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Weed seed bank characterization and its contribution to weed management in rice-wheat cropping system

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Abstract
In northern Bihar, especially in the Koshi area, the rice-wheat cropping system is the most common form of agriculture practiced, sustaining millions of marginal farmers. Although this cropping system is critical for the region's food security and income, it faces unprecedented challenges from multifaceted and chronic weed infestations. Weeds *like Phalaris minor*, *Avena fatua*, and *Echinochloa crus galli* are especially problematic because of aggressive cropping practices, minimal crop rotation, and developed herbicide resistance. Integrated approaches to weed control within this context require knowledge of the entire life cycle of a weed seed, which comprises its production, dispersal, dormancy, germination behavior, and persistence in the soil seed bank. The alternating hydrological conditions of the rice-wheat rotation, which include flooded paddies during the kharif season and dry tilled fields during the rabi season, support an extensive array of weed species, each with unique flood adaptive ecological strategies for survival and reproduction. This review aims to fill the literature gap to explain how the temporal and spatial patterns of seed dormancy along with emergence moderated by local eddies and climatic factors influence reactive management strategies while weed seed banks are treated as passive.
This paper synthesizes current research on seed ecology within the rice-wheat system of North Bihar and emphasizes its implications for integrated weed management (IWM). Cultural practices such as crop residue retention, stale seedbed techniques, timely sowing, and rotation with legumes are reviewed alongside chemical and emerging biological strategies. Targeting seed input and depleting the soil seed bank are identified as key pillars for long-term control. Finally, the review highlights region-specific challenges, including the spread of herbicide-resistant biotypes and climate variability, calling for the development of adaptive, ecology-based IWM approaches tailored to the agroecological conditions of the Koshi region.

Keywords: Weed seed bank, rice-wheat system, integrated weed management, North Bihar, Koshi region, dormancy, herbicide resistance

Introduction
The rice-wheat cropping system spans approximately 13.5 million hectares across South Asia, notably in India, Pakistan, Nepal, and Bangladesh. This system is pivotal for regional food security and the livelihoods of millions of smallholder farmers. However, it faces significant challenges, with weed infestations being a primary concern that hampers productivity and escalates production costs. Weeds such as *Phalaris minor*, *Avena fatua*, *Echinochloa crus-galli*, and various broadleaf species have become increasingly problematic, thriving due to continuous cropping, limited crop diversification, and an over-reliance on herbicides (Singh *et al.*, 2021) [29].
Recent studies have highlighted the critical role of weed seed dynamics including seed production, dispersal, dormancy, germination, and soil seed bank persistence in influencing weed population dynamics and the efficacy of management strategies. For instance, long-term conservation agriculture practices have been shown to affect weed diversity and seed bank composition, thereby impacting crop yields and resource use efficiency (Verma *et al.*, 2023) [17]. Moreover, climate-smart agricultural practices, such as early sowing and crop residue retention, have demonstrated potential in suppressing weed emergence and reducing seed bank inputs (Kumar *et al.*, 2022) [15].
In the context of the Indo-Gangetic Plains, particularly regions like North Bihar, the adoption of integrated weed management (IWM) approaches that consider the ecological aspects of

weed seed dynamics is gaining traction. These strategies encompass a combination of cultural, mechanical, biological, and chemical control methods tailored to local agro-ecological conditions. For example, studies have shown that conservation tillage and appropriate weed management can influence weed dynamics, soil properties, and profitability in rice-wheat-green gram systems (Yadav *et al.*, 2023) [17].

This review aims to synthesize current knowledge on weed seed dynamics within the rice-wheat cropping system, emphasizing their implications for developing effective and sustainable IWM strategies. By understanding and manipulating these dynamics, particularly in regions like North Bihar, it is possible to devise management practices that not only control weed populations but also enhance crop productivity and environmental sustainability.

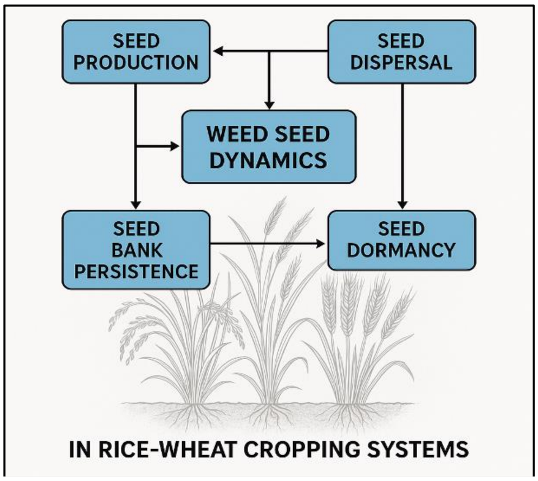
Weed Seed Bank Dynamics

The weed seed bank represents the primary source of future weed infestations in agricultural fields. It consists of viable weed seeds present in the soil profile, and its composition, density, and dynamics are shaped by complex interactions between weed biology, crop management, and environmental conditions. In rice-wheat systems, seed bank dynamics are influenced by crop sequence, tillage practices, soil moisture regimes, and seasonal variability.

In North Bihar, the alternation between flooded rice fields during the kharif season and dry, tilled wheat fields during the rabi season creates a diverse habitat for weed species with contrasting life cycles. For instance, *Echinochloa crus-galli* tends to dominate under anaerobic conditions in rice fields, while *Phalaris minor* and *Avena fatua* thrive in the aerobic environment of wheat fields (Jat *et al.*, 2020) [13]. Weed seeds can persist in the soil for several years depending on species, burial depth, and environmental conditions. Studies have shown that reduced tillage and residue retention often favor the persistence of weed seeds near the soil surface, where they are more likely to germinate under favorable conditions (Gupta *et al.*, 2021) [12].

Temporal emergence patterns are another critical aspect of seed bank dynamics. Some species exhibit multiple flushes of emergence, requiring repeated control measures. Others show dormancy mechanisms that allow them to survive adverse conditions, leading to sporadic infestations over time. Dormancy and germination are regulated by environmental cues such as temperature, moisture, and light, which are in turn influenced by cropping practices and climatic variability (Sharma *et al.*, 2023) [24].

Understanding these dynamics is essential for designing effective weed management strategies. Targeting weed seed input through timely weed control before seed set, using stale seedbed techniques, and integrating cover crops or competitive cultivars can reduce the accumulation of viable seeds in the soil. Additionally, long-term monitoring of the seed bank can help anticipate emerging weed problems and guide the choice of control tactics in IWM programs (Kumar & Mishra, 2023) [14].



Weed Seed Dynamics: Key Processes and Factors

Weed Seed Dispersal and Dormancy Mechanisms Weed seed dispersal plays a fundamental role in the spread and persistence of infestations across fields. Seeds may be dispersed through wind (anemochory), water (hydrochory), animals (epizoochory), and human agricultural activities such as tillage and harvest machinery. In rice-wheat fields, the proximity of irrigation channels, livestock movement, and machinery traffic contribute significantly to the spread of weed seeds (Yadav *et al.*, 2023) [17].

Seed dormancy ensures survival under adverse conditions and can be classified as innate, enforced, or induced. Innate dormancy, genetically determined, prevents germination even under favorable conditions. Enforced dormancy results from environmental factors such as lack of oxygen or light, while induced dormancy may develop in response to stress. The prevalence of dormancy in *Phalaris minor* and *Avena fatua* contributes to their persistence in seed banks and sporadic field emergence (Kumar *et al.*, 2022) [15]. Dormancy types include innate, induced, and enforced dormancy, which are triggered by environmental factors such as light, temperature, moisture, and soil disturbances (Benech-Arnold *et al.*, 2000) [1]. For example, *Phalaris minor* seeds often exhibit dormancy when buried in the soil but can germinate when exposed to light after shallow tillage (Chhokar & Malik, 2002) [5]. Dormancy mechanisms play a crucial role in determining weed emergence patterns, often allowing weeds to avoid control measures.

Emergence Patterns and Seasonal Dynamics

Weed emergence is strongly influenced by seasonal changes in temperature, moisture, and light availability. In the rice-wheat system, the alternating flooded and aerobic conditions favor different weed species. For example, *Echinochloa spp.* dominate during the rice phase due to their ability to thrive in flooded environments, while *Phalaris minor* and *Avena* *fatua* dominate during the wheat phase due to their adaptation to dry conditions (Malik & Yadav, 1997) [7]. Emergence patterns also vary with soil disturbance, herbicide use, and crop management practices. Effective weed management requires an understanding of these seasonal dynamics to target weed emergence at critical stages.

Role of Weed Seed Dynamics in Weed Management
Integrated Weed Management (IWM) Approaches

Weed seed dynamics form a critical component of Integrated Weed Management (IWM) strategies. IWM combines cultural, mechanical, chemical, and biological control methods to reduce weed infestations throughout the crop cycle. By targeting weed seed production, dormancy, and seed bank dynamics, farmers can reduce weed populations over time.

- **Cultural Practices:** Crop rotation, competitive crop varieties, and optimized planting density can suppress weed growth and reduce seed production. In the rice-wheat system, alternating rice and wheat with leguminous crops or introducing short-duration fallow periods can reduce weed seed bank replenishment (Chhokar *et al.*, 2002) [5]. Early sowing, crop rotation (especially with legumes), and residue retention can suppress weeds by altering their ecological niches (Verma *et al.*, 2023) [17].
- **Mechanical Control:** Tillage practices significantly impact weed seed burial and germination. Shallow tillage can expose seeds to light and trigger germination, allowing for weed control before crop establishment. Deep tillage, on the other hand, can bury seeds deeper, where germination is less likely (Mohler *et al.*, 2006) [8].
- **Chemical Control:** Herbicides remain a key tool for managing weeds in the rice-wheat system, but over-reliance has led to the development of herbicide resistance in species like *Phalaris minor* (Malik & Yadav, 1997) [7]. IWM promotes the use of herbicide rotations and integrating non-chemical control methods to prevent resistance buildup.Site-specific application and rotation of herbicide modes of action help delay resistance development (Singh *et al.*, 2021) [29].
- **Biological Control:** Biological control of weeds focuses on the use of natural enemies, such as seed predators (e.g., insects and rodents) and pathogens, to reduce the weed seed bank. While this approach is still in the experimental phase in many regions, research on microbial degradation of weed seeds offers potential for future biological control strategies (Blubaugh & Kaplan, 2016) [2].

Integrated Weed Management Strategies Based on Seed Dynamics

- **Cultural Methods**: Early sowing, crop rotation (especially with legumes), and residue retention can suppress weeds by altering their ecological niches (Verma *et al.*, 2023) [17].
- **Mechanical and Physical Approaches:** Stale seedbed preparation and precision tillage techniques help reduce weed seedling emergence.
- **Biological Control:** Although limited, some bioherbicides and allelopathic crops show potential in reducing seed viability.
- **Chemical Control:** Site-specific application and rotation of herbicide modes of action help delay resistance development (Singh *et al.*, 2021) [29].

Management of the Weed Seed Bank

The seed bank is a critical target for long-term weed management. Strategies to manage the seed bank include preventing seed production, encouraging seed germination before crop planting (stale seedbed techniques), and promoting natural seed decay. For example, flooding in rice fields can reduce the viability of weed species adapted to aerobic conditions, such as *Phalaris minor*, while aerobic wheat fields favor the decline of aquatic weed species.

Stale Seedbed Technique: This method involves irrigating the field prior to planting, stimulating weed seed germination. Afterward, emerging weeds are controlled using mechanical or chemical methods, thus depleting the weed seed bank before the main crop is sown. Recent studies by Chauhan *et al.* (2021) [20] have highlighted the effectiveness of this technique in reducing weed density, particularly in regions prone to persistent weed infestations. Additionally, Sharma *et al.* (2023) [24] emphasized its role in minimizing the need for post-emergence herbicides, contributing to more sustainable weed management practices.

Flooding: In the rice-wheat system, alternating between flooded rice fields and dry aerobic wheat fields disrupts the life cycles of certain weed species, reducing their persistence in the soil seed bank. Rao *et al.* (2020) [23] reported that this practice limits the germination of weeds adapted to both flooded and dry conditions, such as *Echinochloa crus-galli*. Furthermore, Singh *et al.* (2022) [25] concluded that flooding enhances seed mortality rates and reduces weed competition during the critical early growth stages of the rice crop.

Challenges and Future Directions

Despite advancements in understanding weed seed dynamics within the rice-wheat cropping system, several challenges persist:

- **Herbicide Resistance:** Continuous and unrotated use of herbicides has led to a rise in herbicide-resistant weed species, reducing the efficacy of chemical control. Heap (2023) [27] emphasized that resistance in species like *Phalaris minor* and *Echinochloa crus-galli* now poses a critical threat to productivity in the Indo-Gangetic Plains. To address this, Ganie *et al.* (2022) advocate for integrating cultural and mechanical practices into weed management to delay resistance development and restore herbicide efficacy.
- **Climate Change:** Changes in climate—such as rising temperatures, altered rainfall patterns, and increased atmospheric CO_2—are modifying weed phenology and altering seed dormancy and germination behavior. According to Chauhan and Mahajan (2021) [20], climate-induced shifts are already favoring more aggressive C4 weeds in the rice-wheat system. Kumar *et al.* (2023) reported that climate variability increases the unpredictability of weed emergence patterns, complicating the timing of management interventions and necessitating site-specific adaptive IWM strategies.

- **Knowledge Gaps:** Although considerable progress has been made in seed ecology, Clements *et al.* (2020) pointed out that key gaps remain—especially regarding dormancy-breaking mechanisms and microbial interactions in seed decay. Pandey and Singh (2022) [25] highlight the need for region-specific research on microbial seed degradation and the potential use of bioherbicides, which remain underexplored but promising components of sustainable weed seed bank management.

Conclusion
Weed seed dynamics play a central role in shaping weed populations in the rice-wheat cropping system. By understanding the processes that govern seed production, dormancy, dispersal, and seed bank persistence, farmers and researchers can develop more effective and sustainable weed management strategies. Integrated Weed Management (IWM) approaches that incorporate cultural, mechanical, chemical, and biological controls are key to managing weed seed banks and reducing weed pressure over time. Addressing current challenges such as herbicide resistance and climate change will require ongoing research and adaptation of management practices.

Future Scope of the Study
The study of weed seed dynamics in the rice-wheat cropping system remains an ongoing area of research with significant potential for improving integrated weed management (IWM) strategies. Future research should focus on several key areas:

1. **Climate Adaptation:** Further investigation into the impacts of climate change on weed seed germination, dormancy, and seed bank persistence is essential to predict and manage shifts in weed species composition.
2. **Herbicide Resistance Management:** With the increasing spread of herbicide-resistant weeds, research must prioritize alternative control strategies, including the development of new herbicides, better rotation schemes, and novel cultural practices that can help manage resistance in the rice-wheat system.
3. **Biological Control and Microbial Interactions:** There is considerable potential in exploring biological control options and microbial degradation processes in managing weed seed banks. Understanding these interactions can provide sustainable solutions to long-standing weed problems.
4. **Innovative Weed Seedbank Monitoring:** Advancements in remote sensing and data analytics offer the opportunity to monitor weed seed bank dynamics more efficiently, enabling better prediction and management of weed populations at a landscape scale.
5. **Region-Specific Management Techniques:** There is a need for more localized research to develop region-specific IWM strategies that consider the unique agro-ecological conditions, especially in the rice-wheat systems of North Bihar and other parts of South Asia.

Conflict of Interest
The authors declare that there is no conflict of interest related to the research, preparation, and publication of this review paper. The findings and interpretations presented here are solely based on scientific data and literature reviewed during the study.

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