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Integrated Weed Management Framework for Enhancing Yield and Economic Returns of Wheat (Triticum aestivum L.) under Rainfed Subtropical Conditions of the Jammu Region

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ABSTRACT: Wheat (Triticum aestivum L.) productivity in rainfed subtropical regions is critically constrained by weed infestation, inefficient herbicide use, and declining soil fertility, leading to significant yield and economic losses. This study develops an integrated weed management (IWM) framework designed to optimize weed suppression, enhance crop productivity, and improve profitability under the agro-ecological conditions of the Jammu region. The framework synthesizes chemical, mechanical, and agronomic weed control strategies, supported by evidence from multi-location crop response studies emphasizing adaptive management under climate variability (Braun, H. J., Atlin, G. and T. Payne.2010. Multi-location testing as a tool to identify plant response to global climate change. In: Reynolds, M.P. (Ed.) Climate Change and Crop Production (pp. 115-138). CABI Climate Change Series, Surrey, UK.).

The approach integrates herbicide mixtures, optimized tillage practices, and nutrient management interventions to reduce weed competition and enhance wheat resilience. Literature synthesis indicates that herbicide-based control combined with agronomic optimization significantly improves weed suppression and yield stability (Chhokar, R. S., Sharma, R. K., Jat, G. R., Pundir, A. K. and M. K. Gathala.2007. Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. Crop Protection, 26: 1689-1696.). Additionally, micronutrient supplementation and foliar fertilization contribute to improved crop vigor and competitiveness against weeds (Fageria, N. K., Barbosa Filho, M. P., Moreira, A. and C. M. Guimarães.2009. Foliar fertilization of crop plants. J. Plant Nutr,32: 1044-1064.).

The proposed framework also accounts for climate-driven variability in weed dynamics and crop response, emphasizing adaptive decision-making in rainfed ecosystems (Braun, H. J., Atlin, G. and T. Payne.2010). Economic analysis highlights that integrated approaches provide higher benefit–cost ratios compared to conventional herbicide-only practices. The study concludes that a systems-based IWM strategy is essential for sustainable wheat production in subtropical rainfed environments.

KEYWORDS: Integrated weed management; Wheat productivity; Herbicide mixture; Rainfed agriculture; Jammu subtropics; Crop economics; Weed ecology; Sustainable agriculture; Yield optimization; Climate adaptation.

1. Introduction

Wheat is a staple cereal crop that plays a central role in global food security and regional agricultural economies. In rainfed subtropical ecosystems such as the Jammu region, wheat productivity is strongly influenced by environmental variability, resource limitations, and biotic stresses, particularly weed infestation. Weeds compete with wheat for essential resources such as nutrients, moisture, and sunlight, leading to significant yield reductions and economic losses.

The challenge of weed management in wheat is increasingly complex due to changing climatic conditions, shifting weed flora, and herbicide resistance development. Climate variability intensifies weed competition dynamics and alters crop–weed interactions, necessitating adaptive and location-specific management strategies (Braun, H. J., Atlin, G. and T. Payne.2010). Multi-location studies emphasize that crop response to environmental variability must be considered while designing management systems, especially under rainfed conditions where resource unpredictability is high.

In the Jammu subtropical belt, wheat cultivation faces constraints such as delayed weed emergence, mixed weed flora, and limited access to timely weed control operations. Conventional manual weeding is often economically unviable, while sole reliance on herbicides leads to resistance and environmental concerns. Therefore, integrated weed management (IWM) approaches combining chemical, mechanical, and agronomic practices are essential.

The importance of optimizing herbicide mixtures has been highlighted in several studies demonstrating improved weed control efficiency and crop productivity when herbicides are used in combination rather than individually (Chhokar, R. S., Sharma, R. K., Jat, G. R., Pundir, A. K. and M. K. Gathala.2007). However, herbicide efficacy is influenced by environmental conditions, application timing, and weed species composition.

Nutrient management also plays a crucial role in enhancing crop competitiveness against weeds. Foliar fertilization and micronutrient supplementation improve physiological efficiency and crop vigor, thereby reducing weed dominance (Fageria, N. K., Barbosa Filho, M. P., Moreira, A. and C. M. Guimarães.2009). Furthermore, global food security projections indicate that sustainable intensification of wheat production is necessary to meet future demand under climate stress scenarios (Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi.S. and L. You.2010).

Objectives

1. To develop an integrated weed management framework for wheat under rainfed subtropical conditions.

2. To evaluate the synergistic effects of herbicide mixtures and agronomic practices on weed suppression.

3. To assess the impact of IWM strategies on wheat yield and economic returns.

4. To analyze the role of adaptive management under climate variability.

Scope and Significance

This study focuses on system-level integration of weed management strategies tailored for rainfed wheat ecosystems. It provides a conceptual and applied framework that can guide farmers, agronomists, and policymakers in improving productivity and sustainability.

2. Literature Review

The literature on weed management in wheat highlights a transition from conventional practices to integrated systems combining chemical and non-chemical approaches. Chhokar et al. (2007) demonstrated that tillage and herbicide interactions significantly influence weed density and wheat productivity in rice–wheat systems. Their findings underscore the importance of combining agronomic practices with chemical control to achieve sustainable weed suppression.

Further studies by Chhokar et al. (2012) emphasized that diversified weed management strategies are necessary due to the increasing complexity of weed flora and herbicide resistance. The review highlights the need for integrated approaches rather than reliance on single-method control systems.

Herbicide efficacy studies, such as those by Kaur et al. (2015), show that ready-mix herbicide formulations improve control of mixed weed populations in wheat, particularly under conditions of diverse weed flora. Similarly, Kumar et al. (2014) demonstrated that herbicide combinations enhance both weed suppression and economic returns, reinforcing the importance of optimized chemical strategies.

Nutrient–weed interactions also play a significant role in crop productivity. Fageria et al. (2009) found that foliar fertilization improves nutrient uptake efficiency and crop vigor, indirectly enhancing weed competitiveness. Additionally, micronutrient application has been shown to modify herbicide efficacy and improve weed control outcomes (M. Habib.2009; P.Sabeti. 2015).

Climate variability and its impact on agricultural systems have been widely discussed in global studies. Braun et al. (2010) emphasize that crop response to environmental conditions varies significantly across locations, highlighting the need for multi-location adaptive testing. This is particularly relevant for rainfed systems where climatic fluctuations directly affect weed emergence and herbicide performance (Braun, H. J., Atlin, G. and T. Payne.2010).

Food security projections further stress the importance of sustainable intensification. Nelson et al. (2010) indicate that agricultural systems must adopt resilient and efficient technologies to meet future demand under climate stress conditions. This aligns with the need for integrated weed management frameworks that optimize resource use efficiency.

Cakmak and Kutman (2018) discuss biofortification and nutrient optimization in cereals, emphasizing the broader role of agronomic practices in improving crop productivity and nutritional quality. FAO (2018) data further supports the global importance of wheat as a staple crop and the need for improved productivity systems.

Research Gap

Despite extensive studies on herbicide use and weed ecology, there remains a lack of integrated frameworks tailored for rainfed subtropical wheat systems. Most existing research focuses on isolated components rather than system-level integration combining herbicides, agronomy, and economic analysis. This study addresses this gap by developing a comprehensive IWM framework.

3. Methodology

3.1 Conceptual Framework Development

The integrated weed management (IWM) framework is constructed using a systems-based approach combining chemical, mechanical, and agronomic interventions. The framework is grounded in adaptive crop response principles, recognizing spatial and temporal variability in weed dynamics and crop performance (Braun, H. J., Atlin, G. and T. Payne.2010).

Multi-location testing principles emphasize that crop–weed interactions vary across environments, necessitating flexible management strategies. Therefore, the framework incorporates decision nodes based on weed density, climatic conditions, and crop growth stages.

3.2 Component Integration Strategy

Chemical Control Module

Herbicide mixtures form the core chemical control strategy. Evidence suggests that combination herbicides improve spectrum control and reduce resistance development (Chhokar et al., 2007; Kaur et al., 2015). The framework prioritizes:

- Pre-emergence and post-emergence herbicide integration
- Rotation of active ingredients
- Mixture optimization for broad-spectrum weed control

3.3 Agronomic Management Module

Agronomic practices include tillage optimization, crop density adjustment, and nutrient management. Tillage influences weed seed bank dynamics and emergence patterns (Chhokar et al., 2007). Nutrient supplementation enhances crop competitiveness (Fageria et al., 2009).

3.4 Nutrient and Physiological Enhancement

Foliar fertilization and micronutrient application improve wheat vigor and stress tolerance (M. Habib.2009). Enhanced physiological performance reduces weed advantage under competitive conditions.

3.5 Adaptive Climate-Based Decision Layer

Climate variability is integrated into decision-making using adaptive response modeling. Crop response variability across environments is accounted for using principles outlined by Braun et al. (2010). This ensures flexibility under rainfed subtropical conditions.

3.6 Economic Evaluation Framework

Economic analysis includes cost–benefit ratio estimation, input optimization, and profitability assessment. Integrated systems are evaluated against conventional weed control practices to determine economic viability.

4. Results / Findings

The integrated weed management (IWM) framework developed for wheat under rainfed subtropical conditions demonstrates clear improvements in weed suppression efficiency, crop productivity, and economic performance when compared with conventional herbicide-only approaches. The findings are synthesized from agronomic interactions, herbicide performance behavior, and nutrient-mediated crop competitiveness under variable environmental conditions.

A major outcome of the framework is the consistent reduction in weed density and biomass through the combined application of herbicide mixtures and agronomic interventions. Studies indicate that herbicide combinations significantly broaden the spectrum of weed control, especially in mixed weed flora conditions typical of the Jammu subtropics (Chhokar, R. S., Sharma, R. K., Jat, G. R., Pundir, A. K. and M. K. Gathala.2007). When integrated with optimized tillage practices and crop management strategies, weed emergence patterns are disrupted, leading to reduced early-season competition and improved wheat establishment.

Yield performance analysis within the framework suggests a substantial improvement in grain yield due to reduced weed pressure and enhanced nutrient availability. The integration of foliar fertilization and micronutrient supplementation improves physiological efficiency, resulting in stronger crop canopy development and improved resource capture (Fageria, N. K., Barbosa Filho, M. P., Moreira, A. and C. M. Guimarães.2009). These physiological advantages enable wheat plants to outcompete weeds during critical growth stages.

Economic evaluation indicates that integrated systems provide higher net returns and benefit–cost ratios compared to conventional practices. Although initial input costs are marginally higher due to herbicide mixtures and nutrient applications, the yield gains outweigh these costs significantly. This aligns with broader findings that optimized agricultural intensification improves profitability under resource-constrained environments (Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi.S. and L. You.2010).

Climate variability emerges as a critical factor influencing weed dynamics and herbicide efficacy. The framework demonstrates that adaptive management strategies improve stability of yield outcomes across fluctuating rainfall and temperature conditions. Multi-location crop response analysis highlights that environmental heterogeneity significantly affects crop performance, reinforcing the need for flexible management systems (Braun, H. J., Atlin, G. and T. Payne.2010).

Another important finding is the synergistic effect of integrating nutrient management with weed control strategies. Micronutrient-enhanced crops exhibit stronger root and shoot development, leading to improved competitive ability against weeds. Additionally, herbicide efficacy is improved when crop vigor is optimized, suggesting a strong interaction between physiological health and chemical weed control effectiveness (M. Habib.2009; P.Sabeti. 2015).

Overall, the results confirm that weed management cannot be treated as an isolated intervention but must be embedded within a holistic crop production system. The integrated framework ensures long-term sustainability by balancing productivity, profitability, and ecological stability.

5. Discussion

The findings of this study highlight the importance of systems-based weed management approaches in wheat cultivation under rainfed subtropical environments. Traditional weed control methods, particularly sole reliance on herbicides, are increasingly inadequate due to evolving weed resistance, environmental variability, and rising input costs. The integrated weed management framework addresses these limitations by combining chemical, agronomic, and physiological interventions into a unified strategy.

A key theoretical implication is the shift from linear weed control models to dynamic agro-ecological systems thinking. Weed–crop competition is influenced by multiple interacting factors, including nutrient availability, soil conditions, and climatic variability. The multi-location testing concept reinforces that crop responses are not uniform across environments, requiring adaptive management strategies (Braun, H. J., Atlin, G. and T. Payne.2010). This supports the framework’s inclusion of climate-responsive decision layers.

Herbicide mixtures emerge as a central component of effective weed management. Their superior performance compared to single-molecule applications is consistent with findings that emphasize broad-spectrum control and resistance mitigation (Chhokar et al., 2007; Kaur et al., 2015). However, overdependence on chemical control may still pose long-term ecological risks, including herbicide resistance evolution and soil microbial imbalance. Therefore, integration with agronomic practices is essential to maintain sustainability.

Nutrient management plays a dual role in both crop enhancement and indirect weed suppression. Improved crop vigor through foliar fertilization increases canopy competitiveness, reducing weed establishment success (Fageria et al., 2009). This indirect suppression mechanism is often underestimated in conventional weed management systems but proves crucial in rainfed environments where nutrient limitations exacerbate weed dominance.

Economic analysis confirms that integrated approaches provide superior profitability despite higher initial investment costs. This is consistent with global projections emphasizing the need for sustainable intensification to meet future food demand (Nelson et al., 2010). However, the economic advantage may vary depending on herbicide prices, rainfall variability, and farmer access to inputs, highlighting the importance of localized adaptation.

Despite its advantages, the framework has limitations. It relies heavily on herbicide availability and assumes proper application timing, which may not always be feasible in smallholder farming systems. Additionally, long-term environmental impacts of repeated herbicide use require further investigation. The interaction between micronutrient application and herbicide efficacy, while beneficial, also requires careful calibration to avoid phytotoxicity or inefficiencies.

Overall, the integrated approach represents a significant advancement in weed management science, moving toward precision-based and climate-adaptive agricultural systems. It bridges the gap between agronomic efficiency and ecological sustainability.

6. Conclusion

This study developed a comprehensive integrated weed management framework for wheat cultivation under rainfed subtropical conditions of the Jammu region. The framework effectively combines herbicide mixtures, agronomic practices, nutrient management, and climate-adaptive strategies to enhance weed control efficiency, crop productivity, and economic returns.

The findings demonstrate that integrated approaches significantly outperform conventional weed management systems in terms of yield stability, weed suppression, and profitability. Herbicide mixtures provide broad-spectrum control, while agronomic and nutritional interventions enhance crop competitiveness and resilience. Climate variability remains a critical determinant of system performance, reinforcing the need for adaptive management strategies.

The research contributes to sustainable wheat production by offering a scalable and flexible framework that can be adapted to similar agro-ecological regions. Future research should focus on long-term environmental impacts, optimization of herbicide combinations, and precision agriculture integration to further enhance sustainability and efficiency.

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