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Response of Weed Population Dynamics and Communities on Yield: A Case Study Using *Trigonella foenum-graecum* L.

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***Abstract*:** Field experiments were conducted for two successive years at Agronomy Research farm, CCS Haryana Agricultural University, Haryana during 2018-19 and 2019-20 to evaluate the efficacy of herbicide-based IWM strategies and to study the response of weed population dynamics and communities on fenugreek yield. Total weed density was lower in the first year as compared to second year *i.e.* 80 and 88 weeds m^{-2}, respectively. Dicotyledon/broad-leaved weeds (84.3 and 88.1% relative density) were more prevalent than monocotyledon grassy/sedge weeds, with relative densities of 13.7 and 11.9%, respectively during both years. Lower dry weight of weeds was recorded with two hoeing employed at 30 and 60 DAS which was statistically at par with PRE application of pendimethalin + imazethapyr (RM) at 1500 g ha^{-1} + one hoeing at 3-4 leaf stage. Among the IWM practices evaluated in fenugreek, pendimethalin + imazethapyr at 1500 g ha^{-1}as pre-emergence and then one spot hand weeding at 30–35 days after sowing was effective in controlling weeds which was 87.0 and 83.7% higher, respectively in first and second year than that in unweeded control. The use of imidazolinones in combination with pendimethalin (RM) improved its efficacy in controlling the predominant weeds. We concluded that a management programme based on the combination of herbicides applied at early stages with one hoeing at 3-4 leaf stage will be effective to control the future infestations in legume crops.As a result, coupling pendimethalin and imazethapyr may result in improved weed control as well as increased fenugreek productivity and profitability.

***Keywords*:** Fenugreek, *Trigonella foenum-graecum,* Integrated weed management, Weed dynamics, Weed suppression

Legume is considered as the most valuable plant because of its high grain protein content and potential to fix biological nitrogen. Fenugreek (*Trigonella foenum-graecum* L.), is a multiuse seed spice crop of arid and semi-arid regions of India. India is among the largest producers in the world, occupying 169 thousand ha area with an annual output of 252 thousand MT and average productivity of 1.7 MT ha^{-1} (Anonymous 2021). Improved agronomic approaches, especially effective weed management, have the potential to raise fenugreek yield in Haryana. Weed suppression is one of the most significant factors of a crop's yield advantage, and the influence on production is determined by the interaction of the crop and weed flora. Weed removal is one of the most important ways to circumvent crop losses. In India, the strategy for weed management in legume has not changed except for the introduction of novel combinations or formulations of currently available active ingredients. One alternative is the use of acetolactate synthase (ALS)-inhibitor herbicides. In many crops, this method of action consists of five chemical groups with varied efficacy against dicotyledonous and monocotyledonous weeds. Selectivity is that property of herbicides which help them to eradicate the weeds without affecting the crop plant in the field (Bajwa 2016). Herbicide applications that have a low selectivity trigger phytotoxicity in the crop. In northwestern India, weed poses a severe threat to legumes yield and it must be countered using integrated weed management strategies that include herbicide combinations, crop and herbicide rotations, cultural and mechanical methods, and more. Weed populations resistant to multiple site-of-action (SOA) herbicides are becoming more common and pervasive in many agro zones with high-input intensive cropping (Beckie et al 2020, Heap 2020). In legume crops, post herbicides are used less extensively. For this context, we discuss some feasible weed management options. To suppress economically damaging weeds, are usually treated just before or at seeding. Weeds have a negative impact on crop development and productivity because they compete with crops for limited resources like light, water, and nutrients (Swanton et al 2015). The extent of crop production losses is determined by the intensity and length of the crop-weed competition. Herbicides are the most widely used weed management tools in agriculture, with a global herbicide market worth an estimated $27 billion per year (Kraehmer 2012). As a result of this over-reliance on same-site-of-action herbicides in cropping systems, herbicide-resistant (HR) weed populations have grown substantially over the world (Heap 2016). Insurgent reports on HR weed numbers represent a severe danger to the US cropping systems' long-term resilience. Furthermore, given the absence of any new site-of-action herbicide discovery in the last two decades, the expense of managing HR weeds has risen, exacerbating the situation (Duke 2012). In herbicide-restricted environment, effectively and profitably managing troublesome weeds in key agronomic field crops will be difficult, but it might be viewed as a chance for much more adoption of ecologically based weed management approaches, strategies, and systems. The success of integrated weed management techniques depends on the reliability of control operations in both time and space. While spatial precision has gotten a lot of attention, time accuracy has gotten the short end of the stick. Developing integrated weed management (IWM) solutions has long been a goal of agricultural research, particularly for economic and ecological sustainability (Clements et al 1994, Bajwa 2014). The IWM system necessitates a thorough understanding of weed biology and their significance in the agro-ecosystem, as well as the development of criteria for determining when to manage these weeds. These criteria must encompass agronomic and economic considerations (Wilkerson et al 2002). In addition, IWM must include a number of complementary measures aimed at suppressing or eliminating weed establishment throughout the year in order to satisfy production goals, whether they be economic or ecological. The goal of weed control, on the other hand, is to successfully eliminate unwanted plants by the use of mechanical or chemical methods. Achieving IWM needs not only a variety of tools, but also quick response. It is not rare for weed control techniques to be deployed too late for effective control of individuals, resulting in escapes, an augmented soil seed bank, and the evolution of herbicide resistance (Neve et al 2010). Understanding how crop management practises affect weed emergence, survival, and seed production is critical for optimising long-term weed management strategies. Preplant weed control, on the other hand, will be less effective if a weed species has a protracted emergence pattern or emerges in numerous flushes and becomes tall quickly. Herbicides are primarily used in the field to reduce weed competition with crops that emerge at the same time. Imazethapyr can be used as pre-plant incorporated (PPI), pre, and post treatments to control a wide range of grass and broad-leaved. Therefore, the purpose of this study is to quantify the impact of different management tools on dominant weed flora in fenugreek crop. These findings may lead to more proactive, long-term approaches for effective weed management, thus, reducing producer reliance on herbicides. As a result, using non-chemical weed management methods in weed management programmes is critical for long-term crop performance. Herbicide resistance is evolving, and chemical alternatives are limited, thus a rational way of tackling problematic weeds is necessary.

MATERIAL AND METHODS

Description of field sites and experimental design: Against the predominant weeds in fenugreek, to assess the bio-efficacy of pre and post herbicides both separately and in combination, two field experiments were conducted on the Research farm of CCS Haryana Agricultural University, Hisar, Haryana, India (29° 10´N, 75° 46´E) during the winter seasons of 2018-19 and 2019-20. The rainfall received in the 2018 and 2019 cropping seasons was 28.6 and 32.4 mm, respectively. The experimental design was randomized complete block with three replications. The soil of the field was sandy loam in texture, low in nitrogen (181 kg ha^{-1}), medium in phosphorus (17 kg ha^{-1}) and high in potassium (285 kg ha^{-1}). With the help of a tractor-drawn cultivator, the field was ploughed twice to crush the clods. The field was cleared of previous crop leftovers. Ploughing was accomplished again by cross harrowing, followed by cultivator twice, and planking to achieve a fine tilth of the soil. Fields were fertilised with 20 and 40 kg ha^{-1} of nitrogen and phosphorous, respectively through DAP before sowing in each year. Each plot size was 6.0m × 6.0m. The fenugreek variety HM-51 was sown on 22 November 2018 and 19 November 2019 during 2018-19 and 2019-20, respectively. At 20 cm row spacing, the seeding rate was 25 kg per hectare. With a knapsack sprayer equipped with a flat fan nozzle and a 500 L ha^{-1} spray volume, preemergent herbicides were sprayed right away after sowing in moist soil, and additional post-emergent herbicides were applied at 46 DAS. The crop was managed according to the standard agronomic practices of the state university. Most abundant species (>5% of the relative density) found in the experimental area during 2018 and 2019 were (Table 1). *Melilotus indica* (7.7 and 8.6%), *Anagallis arvensis* (23.5 and 22.5%), *Rumex dentatus* (14.0 and 14.0%), *Lathyrus aphaca* (11.8 and 11.3%), *Medicago denticulata* (21.6 and 20.6%), *Phalaris minor* (13.7 and 14.4%) and *Coronopus didymus* (7.7 and 8.6%) at 45 DAS.

Treatments: Treatments in the study were T1: PRE imazethapyr at 80 g ha^{-1}, T2: PRE imazethapyr at 80 g ha^{-1} + one hoeing, T3: POE imazethapyr at 80 g ha^{-1}, T4: PRE imazethapyr + imazamox (RM) at 70 g ha^{-1}, T5: POE imazethapyr + imazamox (RM) at 70 g ha^{-1}, T6: PRE imazethapyr + imazamox (RM) at 70 g ha^{-1}, T7: PRE pendimethalin at 1000 g ha^{-1}, T8: PRE pendimethalin at 1000 g ha^{-1}+ one hoeing, T9: PRE pendimethalin + imazethapyr (RM) at 1000 g ha^{-1}, T10: PRE pendimethalin + imazethapyr (RM) at 1250 g ha^{-1}, T11: PRE pendimethalin at 1500 g ha^{-1}, T12: PRE pendimethalin + imazethapyr (RM) at 1500 g ha^{-1} + one hoeing, T13: weed-free along with T14: weedy check and T15: two hoeing at 30 and 60 DAS. Treatments 3 and 5 follow the post-emergence timing (3-4 leaf stage/46 DAS) of the weed control strategy, treatments 2, 6, 8 and 12 exemplify weed control strategies with PRE application of herbicides along with one hand hoeing at 3-4 leaf stage. The weed-free control plots were kept weed-free by hand-weeding as and when required, and weeds were not removed in weedy check plots.

Weed sampling: Observations on weed density from two random spots was recorded at 75 DAS by placing a quadrate of size 0.5 m × 0.5 m. The weed biomass was recorded at 75 DAS. Dry weight of weeds was recorded after drying the weeds in the sun and later in an oven at 60ºC up to 72 hr. till a constant weight was attained. Then, prior to conducting a statistical analysis, the dried weed sample weight was measured in units of g m^{-2}. The effectiveness of weed management was calculated as a percent decrease in total weed biomass under various treatments compared to weedy check at 75 DAS. On March 21, 2019 and 25, 2020, respectively, the crop was harvested when it reached complete physiological maturity. An area of 0.2 m on each side of the plot and one border row on both sides of the experimental plots were harvested first, thereafter the net area separately. Grain yield was determined at a moisture content of 14% after threshing with a plot thresher, followed by cleaning. The recorded data was converted into kg ha^{-1}. In order to calculate the weed index, crop production loss was added up throughout treatments in comparison to the weed-free plot.

Statistical analysis: Before statistical analysis, to increase the homogeneity of the variance, weed data was subjected to square root transformation (√X+1). Utilizing R statistical software version 0.1.0, all data were examined. The estimated regression equation has been constructed for both years and was used to study the relationship between seed yield and major weed densities using a linear bivariate regression analysis. In order to analyse the joint or combined effect of factors on grain production, various correlation studies were conducted on the relationship between wheat grain yield and total weed density, weed dry weight, total N, P, and K absorption.

RESULTS AND DISCUSSION

Weed interference: There were two monocotyledon grasses and six dicotyledon weeds in the experimental pea field (Table 1). In comparison to the second year, the total weed density was lower in the first year (80 and 88 weeds m^{-2} respectively). Dicotyledon/broad-leaved weeds (84.3 and 88.1 percent relative density) were more prevalent in the first and second year than monocotyledon grassy/sedge weeds, which had relative densities of 13.7 and 11.9 percent, respectively. Weed species that showed up in the experimental field were gathered, identified, and listed in Table 1. *Anagallis arvensis* was the most prevalent weed *(23.5 and 22.5 percent relative density)* followed by *Medicago denticulata* , *Rumex dentatus* , *Lathyrus aphaca* and *Phalaris minor* during 2019 and 2020, respectively.

Regression studies between weed density and yield in fenugreek: The results of the regression analysis showed unequivocally that the fenugreek seed yield was inversely related to the total density of weeds (Fig. 3). Strong correlation was observed between weed density and yield in case of *Coronopus didymus* and *Melilotus indica* (Table 2). The robustness of the relationship between seed yield and weed density under various weed control methods was confirmed by the fitted regression model's goodness of fit for the years 2018–19 and 2019–20 (R^2 = 0.93) and (R^2 = 0.92).

Crop growth that is morphological is the outcome of interactions between a plant's environment and its genetic characters. At all the stages of crop growth, *Anagallis arvensis* and *Medicago denticulata* dominated the weed flora. The regression model for seed yield on density of predominant weeds *viz. Melilotus indica* (R^2 = 0.92, 0.93),

Table 1. Weed flora of the experimental field and their relative density

Scientific name	Common name	Family	Habit and characteristics	Relative weed density in weedy check at 45 DAS (%)	
				2018-19	2019-20
Melilotus indica L.	Sweet clover	Leguminosae	Annual broad- leaved herb	7.7	8.6
Anagallis arvensis L.	Pimpernel	Primulaceae	Annual broad- leaved herb	23.5	22.5
Medicago deniculata L.	Bur clover	Leguminosae	Annual broad- leaved herb	21.6	20.6
Rumex dentatus L.	Golden dock	Polygonaceae	Annual broad- leaved herb	14.0	14.0
Lathyrus aphaca L.	Yellow pea	Leguminosae	Annual broad- leaved herb	11.8	11.3
Phalaris minor L.	Canary grass	Poaceae	Annual grass herb	13.7	14.4
Coronopus didymus L.	Swinecress	Brassicaceae	Annual broad- leaved herb	7.7	8.6

Anagallis arvensis (R^2=0.86, 0.85), *Coronopus didimus* (R^2=0.93, 0.94), *Rumex dentatus* (R^2=0.82, 0.73) and *Medicago denticulata* (R^2 = 0.86, 0.87) demonstrated significant dependence. Population dynamics (number m^{-2}) was significantly influenced by different weed management practices. The degree of goodness of the fitted regression model for seed yield on total weed density during both the years (R^2 = 0.91, 0.87, respectively) showed strong relation of weed densities on seed yield. Effective weed management have developed suitable environmental conditions for water and nutrient absorption in fenugreek crop. Thus, enabled availability of nutrients, water, light and space to the crop which resulted into increased plant height. The results of this study are validated by Kamboj et al (2005) and Chovatia et al (2010).

Correlation of total weed density, weed dry weight, total N, P and K uptake with yield: The correlation matrix (Table 3) demonstrated the linear relationship between the variables, highlighting the significant influence of each parameter, including total weed dry weight and density, total N uptake, total P uptake, and total K uptake on fenugreek seed yield under various weed control methods. The matrix showed that there was a strong negative association between fenugreek seed yield and total weed density (r = -0.95) and dry weight (r = -0.93) of weeds, but a strong positive correlation between fenugreek seed yield and total N, P, and K uptake. The uptake of total N (r = -0.94 and -0.95), P (r = -0.93 and -0.96), and K (r = -0.94 and -0.96) was negatively correlated with the total density and dry weight of weeds. The negative relationship between weed density and yield was observed under all the weed control treatments during 2018-19 (Fig. 1a) and 2019-20 (Fig. 1b).

Impact of weed management on weeds in fenugreek: Through this experiment, the types of weed species, including susceptibility/tolerance and growth stages, as well as the chemical make-up and timing of herbicide applications, all had an impact on weed control. Temperature and rainfall have also had an impact on the effectiveness of herbicides throughout time. Pendimethalin and imazethapyr are broad-spectrum herbicides that are selective to pea and belong to two classes of herbicides with distinct mechanisms of action (Shalini and Singh 2014, Kukharchik et al 2013). Pendimethalin + imazethapyr (RM) at 1500 g ha^{-1} applied as pre-emergence, effectively controlled the dominant weed species in fenugreek (Singh et al 2016). All the weed species reported in this study were effectively managed by ready-mix herbicide formulations *viz.* imazethapyr + imazamox and pendimethalin + imazethapyr as compared to application of pendimethalin as PRE and imazethapyr as PRE and POE (Yadav et al 2015). Pendimethalin's ability to inhibit the growth of emerging weeds' roots and shoots is responsible for higher weed control effectiveness and percent weed control (Appleby and Valverde 1988; Holt et al 1993; Gilliam et al 1993) and imazethapyr's longer half-life, which ranges from 78 to 270 days, is responsible for the higher persistence of imazethapyr and as a result better control at later stages (Goetz et al 1990). The variation in weed count, their dry matter and weed control efficiency might be due to

Table 2. Regression relationship of grain yield with major weed densities (independent variables)

Independent variable	2018-19		2019-20	
Weed density	Estimated regression line	Adjusted R^2 value	Estimated regression line	Adjusted R^2 value
Melilotus indica	y = -0.0065x + 14.678	0.9244	y = -0.0075x + 15.36	0.9297
Anagallis arvensis	y = -0.013x + 31.725	0.8581	y = -0.0138x + 31.155	0.8491
Coronopus	y = -0.0049x + 10.884	0.9295	y = -0.0068x + 13.428	0.9452
Rumex dentatus	y = -0.0072x + 18.391	0.8243	y = -0.0082x + 19.966	0.7318
Medicago denticulata	y = -0.0136x + 31.932	0.8629	y = -0.0144x + 31.452	0.8755

Table 3. Correlation coefficient (n = 60) with exact probability level of significance

Pearson correlation coefficients	Seed yield	TWD	WDW	TNU	TPU	TKU
Seed yield	1	-0.951**	-0.933**	0.992**	0.992**	0.990**
Total Weed density (TWD)		1	0.869**	-0.940**	-0.932**	-0.944**
Total weed dry weight (WDW)			1	-0.955**	-0.958**	-0.962**
Total N uptake (TNU)				1	0.990**	0.997**
Total P uptake (TPU)					1	0.989**
Total K uptake (TKU)						1

differences in the effectiveness of herbicides used against different weeds in the field (Meena et al 2018). Lower dry weight of weeds was recorded with two hoeing employed at 30 and 60 DAS (Fig. 2) which was statistically at par with PRE application of pendimethalin + imazethapyr (RM) at 1500 g ha^{-1} + one hoeing at 3-4 leaf stage (Gupta et al 2017). Due to the pre-emergence treatment of various herbicides, a significant decrease in weed density and dry weight was seen, which produced a favourable environment for the crop. The weeds that germinate either before or along the crop offer higher competition as compared to later germinating ones. Weeds accumulates dry matter faster as compared to crop plants. The prolonged time of weed control and weed spectrum in herbicide mixtures lead to better weed control. The weaker second and third cohorts of weeds were managed by imazethapyr due to its increased persistence and one hand hoeing at 3-4 leaf stage. Pre pendimethalin eliminated the initial cohorts of weeds. The principal weed cohorts in PoE alone treatments get an early start due to the initial slow growth of the crop and are subsequently not efficiently eliminated by PoE herbicides, in alone pretreatments the later appearing weeds continued to contend with the crop. Most effective herbicide treatment *i.e.* pre pendimethalin + imazethapyr (RM) at 1500 g ha^{-1} + one hoeing at 3-4 leaf stage recorded highest seed yield. This may be attributed to a decrease in weed density and dry weight caused by the sequential application of herbicides that killed the majority of the weed cohorts. This helped the

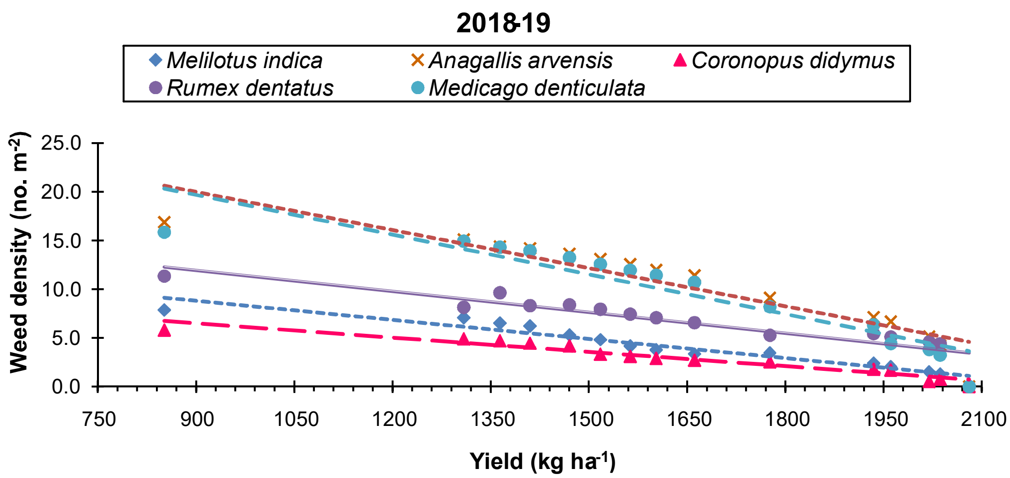

Fig. 1a. Relationship between weed density (no. m^{-2}) and yield in different weed control treatments during the year 2018-19

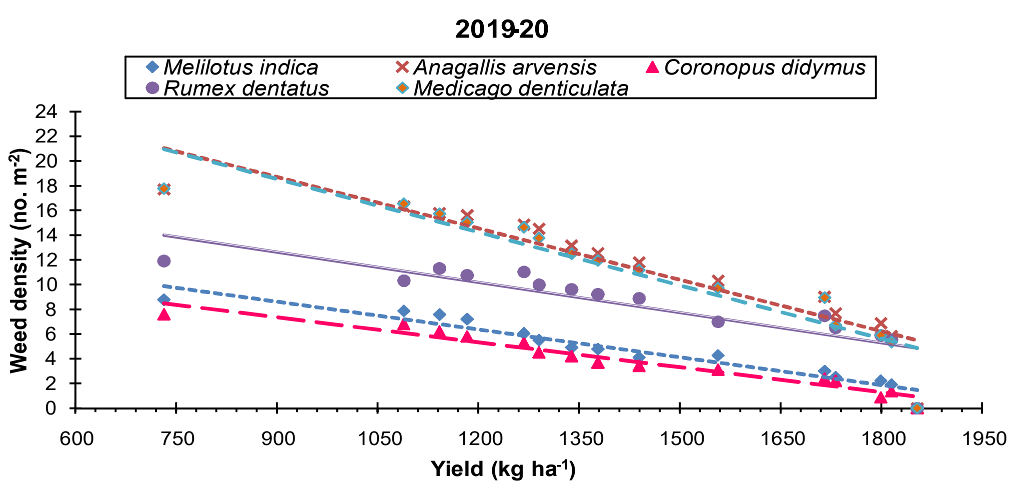

Fig. 1b. Relationship between weed density (no. m^{-2}) and yield in different weed control treatments during the year 2019-20

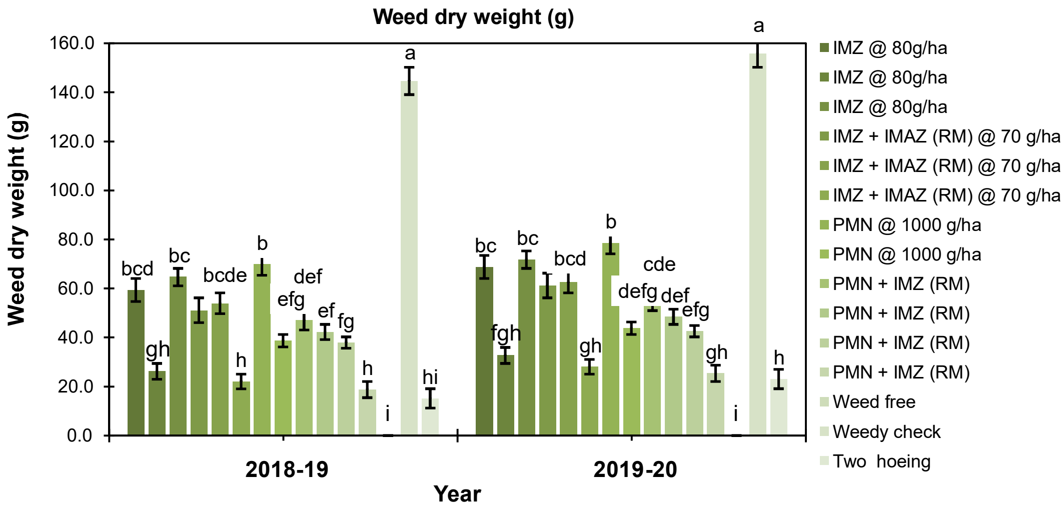

Fig. 2. Effect of weed control treatments on weed dry weight in fenugreek during both the years

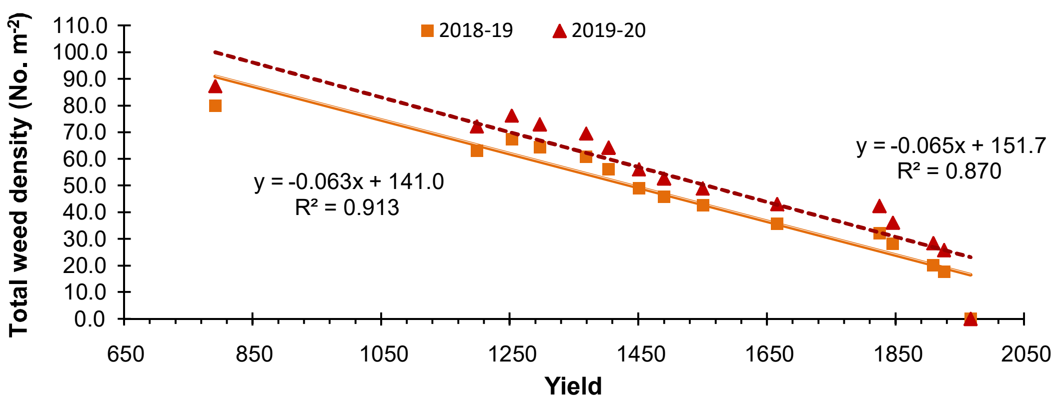

Fig. 3. Effect of total weed density on seed yield in fenugreek during both the years

crop utilise nutrients, moisture, light, and space more effectively, resulting in higher dry weight, more effective tillers, more grains per spike, and higher test weight, all of which increased grain yield.

CONCLUSION

The findings of this study will assist reduce reliance on a single site-of-action herbicide, lowering the selection pressure for herbicide-resistant weed populations in a crop production systems. Integrated weed management strategies are a beneficial weed management tool for inclusion in Indian agricultural production systems in the light of changing weed flora in response to management practices. Herbicides should be used with prudence, avoiding higher-than-recommended doses and employing a variety of control methods such as mechanical, manual, and cultural control. Herbicide alternatives for the treatment of innumerable weed flora issues in legumes are suggested by the findings of this study. The ready mix formulation *viz.* pendimethalin + imazethapyr at 1500 g ha^{-1} in combination with one hoeing applied at 3-4 leaf stage can be a profitable alternative to the single site-of-action herbicides in fenugreek. Incorporating integrated techniques into a weed management programme as a routine weed control approach will surely result in more effective control and a reduction in herbicide resistance evolution. These herbicide mixtures look to be a realistic alternative till then. This approach can be used in similar agro-ecologies in the tropics and subtropics as well as in India's North-western Indo-Gangetic Plains.

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AUTHOR CONTRIBUTIONS

Conceptualization, Isha Ahlawat and Todarmal; Formal analysis, Todarmal; Methodology, Sumit Bhardwaj and Anjali

Rana; Supervision, Todarmal; Writing-review & editing, Anjali Rana and Abhishek. All authors have read and agreed to the published version of the manuscript.

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