Bensulfuron methyl + pretilachlor 660 g ha^{-1}, T_{16} - Bensulfuron methyl + pretilachlor 500 g ha^{-1}, T_{17} - Penoxsulam + cyhalofop butyl 135 g ha^{-1}, T_{18} - Penoxsulam + cyhalofop butyl 101.25 g ha^{-1}, T_{19} - Imazethapyr 100 g ha^{-1}, T_{20} - Imazethapyr 100 g ha^{-1}, T_{21} - Bispyribac sodium 25 g ha^{-1}, T_{22} - Bispyribac sodium 18.75 g ha^{-1}, T_{23} - Tembotrione 120 g ha^{-1}, T_{24} - Tembotrione 90 g ha^{-1}, T_{25} - Topramezone 25 g ha^{-1}, T_{26} - Topramezone 18.75 g ha^{-1}, T_{27} - Triafamone + ethoxysulfuron 60 g ha^{-1}, T_{28} - Triafamone + ethoxysulfuron 45 g ha^{-1}, T_{29} - Fomesafen + fluzifop-p-butyl 250 g ha^{-1}, T_{30} - Fomesafen + fluzifop-p-butyl 187.5 g ha^{-1}, T_{31} - Quizalofop ethyl 50 g ha^{-1}, T_{32} - Quizalofop ethyl 37.5 g ha^{-1}, T_{33} - Pyrithiobac sodium 62.5 g ha^{-1}, T_{34} - Pyrithiobac sodium 47 g ha^{-1}, T_{35} - Control (no herbicide).

Table 7. Effect of herbicide treatments on growth parameters in quinoa (Conformity trial)

Treatments		Plant height (cm)		No. of leaves plant^{-1}		Leaf area (cm^2)		Plant dry matter (g plant^{-1})	
		15 DAS	30 DAS	15 DAS	30 DAS	15 DAS	30 DAS	15 DAS	30 DAS
T_1	Pretilachlor @ 750 g ha^{-1}	9.93	21.23	14.83	30.60	20.99	72.39	0.21	0.65
T_2	Pretilachlor @ 560 g ha^{-1}	8.23	18.93	12.20	25.67	18.36	67.53	0.18	0.56
T_3	Butachlor @ 1000 g ha^{-1}	9.77	20.60	14.50	30.40	20.80	71.13	0.20	0.63
T_4	Butachlor @ 750 g ha^{-1}	8.17	18.73	12.17	24.23	18.40	65.16	0.18	0.55
T_5	Bensulfuron methyl + pretilachlor @ 660 g ha^{-1}	9.67	20.40	14.40	30.33	20.28	71.12	0.20	0.63
T_6	Bensulfuron methyl + pretilachlor @ 500 g ha^{-1}	8.07	18.47	12.07	24.67	18.26	66.40	0.18	0.55
T_7	Pyrazosulfuron ethyl @ 30 g ha^{-1}	6.50	11.30	8.33	10.33	10.33	12.47	0.12	0.35
T_8	Pyrazosulfuron ethyl @ 22.5 g ha^{-1}	6.43	13.73	8.33	10.67	10.41	12.82	0.13	0.34
T_9	Control (no herbicide)	5.13	10.00	8.00	10.00	10.29	12.64	0.11	0.34
	SEd	0.55	0.89	0.93	1.09	0.72	1.86	0.01	0.03
	CD (p=0.05)	1.16	1.86	1.96	2.29	1.52	3.90	0.02	0.06

moisture for quinoa, improving nutrients uptake and consequently leading to better growth. Similar findings were reported by Thimmegowda et al., who observed that better weed control created a favourable soil environment in herbicide-treated plots, resulting in improved growth parameters (49). Additionally, previous studies on rice also highlighted similar improvements in growth parameters due to superior weed management, consistent with the results of the present study on quinoa (48, 50).

Conclusion

Based on the findings from two screening experiments followed by a conformity investigation, it can be concluded that PE herbicides such as pretilachlor (750 g ha^{-1}), butachlor (1000 g ha^{-1}) and bensulfuron methyl + pretilachlor (660 g ha^{-1}) are effective for controlling weeds in quinoa with minimal phytotoxicity, making them highly recommended herbicide candidate for use in quinoa cultivation. In contrast, the application of atrazine, metribuzin, oxyfluorfen, tembotrione, topramezone, pendimethalin, imazethapyr, triafamone + ethoxysulfuron, penoxsulam + cyhalofop butyl, pyrazosulfuron ethyl, bispyribac sodium, fomesafen + fluzifop-p-butyl, quizalofop ethyl and pyrithiobac sodium resulted in phytotoxicity on quinoa plants, making these herbicides unsuitable for quinoa cultivation.

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Authors' contributions

All the authors have contributed equally to data collection, analysis, writing the original manuscript draft, editing and reviewing.

Compliance with Ethical Standards

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