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VARIABLE-RATE FLAME WEEDING: A STAGE-SPECIFIC APPROACH FOR ENHANCED WEED CONTROL AND REDUCED REGROWTH

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ABSTRACT

Herbicide resistance, environmental concerns and restrictions on chemical inputs have increased the need for sustainable weed management alternatives. Flame weeding is a promising non-chemical technique; however, its effectiveness depends on weed growth stage and operating conditions. The present study evaluated the effectiveness of flame weeding at different weed growth stages and optimized operating parameters for maximizing weed mortality while minimizing regrowth under field conditions. Experiments were conducted under natural weed infestation using Response Surface Methodology with a Central Composite Design, considering operating pressure, exposure duration and burner distance as independent variables. Weed mortality was assessed at 7 days after treatment, and weed regrowth was recorded at 21 days after treatment. Results showed that weed mortality increased significantly with operating pressure and exposure duration, whereas weed regrowth decreased with increasing thermal exposure. Burner distance influenced treatment efficiency by affecting heat transfer to plant tissues. Weed growth stage was identified as the most influential factor, with early-stage weeds showing high susceptibility and mature weeds exhibiting greater tolerance and recovery potential. Optimization using the desirability function approach indicated that the advanced vegetative stage provided the most effective operating conditions, achieving high weed mortality with minimal regrowth. The study demonstrated that uniform flame application is inefficient and that stage-specific adjustment of operating parameters improves control efficiency while reducing unnecessary energy use. The findings highlight the potential of variable-rate, stage-specific flame weeding as a practical and sustainable precision weed management strategy.
***Keywords* :** Flame weeding; thermal weed control; weed growth stage; weed mortality; weed regrowth; response surface methodology; precision weed management.

Introduction

Weeds are one of the most serious biological constraints affecting agricultural productivity, causing significant yield and quality losses due to competition for nutrients, water, light and space. In many cropping systems, uncontrolled weed infestation can reduce yield by 30–40% depending on crop type and weed density (Kumawat *et al.,* 2019). Chemical herbicides remain the dominant weed control strategy worldwide because of their rapid and effective action. However, continuous reliance on herbicides has resulted in widespread evolution of herbicide-resistant weed species, environmental contamination and increasing public concern regarding food safety (Bond and Grundy, 2001; Datta and Knezevic, 2013; Heap, 2023). The rapid increase in herbicide resistance globally has emphasized the urgent need for alternative and integrated weed management strategies (Duke and Dayan, 2022; Beckie *et al.,* 2019).

In response to these concerns, non-chemical weed control approaches have gained renewed attention in both conventional and organic production systems. Among these alternatives, thermal weed control particularly flame weeding has emerged as a promising residue-free technique (Ascard, 1995; Ascard *et al.,* 2007). Flame weeding exposes plant tissues to high temperature for a short duration, causing rapid heating of cells that leads to protein denaturation, membrane rupture and loss of cellular integrity (Peerzada and Chauhan, 2018). Importantly, flaming does not burn the plant tissue; rather, it delivers a lethal heat dose that disrupts physiological functions and results in desiccation (Knezevic *et al.,* 2012). Because no chemical residues are involved, flame weeding is well suited for organic farming and environmentally sensitive production systems (Merfield *et al.,* 2017; Stepanovic *et al.,* 2016).

The success of flame weeding depends strongly on weed biological characteristics, particularly growth stage. Young seedlings are generally more susceptible to thermal injury because they possess thin cuticles, small biomass and limited carbohydrate reserves, whereas mature plants develop thicker protective tissues and deeper root systems that enhance their recovery ability (Datta and Knezevic, 2013; Knezevic *et al.,* 2014, Peerzada and Chauhan, 2018). Ascard (1995) demonstrated that weed susceptibility to flaming decreases significantly with plant age, and similar observations were reported by Knezevic *et al.* (2012), who emphasized that timely application at early growth stages was critical for achieving high control levels. The lethal temperature threshold for most plant tissues typically ranges between 55 and 70 °C, although tolerance varies with species and developmental stage.

Apart from biological factors, operational parameters such as gas pressure, burner height and exposure duration influence the heat energy delivered to weeds. Increased flame intensity enhances heat flux, whereas longer exposure duration increases cumulative heat dose received by plant tissues (Knezevic *et al.,* 2014; Merfield *et al*., 2017; Sindhuja *et al.,* 2026). Conventional flame weeding practices generally apply uniform flame intensity across the entire field without considering variability in weed size or density. This often leads to excessive fuel consumption in lightly infested areas and insufficient control in advanced growth stages. Therefore, variable-rate or site-specific weed management has been proposed as a precision approach to improve efficiency and sustainability (Slaughter *et al.,* 2008; Peteinatos *et al.,* 2014).

Recent advancements in precision agriculture highlight the importance of stage-specific and site-specific weed control strategies for reducing input use and improving sustainability (Westwood *et al.,* 2018; Beckie *et al.,* 2019). Although flame weeding has been widely investigated as an alternative to chemical control, most existing studies have primarily focused on fixed operating conditions and controlled experimental environments, with limited emphasis on field-scale optimization under varying weed growth stages. In addition, the combined and interactive effects of critical operational parameters such as gas pressure, burner height and exposure duration on weed mortality and regrowth behavior are not sufficiently quantified under practical field conditions (Knezevic *et al.,* 2014; Merfield *et al.,* 2017).

Consequently, a clear research gap exists in developing optimized, stage-specific operational strategies for variable-rate flame weeding that can improve weed control efficiency while minimizing fuel consumption and regrowth. It is hypothesized that weed susceptibility to flame weeding decreases significantly with advancement in growth stage, thereby requiring higher thermal doses for effective control (Ascard, 1995; Knezevic *et al.,* 2012), and that optimization of key operating parameters such as gas pressure, exposure duration and burner distance using response surface methodology can significantly enhance weed control efficiency while reducing energy use (Knezevic *et al.,* 2014; Merfield *et al.,* 2017). Furthermore, it is also hypothesized that variable-rate flame weeding based on weed growth stage will provide superior weed control and reduced regrowth compared to conventional uniform flame application (Slaughter *et al.,* 2008; Peteinatos *et al.,* 2014). Therefore, the present study was undertaken to evaluate the effect of variable-rate flame weeding at different weed growth stages and to optimize operating parameters using response surface methodology for effective, energy-efficient and sustainable weed management.

Materials and Methods

Experimental Site and Crop Establishment

The field experiment was conducted under open field conditions during the cropping season at the experimental farm of Dr. NTR College of Agricultural Engineering. The experimental site is characterized by a tropical coastal climate with high temperatures and moderate relative humidity during the cropping period, and the soil is predominantly sandy in texture, facilitating rapid weed emergence and uniform field conditions. The field was ploughed and prepared to a fine tilth to ensure uniform germination of both crop and weeds. Cotton was sown in rows during the first week of July to coincide with the onset of monsoon, enabling natural weed infestation to develop along with the crop. No herbicides were applied throughout the experimental period in order to maintain a natural and diverse weed population.

The experimental field consisted of a mixed weed flora including broadleaf, grassy and some perennial species commonly found under such agro-ecological conditions. However, the present study does not focus on control of any specific weed species or group. Instead, it evaluates the overall effectiveness of flame weeding as a non-selective thermal method intended to control all types of weeds present within the crop field. Although it is well established that thermal susceptibility varies among weed species and categories, the objective of this study is to develop and optimize variable-rate flame weeding based on weed growth stage and field conditions rather than species composition. This approach reflects practical field scenarios, where multiple weed species coexist and site-specific management targets weed intensity and growth stage instead of individual species identification. Therefore, the natural infestation was retained without selective classification or species-wise treatment, allowing assessment of the system's performance under realistic and heterogeneous field conditions. Such an approach is consistent with precision weed management strategies aimed at improving operational efficiency and adaptability in diverse weed environments (Knezevic *et al.,* 2012; Merfield *et al.,* 2017).

Flame Weeding Treatments

Flame weeding treatments were imposed at different weed growth stages beginning two weeks after crop emergence (Knezevic *et al.,* 2014). Weed growth stage was considered a major experimental factor because susceptibility of weeds to thermal injury varies significantly with plant age (Ascard, 1995; Datta and Knezevic, 2013).

Four weed growth stages were considered:

- 2nd week after emergence (early seedling)
- 3rd week after emergence (young vegetative)
- 4th week after emergence (advanced vegetative)
- 5th week after emergence (mature stage)

Experimental Design

The experiment was designed using Response Surface Methodology (RSM) with a Central Composite Design (CCD) generated in Design-Expert®13 software. Three operating parameters were selected as independent variables mentioned in table 1. A total of 80 experimental runs consisting of factorial points, axial points and replicated centre points were conducted at each weed growth stage. Each treatment was replicated three times.

Table 1 : Experimental operating parameter levels

Parameter	Range
Operating pressure (kg cm^{-2})	0.5, 1.0, 1.5, 2.0, 2.5
Flame exposure duration (s)	0.5,1.0, 2.0, 3.0, 4.0s
Burner distance (cm)	5, 10, 15, 20, 25

Experimental Procedure

A square sampling area of 50 × 50 cm was marked for each treatment plot within the experimental field. The selection of sampling plots was carried out using a randomization approach across the entire field to ensure unbiased representation of natural weed variability under field conditions. Each experimental run was replicated three times, and independent plots were selected randomly for each replication to minimize the effect of spatial variability in weed distribution. The number of weeds present within each marked plot was counted and recorded as the initial weed population prior to treatment. Flame application was then performed by moving the burner uniformly across the selected plot while maintaining the specified operating parameters, including operating pressure, exposure duration and burner distance. Immediately after treatment, visual injury symptoms such as leaf wilting, tissue softening and discoloration were observed and recorded. Thermal weed control induces rapid cellular damage due to heat exposure, which becomes visible within a few hours after flaming (Ascard *et al.,* 2007).

Measurement of Weed Mortality

Weed mortality was recorded 7 days (Knezevic *et al.,* 2012; Datta and Knezevic, 2013) after treatment. Surviving weeds in each plot were counted and mortality percentage was calculated using the following equation:

$$\text{Weed mortality}\,(\%) = \frac{N_i - N_S}{N_i} \times 100 \quad \text{(Ascard, 1995)}$$

Where:

N_i =initial weed count before treatment

N_S = number of surviving weeds at 7 days after treatment

In flame weeding, plant death is not always immediate, as the technique primarily causes thermal injury that disrupts cellular structure and physiological processes, leading to gradual desiccation and eventual plant death. Therefore, assessment at 7 days provides a reliable measure of effective mortality after the delayed expression of heat-induced damage.

Measurement of Weed Regrowth

Weed regrowth was recorded at 21 days after treatment (Ascard, 1995; Rask and Kristoffersen, 2007) to evaluate delayed recovery of weeds following thermal exposure. Some weeds are capable of regenerating after flaming if the growing points or meristematic tissues are not completely destroyed. Since flame weeding aims at inducing sub-lethal or lethal thermal injury rather than instant plant death, monitoring regrowth is essential to assess the long-term effectiveness of the treatment. Regrowth percentage was calculated as:

$$\text{Weed regrowth}\,(\%) = \frac{N_r}{Ni} \times 10 \quad \text{(Knezevic \textit{et al.}, 2012)}$$

Where:
N_r = number of weeds showing regrowth 21 days after treatment

Statistical Analysis and Optimization

The experimental data for weed mortality and weed regrowth were analysed using Design-Expert® 13 software. Second-order polynomial regression models were developed to evaluate the effect of operating parameters and weed growth stage. Analysis of variance (ANOVA) was performed to determine significant factors and their interactions.

Optimization was carried out using the desirability function method to maximize weed mortality and minimize weed regrowth. Response surface methodology has been widely used in agricultural experiments for optimizing operating parameters and identifying suitable treatment combinations (Myers *et al.,* 2016; Montgomery, 2017).

Results and Discussion

Weed Mortality as Influenced by Operating Parameters and Growth Stage

The combined effect of operating pressure and exposure duration on weed mortality is presented in Fig. 1(a).

Weed mortality increased significantly with increasing operating pressure and exposure duration, indicating a strong positive influence of both factors on thermal weed control. However, the presence of negative quadratic coefficients for pressure (–2.079) and exposure duration (–2.259) indicates that beyond a certain level, further increase in these parameters does not proportionally increase weed mortality. Instead, it suggests a diminishing return or saturation effect, where excessive heat input does not significantly enhance plant damage but may lead to energy inefficiency. Similarly, the negative interaction term between pressure and exposure duration (e.g., –5.248 in stage 1 and –18.165 in stage 2) does not imply a reduction in mortality, but rather indicates that the combined effect of both factors is less than additive at higher levels. In other words, applying very high pressure along with long exposure duration does not result in a proportional increase in mortality compared to their individual effects. This highlighted the importance of optimizing parameter combinations rather than simply maximizing each factor independently.

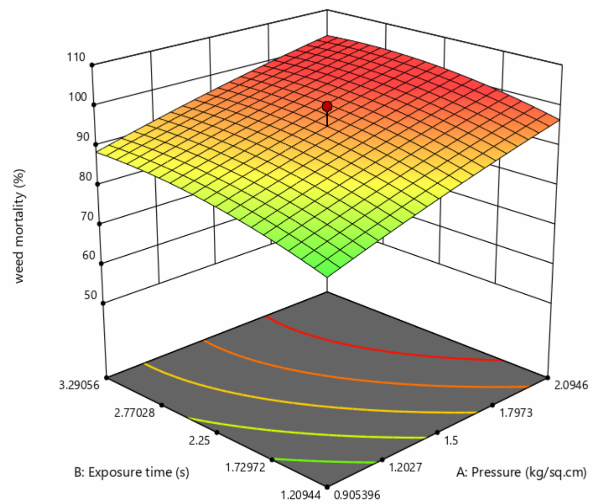

Fig. 1(a): Response surface plot showing the combined effect of operating pressure and exposure duration on weed mortality.

The interaction between operating pressure and burner distance is shown in Fig. 1(b). Maximum weed mortality was observed at higher operating pressure combined with shorter burner distance, confirming that proximity of the flame significantly enhances heat transfer efficiency. The regression coefficients indicate that pressure had a strong positive effect across growth stages (e.g., 55.16 in stage 2 and 30.91 in stage 3), whereas burner distance showed relatively smaller and sometimes negative effects (e.g., –0.576 in stage 1), highlighting that increasing distance reduces effective heat delivery. The interaction between pressure and distance was positive but small (e.g., 1.96 in stage 1), indicating that higher pressure can partially compensate for increased burner distance, but not completely offset heat loss due to air entrainment. Increasing burner distance resulted in reduced mortality due to dispersion and cooling of the flame, which is consistent with findings of Kang (2001) and Rask and Kristoffersen (2007), who reported a rapid decline in thermal efficiency with increasing burner height.

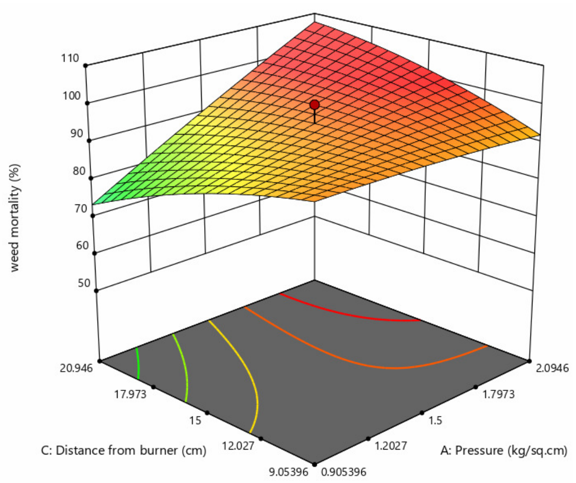

Fig. 1(b) : Response surface plot showing the combined effect of operating pressure and burner distance on weed mortality

The combined effect of exposure duration and burner distance is illustrated in Fig. 1(c). Mortality increased consistently with increasing exposure duration across all burner distances, confirming that cumulative thermal load plays a critical role in plant destruction. The positive coefficients of exposure duration across all growth stages (e.g., 25.38 in stage 1 and 40.93 in stage 2) indicate its dominant influence on mortality. However, the negative interaction term between exposure duration and burner distance (e.g., –0.636 in stage 1) suggests that longer exposure is less effective when the burner is positioned farther away due to reduced heat intensity at the target surface. This highlighted the importance of maintaining an optimal burner distance to ensure efficient heat transfer even when exposure duration is increased. Similar observations were reported by Knezevic *et al.* (2014), who demonstrated that sufficient exposure duration can compensate for moderate flame intensity but only under effective heat transfer conditions.

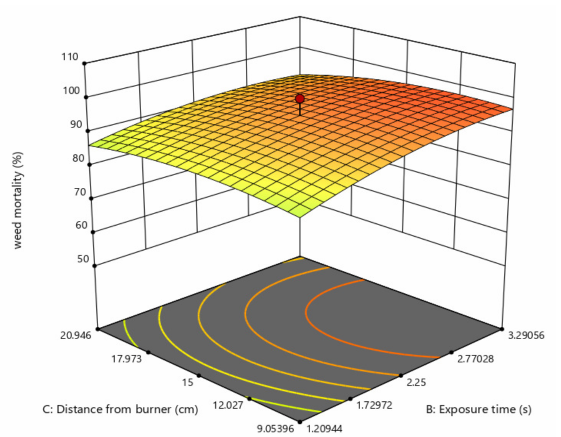

Fig. 1(c) : Response surface plot showing the combined effect of exposure duration and burner distance on weed mortality

Weed growth stage had a significant influence on mortality, as reflected by variations in regression coefficients across stages. Early growth stages (stage 1 and 2) showed higher sensitivity to operating parameters, achieving greater mortality at lower energy input, whereas later stages (stage 3 and 4) required higher thermal doses. The pressure coefficient decreased from 55.16 in stage 2 to a negative value (–9.92) in stage 4, indicating reduced effectiveness of pressure alone on mature weeds. However, the positive interaction between pressure and exposure duration in stage 4 (9.64) suggests that their combined effect is essential for improving control at advanced growth stages. This confirms that weed susceptibility decreases with plant age due to increased biomass and structural resistance (Datta and Knezevic, 2013; Peerzada and Chauhan, 2018). The developed regression models in actual factors can be used to predict weed mortality for different combinations of operating parameters. However, since the coefficients are not standardized, they are suitable for prediction rather than direct comparison of factor effects.

Weed Regrowth as Influenced by Operating Parameters and Growth Stage

The response surface plot in Fig. 2(a) illustrates the combined effect of operating pressure and exposure duration on weed regrowth. Regrowth decreased with increasing pressure and exposure duration, as indicated by negative linear coefficients across most growth stages (e.g., –34.35 for pressure and –8.75 for exposure time in stage 1). This confirms that higher thermal dose effectively damages meristematic tissues and reduces recovery potential. However, the presence of positive quadratic terms for pressure (1.997) and exposure duration (0.025) suggests that beyond a certain level, further increase in these parameters resulted in diminishing reduction in regrowth, indicating an optimum operating range rather than continuous improvement. Negative interaction terms (e.g., –3.69 in stage 1) indicated that combined high levels of pressure and exposure duration are less effective than expected due to overlapping thermal effects. These results support findings of Ascard (1995) and Rask and Kristoffersen (2007), who emphasized that sufficient heat must reach growing points to prevent delayed recovery.

The interaction between operating pressure and burner distance (Fig. 2(b)) showed that regrowth was minimized at higher pressure and shorter burner distance. The negative coefficients of distance (e.g., –4.07 in stage 1) indicated that increasing burner distance reduces heat penetration and increases the likelihood of regrowth. Positive interaction terms between pressure and distance suggest that higher pressure can partially compensate for increased distance, but not fully offset heat losses. Similar trends were reported by Merfield *et al.* (2017), who highlighted the importance of effective heat transfer to regenerative tissues.

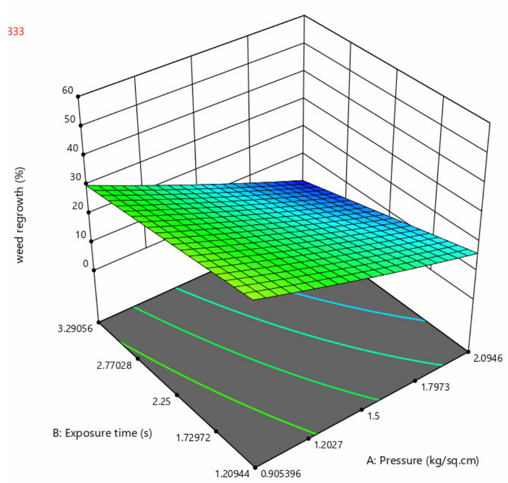

Fig. 2(a) : Response surface plot showing the combined effect of operating pressure and exposure duration on weed regrowth.

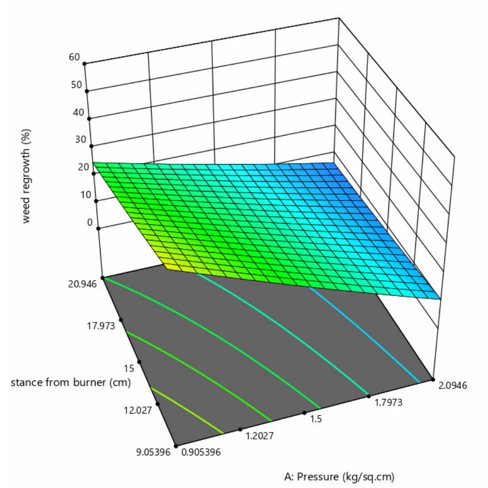

Fig. 2(b) : Response surface plot showing the combined effect of operating pressure and burner distance on weed regrowth

The combined effect of exposure duration and burner distance (Fig. 2(c)) showed that increasing exposure duration reduced regrowth across all burner distances. However, interaction effects indicated that longer exposure is less effective at larger burner distances due to reduced heat intensity at the target surface. Knezevic *et al.* (2012) reported similar behaviour, where insufficient heat exposure resulted in delayed weed recovery.

Weed growth stage significantly influenced regrowth behaviour. Early growth stages showed minimal regrowth due to complete damage of growing tissues, whereas mature weeds exhibited higher recovery potential. This is supported by variation in coefficients, where pressure remained strongly negative across stages, but exposure time showed reduced or even positive influence in later stages (e.g., +4.18 in stage 3), indicating variability in response. This confirmed that older weeds possess greater regenerative capacity due to stored carbohydrates and protected meristems (Datta and Knezevic, 2013). The developed regression equations in actual factors can be used to predict weed regrowth under different operating conditions. However, as the coefficients are expressed in actual units, they are suitable for prediction purposes and not for direct comparison of factor importance.

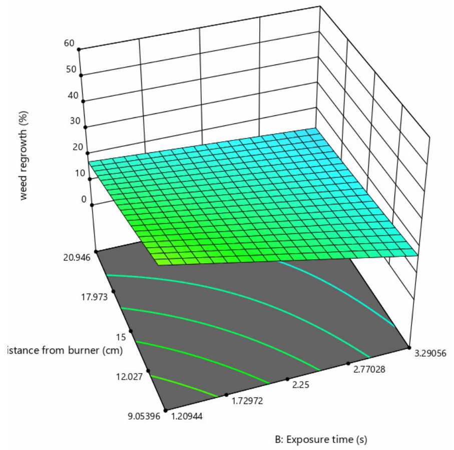

Fig. 2(c) : Response surface plot showing the combined effect of exposure duration and burner distance on weed regrowth

Statistical Analysis and Model Adequacy

The experimental data for weed mortality and weed regrowth were analysed using Response Surface Methodology (RSM) and second-order polynomial equations were developed in terms of actual factors to predict the responses under different operating conditions and weed growth stages. The developed models incorporated linear, interaction, quadratic and three-factor interaction terms, indicating that weed response was governed by both individual and combined effects of operating pressure, exposure duration and burner distance.

For weed mortality, the regression equations showed that operating parameters significantly influenced the response, with variation observed across different growth stages. Positive linear coefficients of pressure and exposure duration in early stages indicated their strong contribution to increasing mortality, whereas negative quadratic terms (e.g., –2.079 for pressure² and –2.259 for exposure time²) confirmed the presence of an optimum region beyond which further increase in these factors resulted in diminishing returns. Interaction terms further indicated that the combined effects of parameters were not purely additive and required optimization to achieve maximum effectiveness.

For weed regrowth, the regression equations indicated that operating pressure had a strong negative effect across all growth stages (e.g., –34.35 in stage 1), confirming its dominant role in reducing regrowth by damaging regenerative tissues. Exposure duration also contributed to regrowth reduction in early stages, although its effect varied in later stages. The positive quadratic coefficients (e.g., 1.997 for pressure²) indicated that excessive increase in parameters did not continuously reduce regrowth and instead led to reduced efficiency, suggesting the presence of an optimum range. Interaction effects demonstrated that parameter combinations influenced the extent of thermal damage to meristematic tissues.

The adequacy of the developed models was evaluated using statistical fit parameters. The coefficient of determination (R^2 = 0.6105) indicated that approximately 61% of the variability in the response was explained by the model. However, the adjusted R^2 (0.3721) suggested moderate model fitting after accounting for the number of predictors. The predicted R^2 value was negative (–0.6358), indicating that the model had limited predictive capability for new observations and that the overall mean could serve as a better predictor under certain conditions. This was attributed to variability in field conditions, natural weed heterogeneity, and possible limitations in model complexity. Despite this, the adequate precision value of 8.55 (greater than the desirable value of 4) indicated an adequate signal-to-noise ratio, confirming that the model could be used to navigate the design space and identify trends.

The relatively high coefficient of variation (C.V. = 73.45%) reflected the inherent variability associated with natural weed populations under field conditions. The developed equations in actual factors were therefore suitable for prediction within the experimental range but were not used for comparing the relative importance of factors, as coefficients were influenced by the units of measurement and the intercept was not centered within the design space.

Overall, the statistical analysis indicated that while the models adequately captured the general trends and interactions among operating parameters, further refinement or inclusion of additional variables could improve predictive accuracy. Similar limitations under field variability have also been reported in thermal weed control studies (Knezevic *et al.,* 2012; Datta and Knezevic, 2013).

Optimization of Flame Weeding Parameters

Optimization of operating parameters was carried out using the desirability function approach by considering only biological response variables. Weed mortality was assigned the objective of maximization, while weed regrowth was minimized. Operating pressure, exposure duration and burner distance were allowed to vary within their experimental ranges at each weed growth stage. The optimum treatment combination corresponded to the maximum composite desirability value, as illustrated in Fig. 3.

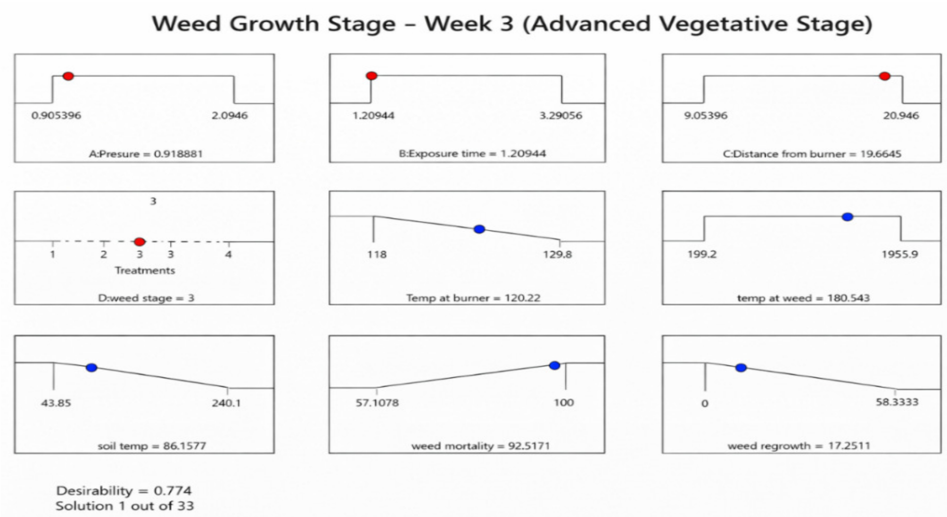

Fig. 3 : Desirability function plot showing optimized operating parameters for maximizing weed mortality and minimizing weed regrowth

The results indicated that optimum operating conditions varied among weed growth stages. Early-stage weeds required relatively low thermal input due to their higher susceptibility, whereas mature weeds required higher operating pressure and longer exposure duration to achieve comparable levels of control. Among all growth stages, the advanced vegetative stage produced the highest composite desirability value, indicating the most effective balance between high weed mortality and minimum regrowth.

The optimized operating parameters and corresponding response values for each weed growth stage were presented in Table 2. At the early seedling stage (Week 1), higher pressure (1.80 kg cm^{-2}) and longer exposure duration (3.29 s) resulted in complete weed mortality (100%) with minimal regrowth (6.81%), although relatively higher soil temperature was observed. During the young vegetative stage (Week 2), lower pressure (0.91 kg cm^{-2}) combined with longer exposure duration resulted in 85.76% mortality with higher regrowth (19.10%). The advanced vegetative stage (Week 3) produced the highest desirability value (0.774) at moderate operating conditions (0.92 kg cm^{-2} pressure, 1.21 s exposure duration and 19.65 cm burner distance), achieving 92.52% weed mortality with limited regrowth (17.25%). In the mature stage (Week 4), relatively higher thermal input (1.16 kg cm^{-2} pressure and 3.29 s exposure duration) was required to obtain 96.57% mortality; however, soil temperature increased substantially.

The optimization results demonstrated that flame weeding should not be applied uniformly across all growth stages. Instead, operating parameters needed to be adjusted according to weed developmental stage to ensure efficient control while avoiding unnecessary thermal input. These findings supported the concept of stage-specific or variable-rate flame weeding. Slaughter *et al.* (2008) and Peteinatos *et al.* (2014) emphasized that site-specific weed management improved efficiency and reduced input use, while Westwood *et al.* (2018) highlighted the importance of adjusting control intensity according to weed size and developmental characteristics.

Temperature responses were not included as optimization criteria in the present study because the focus was on biological effectiveness of flame weeding. However, thermal performance and safe operating limits were evaluated separately by Sindhuja *et al.* (2026). The results showed that operating pressure was the dominant factor influencing flame intensity and temperature, with higher pressure increasing target surface temperature, while burner distance reduced heat transfer due to dissipation. Exposure duration mainly affected cumulative heating and soil temperature. The recorded surface temperatures exceeded the critical threshold (60–70 °C) required for plant tissue damage, ensuring effective thermal injury. Although soil temperatures increased with pressure and exposure duration, heat penetration remained limited due to short exposure time. These findings confirmed that the optimized conditions in the present study were within safe and effective thermal limits for field application.

Table 2: Optimized operating parameters and response values for variable-rate flame weeding at different weed growth stages.

Weed growth stage	Pressure (kg cm^{-2})	Exposure duration (s)	Burner distance (cm)	Burner temperature (°C)	Weed surface temperature (°C)	Soil temperature (°C)	Weed mortality (%)	Weed regrowth (%)	Desirability
Week 1 (Early seedling)	1.80	3.29	20.95	126.37	184.23	119.22	100.00	6.81	0.730
Week 2 (Young vegetative)	0.91	3.29	13.05	120.50	171.66	65.95	85.76	19.10	0.734
Week 3 (Advanced vegetative)	0.92	1.21	19.65	120.22	180.54	86.16	92.52	17.25	0.774
Week 4 (Mature stage)	1.16	3.29	18.16	123.08	175.35	127.29	96.57	11.85	0.737

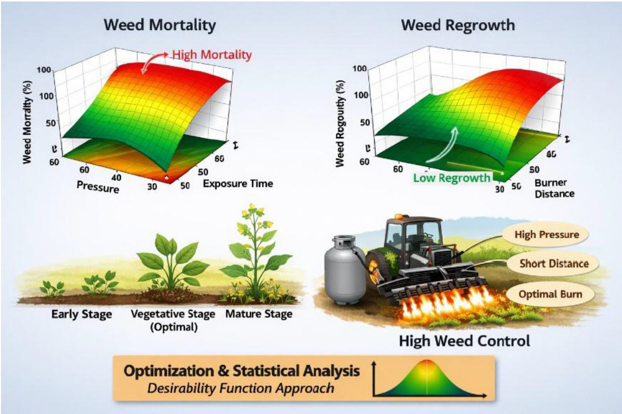

Fig. 4 : Conceptual diagram illustrating stage-specific flame weeding and optimization of operating parameters based on the desirability function approach

The overall relationship between weed growth stage, operating parameters and optimization outcome is summarized schematically in Fig. 4. The conceptual diagram illustrates that early-stage weeds require lower heat input, mature weeds require higher thermal exposure and the advanced vegetative stage provides the most suitable compromise between weed mortality and regrowth suppression.

Conclusion

The present study evaluated the effectiveness of flame weeding at different weed growth stages and identified suitable operating parameters for maximizing weed control while minimizing regrowth. Weed mortality increased with operating pressure and exposure duration, whereas regrowth decreased with higher thermal exposure. Burner distance influenced treatment efficiency by affecting heat transfer to plant tissues. Weed growth stage was the most influential factor, with early-stage weeds showing high susceptibility and mature weeds exhibiting greater tolerance due to developed tissues and stored reserves. Statistical analysis confirmed significant interactions between operating parameters and growth stage, indicating that uniform operating conditions are not suitable for all stages.

Optimization results showed that the advanced vegetative stage provided the best balance between high mortality and low regrowth. The findings demonstrated that flame weeding should be applied based on weed developmental stage, with appropriate adjustment of pressure, exposure duration and burner distance to improve efficiency and reduce unnecessary energy use. The optimized conditions were biologically effective and thermally safe as supported by Sindhuja *et al*. (2026).

From a practical perspective, lower thermal input is sufficient for early-stage weeds, whereas higher pressure and exposure duration are required for later stages. Maintaining an optimum burner distance is essential for effective heat transfer. However, the study was influenced by field variability under natural weed infestation, and species-specific responses and environmental factors were not explicitly considered.

Future studies should focus on integrating sensor-based variable-rate systems, evaluating performance under diverse field conditions, and improving energy efficiency for large-scale applications.

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