Evaluating the Efficacy of Different Chemical Treatments on Weed Density, Biomass Accumulation, and Physiological Traits in Pearl Millet

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Weeds are one of the major limitations to the productivity of crops in that they compete with vital resources like light, nutrients, water, and space. The current research aimed to determine the efficacy of various weed management treatments on the weed density, biomass production, weed moisture content and species composition. The experiment was planned in a randomized complete block design (RCBD) involving seven treatments (T1–T7) and three replications. The data were systematically measured on weed flora, weed density (2.54–33.79 plants m⁻²), fresh biomass (14.04–241.29 g m⁻²), dry biomass (7.00–149.21 g m⁻²), moisture content (41.99–241.29%), and dry-matter percentage (35.49–57.00%). The ANOVA showed that the effect of treatments on all the parameters measured was highly significant ($p < 0.01$), especially on fresh and dry biomass, indicating that the treatments strongly suppressed weeds. T1 had the lowest weed density (2.54 plants m⁻²), fresh biomass (14.04 g m⁻²), and dry biomass (7.00 g m⁻²), while T7 had the highest values (33.79 plants m⁻², 241.29 g m⁻², and 149.21 g m⁻², respectively), indicating weed suppression of more than 90% under T1 compared to T7. Correlation analysis showed strong positive relationships among weed density, fresh biomass, and dry biomass ($r = 0.86$–0.98, $p < 0.01$). This confirms that higher weed populations lead to increased biomass. The content of moisture had weak and non-significant correlations ($r = -0.13$ to -0.03) with other characteristics, indicating its weak influence on weed growth dynamics. Weed density data showed that T1 recorded the lowest populations of broad-leaves (5.00 plants m⁻²), sedges (0.67 plants m⁻²), khabal (2.00 plants m⁻²), and madhana (0.00 plants m⁻²) at 15 DAS, whereas T7 exhibited the highest densities for broad-leaves (92.00 plants m⁻²) and sedges (28.67 plants m⁻²), indicating severe infestation under untreated conditions. At 30 DAS, T4 recorded the lowest densities of broad-

leaves and sedges (3.33 plants m⁻² each), and T3 had the lowest khabal density (0.67 plants m⁻²), while T7 again recorded the maximum values for most weed groups, confirming its lowest weed suppression efficiency. In general, the findings indicated the significance of proper weed-management methods to minimize weed pressure and improve crop production systems. The results are useful in the choice of suitable weed control measures in similar agro-ecological settings. The graphical abstract has been drawn in Figure 1.

Keywords: Herbicide, Weeds, Weed Density, Pearl Millets, Chemical Treatment.

Figure 1. Graphical abstract on the structure of the whole experiment and findings.

Introduction:

The world has had its share of the most major biological constraints in regard to crop production, which includes weeds that have contributed significant proportions of yield loss due to competition for light, nutrients, water, and space. Yield losses due to weeds are more common than losses caused by insect pests or diseases, unless these are properly controlled [1][2]. In pearl millet, yield losses due to uncontrolled weeds have been reported to range from 30–55% globally, and in severe infestations, losses may exceed 60%, particularly in rainfed and semi-arid production systems [3][4]. In Pakistan, weed infestation in pearl millet and related millet crops has been reported to cause yield reductions ranging from 35–50%, depending on weed density, species composition, and timing of control measures [5][6]. The uncontrolled weeds reduce crop vigor, resource efficiency, and produce quality. The size of the losses caused by weeds is conditioned to a large extent by the density of weeds, the composition of the species, and the quality and timeliness of the control actions [7][8]. As a result, it is necessary to have a full picture of the weed population dynamics and effective management strategies to ensure sustainable agricultural production.

Successful management of weeds is based on combined strategies that entail the combination of chemical, cultural, mechanical, and biological methods to curb the growth of the weed and reduce the environmental hazards [9][10]. Herbicides have also been one of the most popular means because they are fast and cost-effective in their control, but they have caused resistance to herbicides, environmental pollution, and changes in the composition of the weeds [11][12]. In line with this, the current weed science highlights the importance of the optimal choice and timing of treatments to attain the proper control with the minimum ecological footprint [13][14].

Comparison of various weed-management regimens is thus essential in determining methods that are effective and sustainable at the same time. Weed density and biomass are important measures of the effectiveness of treatment since they directly indicate how competitive the crops are [15][16]. Fresh and dry biomass measurements indicate weed growth

vigor and resource capture., and the percentage of dry matter is used to determine the physiological maturity of weed plants. On the same note, weed flora analysis is used to establish whether the management practices affect the species diversity or simply lower the weed abundance. Correlation studies contribute to understanding weed growth patterns and their interrelationships, supporting evidence-based management decisions.

In that regard, the current research was concerned with assessing the efficacy of the various weed-management regimens with respect to the weed density, biomass production, moisture content, and species composition. This study combines both the analysis of variance and correlation analysis to give a holistic evaluation of the effect of treatments on the dynamics of the weed. The results are expected to guide effective and sustainable weed-management practices tailored to specific agro-ecological conditions., which will eventually lead to increased crop yield and resource saving.

Research Gap and Novelty of the Study:

Despite the widespread cultivation of pearl millet in semi-arid and arid regions, limited recent information is available on the comparative effectiveness of different chemical weed management treatments on weed density, biomass accumulation, and physiological traits under local agro-ecological conditions. Recent studies have largely focused on generalized weed control strategies in cereals, with insufficient emphasis on treatment-wise quantitative assessment of weed suppression and interrelationships among weed growth parameters. Therefore, the present study provides novel insights by integrating treatment-wise evaluation of different chemical weed management practices with correlation-based interpretation of weed growth dynamics, thereby contributing original and location-specific evidence to improve chemical weed management in pearl millet production systems.

Objectives:

To determine the effects of different chemical weed management treatments on the density of weeds and biomass accumulation in pearl millet.

To ascertain the impact of different chemical treatments on the physiological characteristics of weeds in pearl millet plots.

Materials and Methods:

Location of Experiment and Field Preparation:

The open-field experiment was arranged in the Fodder Research Institute, Sargodha, from July to November. The experimental area had a uniform soil in terms of texture and fertility to reduce environmental variability. The field was prepared through the normal agronomic activities such as ploughing, harrowing, and leveling before sowing.

Experimental Design:

The trial was designed in a randomized complete block design (RCBD) comprised of seven treatments (T1-T7) of weed management and three replications. The experimental units had plots of the same size, with buffer spaces between them to avoid interference of treatments. Any agronomic activities that were not related to the weed management were maintained the same in all treatments to make sure that any effect that was observed could only be attributed to the treatments that were imposed [17].

The treatments included various weed management methods, such as chemical and cultural methods, with T7 being the control group. The techniques were used at the suggested crop development phases and in line with the established weed-management protocols. Where necessary, herbicide application was done on a calibrated knapsack sprayer to ensure even application of the spray. Weed dynamics were observed by recording observations at particular intervals after the application of treatments.

Treatment Plan:

Table 1. Detail of treatments applied in the experiment for studying weed related parameters in pearl millet

Treatment	Chemical used	Dose
T1 (pre-emergence)	Pendimethalin	800 ml per acre
T2 (pre-emergence)	S-Metolachlor+ Pendimethalin	700 ml per acre
T3 (Post emergence)	Quizilofop-p-ethyl	400 ml per acre
T4 (Post emergence)	Atrazine+Mesotrine	400 ml per acre
T5 (Post emergence)	Atrazine+Mesotrine	300 ml per acre
T6 (Post emergence)	Atrazine	500 ml per acre
T7 (control)	No weedicide	Weedy check

The details of the treatment applied are mentioned in Table 1

Before sowing, composite soil samples (0–15 cm depth) were collected from the experimental site and analyzed for physico-chemical properties. The soil was sandy loam, pH 7.8, with low to moderate fertility (organic matter 0.82%, total N 0.045%, available P 8.6 mg kg^{-1}, and K 165 mg kg^{-1}), indicating low to moderate fertility status. Meteorological data for the cropping season (July–November) were obtained from the nearest meteorological observatory located within 5 km of the experimental site. During the study period, total rainfall was 312 mm, with mean monthly temperatures ranging from 28.4°C (July–August) to 19.6°C (November), and average relative humidity varying between 58% and 76%, typical semi-arid subtropical conditions suitable for pearl millet.

Pearl millet (*Pennisetum glaucum* L.) cultivar 'Sargodha Bajra 2017' was used as the test crop in this study. The crop was sown using a line sowing method with a seed rate of 4.0 kg ha^{-1}. Sowing was carried out with a row spacing of 30 cm and plant-to-plant spacing of 15 cm. All agronomic practices, except weed management treatments, were kept uniform across experimental plots to ensure that treatment effects on weed parameters were not confounded by crop management factors. Herbicides were applied using a 16-L manually operated knapsack sprayer (Jacto® XP-16, Jacto Inc., Brazil) fitted with a flat-fan nozzle (TeeJet® 8002 VS, Spraying Systems Co., USA) to ensure uniform spray distribution. The sprayer was calibrated before application to deliver a spray volume of 250 L ha^{-1} at an operating pressure of approximately 275 kPa (40 psi), maintained through continuous pumping. All treatments were applied under calm weather conditions to minimize spray drift and ensure accurate herbicide deposition on the target weed flora.

Data Recording:

Data were recorded for following parameters using method described below:

Weed Density:

The density of weeds was calculated by laying a 1m 2 quadrat in two places per plot at random. The total number of weed plants in the quadrat was summed up and divided by the average to get the weed density per square meter.

Weed Flora:

The weed flora was also determined by determining the number of weed species found in each quadrat through standard taxonomic keys, and the total count of the weed species was identified to determine the species richness.

Weeds Fresh biomass:

Weeds Fresh biomass was calculated by uprooting the sampled quadrat, rinsing off the soil particles, and weighing them with a digital balance.

Dry Biomass:

The samples were then dried in the oven at 70 °C until reaching a constant weight, thus establishing the dry biomass.

Dry Matter Percentage:

The percentage of dry matter was determined by using the following formula:

Dry matter (%) = (Dry weight/ Fresh weight) x 100.

Moisture Content:

The content of moisture was determined by the standard gravimetric procedure and was recorded as:

Moisture content (%) = (Fresh weight - Dry weight)/ Fresh weight) × 100.

These techniques are popular in biomass and physiological research of weeds [1].

Statistical Analysis:

Analysis of variance (ANOVA) was used to analyze statistical data on the effect of treatments and days of observation on the parameters of the weed. The value of means under treatment was assessed at 5 percentage probability level. The means of the treatments were compared using the least significant difference (LSD) test when ANOVA showed significant differences [18]. The correlation coefficients by Pearson were calculated to determine the relationships between weed density, biomass, moisture content, and dry-matter percentage. The statistical analysis was performed through the normal statistical software packages.

Results and Discussion:

ANOVA revealed significant effects of both treatments and days on all measured weed parameters. This indicates the dynamism of weed populations and biomass in response to management practices and temporal variation (Table 2). time variation (Table 2). In the case of weed flora (WF), the treatment (0.01459) and day (0.01505) MSS were very similar, indicating that the composition of species was affected more or less by the application of treatment and time. This means that the control measures of the weed, as well as the growth phases, contributed to the formation of the weed community structure during the experimental time. (Table 1)

Weed density (PW) showed higher mean square values for treatments (2395.61) than for days (1946.43), indicating that treatments were the major factor controlling weed population intensity. This demonstrates the power of management intervention to reduce the development and establishment of weeds, and time effects, though important, were relatively less effective. Equally, moisture content (MC) was found to vary slightly among days (410.252) than among treatments (389.580), indicating that the environmental condition and the growth stage of the plant had slightly more influence on the moisture status of the weed compared to the influence of treatments. (Table 1)

Treatments strongly affected fresh biomass (FB), with a mean square of 141,351 compared to 8 for days. This indicates that weed management significantly reduced weed growth, while daily fluctuations had minimal effect. Again, in the instance of dry-matter percentage, treatments (1245.12) were found to be more variable than days (675.33), and it was confirmed that management strategies had a significant effect on the physiological status of the weed and the partitioning of the dry matter. Lastly, dry biomass (DB) also experienced the same trend, where treatments (57038.3) were the most significant factor to days (114.5), and hence the great suppressive effect of treatments on the total accumulation of weed biomass. (Table 2)

Table 2. Mean sum of square value attained through analysis of variance for different growth and physiology-related characters in pearl millet

	Parameters	MS (Treatments)	MS (Days)
1	Weed Flora (WF)	0.01459 **	0.01505**
2	Weed Density (WD)	2395.61**	1946.43**
3	Moisture Content (MC)	389.580**	410.252*
4	Fresh Biomass (FB)	141351**	8**
5	Dry matter percentage % (DMP)	1245.12**	675.33**

| 6 | Dry Biomass (DB) | 57038.3** | 114.5 ** |

Correlation Analysis:

Correlation analysis showed statistically significant positive correlations among most weed growth and biomass traits, highlighting their interdependence. (Table 3). Dry biomass (DB) and fresh biomass (FB) were significantly positively correlated (r 0.98**), indicating that increases in fresh weight directly corresponded to increases in dry matter accumulation. DB was also strongly correlated with dry matter percentage (DMP) ($r = 0.44**$) and weed population (PW) ($r = 0.86**$), indicating that tissue composition and plant density played a major role in final dry biomass production. These relationships suggest that denser weeds with higher fresh biomass are more likely to accumulate greater dry matter.

DMP had moderate but statistically significant positive relationships with FB ($r = 0.44**$), moisture content (MC) ($r = 0.57**$), and PW ($r = 0.44**$), indicating that moisture content, physiological status, and plant density influenced biomass partitioning. The positive correlation between DMP and MC suggests that a change in the water status of the plants was connected to the effectiveness of the dry matter accumulation. Weed population was significantly correlated with fresh biomass ($r = 0.89**$), which supports the idea that an increase in weed density leads to an increase in fresh biomass production per unit area.

Conversely, there were weak and non-significant negative correlations between moisture content and DB ($r = -0.13$), FB ($r = -0.0933$), and PW ($r = -0.0361$), which means that moisture status was not strongly dependent on the accumulation of biomass and population size in the studied conditions. Weed flora (WF) was positively correlated with DB ($r = 0.34**$), DMP ($r = 0.20**$), FB ($r = 0.34**$), and PW ($r = 0.40**$), and indicated significant positive relationships between species diversity or richness and weed growth and biomass. In general, these results show that the properties of weed density and biomass are closely connected, whereas the moisture content is only relatively insignificant in defining the overall dynamics of weed growth.

Table 3. Correlation analysis showing the association of different growth and physiology-related characters in pearl millet

	DB	DMP	FB	MC	PW
DMP	0.44**				
FB	0.98**	0.44**			
MC	-0.13	0.57**	-0.0933		
PW	0.86**	0.44**	0.89**	-0.0361	
WF	0.34**	0.20**	0.34**	-0.0075	0.40**

The comparative study of dry biomass among the treatments revealed that there were major differences in the ability to suppress weeds (Figure 2). T1 had the lowest mean dry biomass (7.00), indicating it was the most effective in weed control. T2 (15.83), T5 (22.75), and T4 (24.92) showed moderate control, though less effective than T1. All in all, these treatments resulted in a significant decrease in the weed biomass compared to the alternative regimes, and this highlights their possible use in integrated weed management.

The treatment-specific means showed that there were differences in the patterns of growth of the weed, physiological conditions, and population dynamics. Dry-matter percentage showed a progressive increase between T1 (35.49) and T7 (57.00), indicating that under suboptimal or unmanaged conditions, weeds accumulated more dry matter. Treatments T4 (49.99), T5 (47.42), and T6 (50.67) also presented high levels of dry-matter percentage, indicating advanced weed development and lower physiological stress. On the other hand, the low value of T1 indicates that the development of plants and the subsequent accumulation of dry matter are restrained by efficient suppression.

Fresh biomass was also a close reflection of these trends, with T1 having the lowest mean (14.04), reflecting strong weed suppression. Moderate fresh biomass was observed in T2 (31.29), T5 (43.96), and T4 (46.83), whereas higher values occurred in T3 (60.96) and T6 (60.70). The highest fresh biomass was recorded in T7 (241.29), reflecting severe weed infestation and low control efficacy. This allocation of values provides serious empirical evidence on the effect of treatments on the dynamics and the accumulation of biomass of weeds.

There was a treatment-related variability in moisture content; in particular, T1 obtained an unusually high value (241.29), possibly due to reduced interspecific competition and limited structural growth resulting from strong weed suppression. The remaining treatments recorded relatively homogenous levels of moisture of between 41.99 and 50.01, which is characteristic of a stable hydric condition under moderate to high weed pressure. Conversely, T3 and T7 had relatively lower moisture content, which was indicative of augmented accumulation of dry matter and higher plant maturity.

The efficacy of treatment was also supported through the metrics of weed density; T1 had the least (2.54), which refers to optimal control. Density values increased gradually throughout the treatments, reaching significantly large values of 13.83, 14.17, and the highest density values in T3 (13.83), T6 (14.17), and T7 (33.79). This tendency clearly shows that poor treatments contribute to more weed growing and setting.

Weed flora proved to be relatively homogenous among the treatments, with means of about 2.50, suggesting that there was no significant difference in species richness between treatments due to their regimes. There was a small decrease in mean richness of " T6 (2.43) which indicated a slight shrinkage in the diversity of species; however, the general effect of treatments was mainly due to the abundance of weeds and their biomass and not necessarily to the species composition.

Combined, the results support the statement that successful management dramatically reduces the density and biomass of weeds, and incompetent administration encourages aggressive growth of weeds and increases physiological growth.
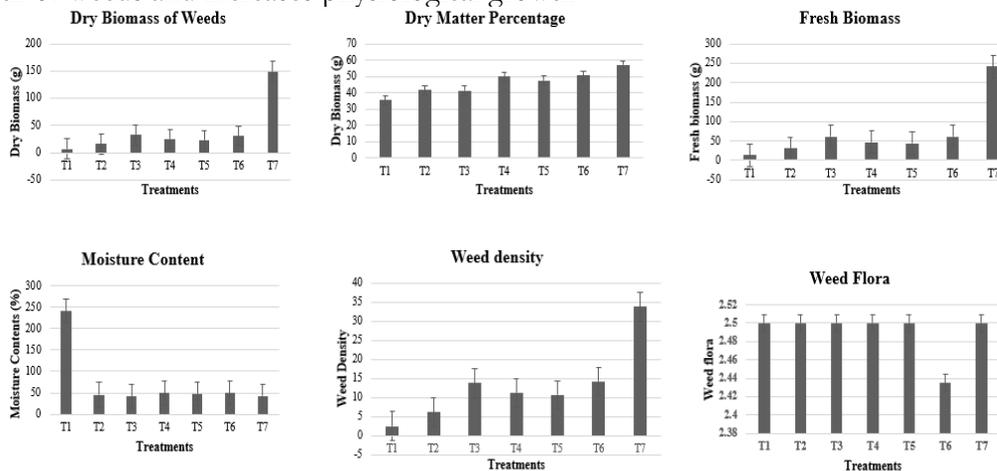

Figure 2. Representation of the mean data of the experiment for different parameters recorded for studying the weed population in the pearl millet

Mean Data Representation:

The results revealed substantial variation among treatments in reducing different weed groups at 15 and 30 days after sowing. For broad-leaved weeds, the minimum density at 15 DAS was recorded in T1 (5.00), whereas the maximum occurred in T7 (92.00). A similar trend was observed at 30 DAS, where T1 maintained the lowest value (5.33), and T7 showed the highest (52.33). In sedges, for sedges, T1 had the lowest population at 15 DAS (0.67), while T7 had the highest (28.67). At 30 DAS, T4 recorded the minimum (3.33), whereas T7 again

had the maximum (52.33). For khabal, the lowest density at 15 days was recorded in T1 and T2 (2.00), whereas T7 had the maximum (15.33); at 30 days, T3 showed the minimum (0.67) and T7 again the highest (24.33). For madhana, T1 completely suppressed the weed at 15 DAS (0.00), and T2 and T3 maintained complete control at 30 DAS (0.00). In contrast, T4 had the highest densities at 15 DAS (26.33) and 30 DAS (11.67). Overall, T1 demonstrated comparatively superior early suppression of most weed categories, whereas T7 consistently recorded the highest weed densities, indicating minimum weed control efficiency (Table 4).

Table 4. Mean data of weed density of different weeds at different treatments of weedicides in pearl millet

Treatments	Broad leaves		Sedges		Khabal		Madhana	
	15 days	30 Days	15 days	30 Days	15 days	30 Days	15 days	30 Days
T1	5	5.33	0.67	5.33	2	4.33	0	0.33
T2	13.67	8.33	3	8.33	2	11	2	0
T3	50.67	31.33	1	31.33	2	0.67	19.33	0
T4	32.33	3.33	4.33	3.33	5.33	4	26.33	11.67
T5	40.67	6.67	7.33	6.67	3.33	5	15	6.67
T6	47	11.33	3.33	11.33	13.67	8.67	14.67	4
T7	92	52.33	28.67	52.33	15.33	24.33	10.33	8

Discussion:

The current findings strongly show that the weed management interventions strongly influenced weed population dynamics, biomass accumulation, and physiological traits., which highlights the critical role of effective control strategies in reducing the spread of weeds. The analysis of variance showed that the treatment effects were greater than the temporal (day) effects in most of the response variables, with the fresh and dry biomass being the biggest. These results affirm the fact that management interventions are the major factors of weed suppression rather than temporal variation. Similar findings have been reported by [19], who observed that weed competitiveness and biomass production in cropping systems are significantly reduced by timely and proper weed control. These observations were further supported by the comparative analysis of treatments. The treatment T1 had the lowest values of weed density, fresh biomass, and dry biomass, which demonstrates the fact that it is the most effective one in reducing the growth and development of weeds. This suggests that T1 represents an optimized herbicidal or integrated weed management strategy capable of effectively suppressing weed establishment. On the other hand, treatment T7 exhibited significantly high weed density and biomass, which was an indication of ineffective control and unrestrained weed growth. This trend is consistent with the observation of [20], who indicated that poor or a lack of weed control results in aggressive growth of weeds and substantial yield loss because of high competition. The intermediate treatments (T2–T6) showed partial suppression, which means that they were partially effective and require more specific management approaches. The correlation test showed a strong and statistically significant positive correlation between weed density, fresh biomass, and dry biomass. This highly significant correlation with fresh and dry biomass ($r = 0.98$, significant) supports the idea that the fresh weight is a good predictor of the end dry mass. Similarly, the relationship between fresh biomass and the density of the weed ($r = 0.89**$) shows that the increase in populations of the weeds is directly proportional to an increase in the production of biomass. These findings align with the competitive growth behavior of weeds and support previous studies showing increased competition for nutrients, light, and moisture under high weed pressure [21][22]. The level of moisture content showed weak and non-significant relationships with the majority of growth parameters, and it was indicated that the water status of the plant under the experimental conditions was relatively independent of the population of the weed and the biomass. Nevertheless, the increased moisture content at T1 could be

explained by the decreased interspecific competition and decreased physiological stress associated with excellent weed suppression. The latter can be confirmed with the assistance of the research by [23], who stated that effective weed control enhances the availability of resources and improves water relations of the crop. There was low treatment-to-treatment variation in weed flora, which meant the management practices had more effect on the abundance of weeds but not their species. As a result, the prevalent weed species were robust in all treatments; however, their abundance was significantly lower when the control was effective, which is also observed by [24]. The findings clearly show that the management of the weeds has had a significant impact on the reduction of weed density and biomass, which has minimized the competition to the crops. The strong interdependence between weed density and biomass emphasizes the importance of early and effective weed control to prevent exponential weed growth. The high performance of T1 indicates that it can be recommended as a good weed management practice in similar agroecological conditions. The results are strong indicators of the need to develop sustainable weed management programs that would help increase crop productivity and use resources more efficiently.

It can be inferred that the significant decrease in the weed density at T1 and T2 at 15 and 30 DAS, respectively, shows the vigorous residual and pre-emergence action of applied herbicides on the soil to suppress early flushes of broad-leaved weeds and sedges. Pendimethalin-based herbicides have been shown to prevent cell division and root growth in germinated weed seeds and slow the establishment of the crop, which gives it an edge over the crop in its sensitive growth phase [25]. The higher performance of T2 suggests that combining herbicides broadens the spectrum of activity by targeting multiple physiological pathways., something that has been previously observed in tank mixtures or premixes, which have indicated improvement in effectiveness against a wide range of weed flora [26][27]. Suppression in the early season, such as T1, is especially crucial since those weeds that appear in the first 3-4 weeks of sowing lead to the highest yield losses because of the high competition over light, nutrients, and moisture [16].

In contrast, the consistently high densities in T7 (weedy check) indicate uncontrolled competition among weeds. Moderate reductions observed in some post-emergence treatments (T4–T6) likely reflect dose dependence and the stage of weed development at the time of application. Lower doses or late applications often result in partial suppression rather than complete control, particularly for sedges and grassy weeds with established root systems [28]. The fact that the khabal and madhana are better suppressed by certain treatments also belongs to the idea that the herbicides' selectivity and time are also major determining factors for the effectiveness of the weed control. On balance, the findings are compatible with the principles of integrated weed management in terms of timely pre-emergence weed application and the reasonable choice of herbicides in order to reduce the level of the weed and ensure the crop yield [28].

Conclusions:

The research concludes that treatments of weed management had a great effect on the density of the weed and the accumulation of biomass. T1 was the most effective treatment that suppressed the growth of weeds, whereas T7 was the least effective, which allowed the weeds to grow to the maximum. The positive relationships between the weed density and biomass traits are very strong, thus indicating that early and effective weed management is essential in curbing excessive growth of weeds. These findings highlight the importance of implementing successful and sustainable weed management techniques to reduce crop-weed interaction and maximize agricultural output.

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