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Mini Review

Dormancy Dynamics in Weed Seeds: Physiology, Ecology, and Control Perspectives

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Abstract

Weed seed dormancy is a key adaptive trait that contributes to the persistence, spread, and management challenges of weeds in agroecosystems. This mini-review synthesizes current knowledge on the types and mechanisms of weed seed dormancy, including physical, physiological, and combinational forms, highlighting the hormonal regulation, structural barriers, and environmental cues involved in dormancy induction and release. The ecological implications of dormancy such as prolonged seedbank longevity, staggered emergence, and resistance to control measures are discussed in the context of crop weed interactions and management timing. Various dormancy-breaking and management strategies, including mechanical scarification, thermal and cold stratification, chemical priming (e.g., gibberellic acid, nitrate), biological degradation, and Integrated Weed Management (IWM), are evaluated for their efficacy and practical application. The review underscores the need for species-specific, climate-resilient approaches that integrate dormancy biology with predictive modeling and precision agriculture tools. By bridging fundamental dormancy mechanisms with field-scale control strategies, this review provides a foundation for more sustainable and targeted weed seedbank depletion practices.

Introduction

Weed seed dormancy is a critical adaptive trait in agricultural systems, enabling seeds to remain quiescent in the soil seedbank for extended periods and thus evade unfavorable conditions and control measures. This persistence contributes directly to the longevity of the seedbank, with many species forming a persistent seedbank that can endure multiple growing seasons before depletion [1]. By spreading germination over time, dormancy also creates a temporal escape from crop competition and mechanical or chemical control tactics, complicating the prediction of emergence patterns and undermining the efficacy of herbicide applications [2]. Moreover, intense selection pressure from repeated herbicide use can co select for higher dormancy levels in weed populations, leading to concurrent evolution of dormancy and herbicide resistance traits that further hamper management efforts [3]. Understanding these dynamics is therefore essential for designing integrated weed management strategies that target both dormant and germinable seed fractions to reduce long term seedbank replenishment and improve control outcomes. Repeated cycles of forced germination and seedbank depletion through agronomic practices have proven effective in reducing the reservoir of dormant weed seeds, thereby easing the long-term burden of weed pressure. For instance, stale seedbed techniques where the soil is repeatedly disturbed prior to planting promote synchronized germination of dormant seeds, allowing subsequent control before crop sowing [4,5]. Similarly, the strategic use of plant growth regulators, such as gibberellic acid (GA_3) to stimulate germination or abscisic acid (ABA) to enforce dormancy, when tank mixed with pre emergence herbicides or applied with cover crop residues, can homogenize weed emergence and enhance herbicide efficacy while mitigating selection for resistance [6]. Integrating these approaches mechanical disturbance, hormonal priming, and chemical control within an IWM framework targets both germinable and dormant seed fractions, significantly reducing seedbank persistence and improving sustainable weed management outcomes over multiple seasons.

Building on the critical role of weed seed dormancy in sustaining long lived seedbanks and evading control measures [1,7], this mini review first delineates the diverse mechanisms physical, physiological, and morphological that underlie dormancy expression and release in major weed species. It then examines how these traits translate into ecological outcomes, shaping emergence timing, seasonal survival, and resistance evolution in agroecosystems. Finally, by surveying both traditional (e.g., stale seedbed, tillage timing) and innovative (e.g., hormonal priming, biocontrol) approaches to manipulate dormancy, we aim to highlight integrated strategies capable of targeting the full spectrum of seedbank fractions. Through this tripartite structure mechanisms, ecology, and management our review will identify key knowledge gaps and propose research directions for more predictive, sustainable weed seedbank depletion.

Types and Mechanisms of Weed Seed Dormancy

Weed seed dormancy is generally classified into three primary types physical, physiological, and morphological each involving distinct mechanisms that regulate germination timing to maximize survival. Physical dormancy is caused by a water-impermeable seed coat, which acts as a barrier to imbibition. This form is typical in species like *Chenopodium album* and *Polygonum aviculare*, where germination requires mechanical or chemical scarification to break the seed coat [8]. Physiological dormancy, the most common type, is regulated by internal hormonal dynamics, particularly the balance between abscisic acid (ABA) and gibberellins (GA). Dormancy is maintained by high ABA levels until environmental conditions such as temperature and light trigger changes that reduce ABA activity and promote GA signaling, leading to embryo growth and germination [9]. In morphological dormancy, seeds possess under developed embryos at dispersal that require a period of growth or specific environmental conditions to complete embryogenesis; this is observed in a few genera such as *Rumex spp* and *Atriplex spp* [10]. Many weed species exhibit combinational dormancy, where multiple mechanisms act together for example, a hard seed coat plus physiological constraints further extending persistence in the soil [11] (Table 1).

Environmental factors play a pivotal role in modulating these dormancy types. Temperature regimes during dry storage (after-ripening) gradually reduce physiological dormancy by shifting ABA/GA balances, while light quality (e.g., red: far red ratios) can act as both a germination cue and a dormancy maintainer, depending on species specific phytochrome responses [12]. Moisture fluctuations and soil microbial activity can weaken the seed coat or metabolize inhibitors, facilitating dormancy escape in physically dormant seeds [13]. Collectively, these mechanisms enable weed seeds to synchronize germination with favorable conditions while buffering against environmental unpredictability.

Table 1: Weed Seed Dormancy Types and Management.

Dormancy Type	Mechanism	Example Species	Key Features	Management Strategies
Physical	Impermeable seed coat prevents water/gas uptake	*Chenopodium album L.*	Hard, often lignified testa; dormancy broken by scarification (mechanical, chemical, microbial)	Mechanical scarification, soil microbial activation, acidic or hot-water treatments
Physiological	Hormonal balance (high ABA: GA ratio); sensitivity to temperature and light cues	*Amaranthus retroflexus L.*	Embryo fully formed but hormonally suppressed; after-ripening, stratification, light trigger	Stratification (cold or warm), nitrate or GA_3 applications, light-quality manipulation
Morphological	Under-developed embryo at dispersal requiring growth period or specific conditions	*Rumex obtusifolius L.*	Embryo continues development post-dispersal; germination delayed until embryo maturation	Extended moist preconditioning, warm stratification, hormonal priming
Combinational	Combination of physical and physiological barriers	*Polygonum aviculare L.*	Hard coat plus hormonal controls; very long persistence	Integrated scarification + hormonal treatments, extended after-ripening

Ecological and Agronomic Implications

Seed dormancy has profound ecological and agronomic implications by shaping seedbank dynamics, emergence patterns, and the effectiveness of control measures. First, dormancy prolongs seedbank persistence: seeds with deep physiological or combinational dormancy can remain viable for years, creating a standing reservoir that continually replenishes weed populations even after seemingly effective control. Second, dormant seeds contribute to asynchronous and often multimodal emergence, allowing a portion of the population to escape pre and post emergence interventions; for example, many species exhibit bi or tri modal emergence peaks in spring and early summer, complicating timing of herbicide applications and cultural controls [14]. Third, agronomic practices interact with dormancy to influence seedbank fate: under no tillage systems, seeds accumulate near the soil surface where light and temperature fluctuations can break dormancy leading to higher seedling emergence but also increased predation, whereas inversion tillage buries seeds deeper, often maintaining dormancy and delaying depletion [1]. Finally, dormancy enables temporal escape from crop competition: delayed germination reduces overlap with crop critical periods, allowing weeds to establish under reduced crop interference and potentially evolve greater competitive ability. Altogether, these dynamics underscore the need for diversified management timely tillage, stale seedbeds, and split application herbicides to target both dormant and germinable seeds and sustainably deplete weed seedbanks (Table 2).

Table 2: Key Ecological and Agronomic Implications of Weed Seed Dormancy.

Ecological / Agronomic Factor	Impact of Dormancy	Example / Consequence	Ref.
Seedbank Persistence	Extended viability delays depletion; persistent reservoirs	Seeds viable >5 years under deep dormancy	[15]
Emergence Timing Spread	Multimodal germination peaks; asynchronous emergence complicates control	Bi- and tri-modal emergence in late spring / early summer	[14]
Tillage Interaction	Surface accumulation vs deep burial alters dormancy break and predation rates	No-till: increased emergence & predation; inversion tillage: maintained dormancy	[1]
Crop Competition Escape	Delayed germination reduces overlap with crop critical periods; enhances weed competitive success	Later-emerging cohorts avoid early season herbicides and crop shading	[16]

Dormancy Removal and Management Approaches

Dormancy removal in weed seeds employs a multifaceted suite of techniques designed to breach physical barriers, alter physiological states, and exploit biological processes to synchronize germination and exhaust soil seedbanks before crop establishment. Mechanical scarification, such as abrasion with sand or nicking of the seed coat, effectively disrupts physical dormancy by creating micro fissures that facilitate water uptake, often increasing germination rates in hard coated species like *Chenopodium album* by 30–50 % [8]. Thermal stratification alternating cold (4°C) and warm (20°C) treatments over several weeks modulates hormonal balances (ABA:GA ratio) within the embryo, transforming deep physiological dormancy into germinability; for example, six weeks of warm stratification have been shown to elevate germination of Brassica weed seeds from under 10 % to over 60 % [11,10]. Chemical priming harnesses growth regulators and signaling compounds most notably gibberellic acid (GA_3) and potassium nitrate (KNO_3) to "flush out" dormant seeds in a controlled flush: seed treatments with GA_3 at 200–400 ppm can boost emergence in Amaranthus retroflexus and Cleome gynandra by 20–30 %, while KNO_3 at 250 mgL^{-1} promotes more uniform radicle protrusion and synchrony across cohorts [17,18]. Biological methods leverage microbial activity particularly from fungal genera such as *Trichoderma* and *Penicillium* to enzymatically degrade seed coat layers or leach dormancy inducing inhibitors, reducing viable dormancy fractions by up to 40 % over 6–8 weeks in species like *Avena fatua* [19]. When these tactics are integrated into an Integrated Weed Management (IWM) framework combining stale seedbeds to induce flush germination, strategic tillage to expose and then rebury seeds, and split applications of pre and post emergence herbicides the cumulative effect can exceed 70 % seedbank depletion within two seasons, markedly diminishing weed pressure and delaying the evolution of resistance [2]. By targeting both dormant and germinable seed fractions through complementary physical, chemical, and biological approaches, growers can more effectively synchronize weed emergence with control measures and sustainably deplete the soil seedbank over time (Table 3) [15,16].

Conclusion and Future Directions

In conclusion, unravelling the intricate biology of weed seed dormancy and translating these insights into field practices is pivotal for achieving durable weed control. By combining detailed knowledge of hormonal and environmental cues with predictive seedbank models, we can better forecast emergence patterns and time interventions more precisely. Emerging technologies such as genome-informed trait selection, cover-crop allelopathy, and precision robotics for stale-seedbed preparation hold promise for synchronizing germination flushes and depleting both dormant and active seed fractions. Moving forward, research should focus on quantifying dormancy plasticity across diverse environments, integrating dynamic climate-aware modeling into management planning, and assessing the practical and economic viability of innovative dormancy-breaking tools within different cropping systems. Such a holistic, science-driven approach will be key to developing adaptive, ecosystem-friendly weed management strategies that sustain crop productivity and support long-term agricultural resilience [17-20].

Table 3: Dormancy-Breaking Methods, Mechanisms, and Efficacy.

Method	Mechanism	Optimal Conditions / Duration	Efficacy Increase	Advantages / Limitations	Representative Species	Ref.
Mechanical Scarification	Abrasion or nicking of impermeable seed coats	Sand-paper abrade for 2 min per batch	+30–50 % germination	+ Rapid; simple– Labor -intensive at scale; uneven effects	*Chenopodium album, Polygonum aviculare*	[8]
Warm Stratification	Sustained warm imbibition shifts ABA:GA balance	20°C, 4–6 weeks in moist substrate	+50–60 % germination	+ Uniform break of physiological dormancy –Time consuming	*Brassica spp., Sinapis arvensis*	[10,11]
Cold Stratification	Chilling promotes embryo development and hormone shifts	4°C, 4 weeks in moist sand	+40–55 % germination	+ Effective for many temperate weeds –Requires refrigeration	*Atriplex spp., Rumex obtusifolius*	[20]
GA_3 Priming	Exogenous gibberellin stimulates embryo growth	200–400 ppm soak, 24 h at 25°C	+20–30 % emergence	+ Fast action; easy to apply –Cost of hormone; variable dose response	*Amaranthus retroflexus, Cleome gynandra*	[17]
KNO_3 Treatment	Nitrate signalling breaks physiological dormancy	250–500 mg·L^{-1} soak, 24 h at room temp	+12–15 % germination	+ Low cost; dual as fertilizer –Can promote unwanted microbes	Broadleaf weeds (e.g., *Amaranthus spp.)*	[18]
Water-Wet/Dry Cycling	Alternating hydration and desiccation weakens seed coats	12 h wet / 12 h dry cycles, 5–7 days	+25–45 % germination	+ Mimics field fluctuation – Logistics for large batches	*Chenopodium album, Avena fatua*	[13]
Biological Decay	Fungal enzymes degrade testa or leach inhibitors	Inoculate with Trichoderma spp., 6–8 wk	–40 % dormant fraction	+ Eco friendly; self sustaining – Variable field efficacy	*Avena fatua, Echinochloa crus-galli*	[19]
Smoke Water / KAR_1	Fire-derived compounds stimulate germination cues	1: 100 dilution spray, single application	+20–30 % germination	+ Useful for fire prone weed management – Formulation costs	*Avena fatua, Eragrostis curvula*	[21]
Integrated IWM	Combines stale seedbed, strategic tillage, split herbicides	Seedbed flush 2 wk pre-sowing; 2 cultivations; herbicide split	>70 % seedbank depletion over	+ Holistic; reduces resistance risk – Requires careful timing and labor	Multiple weed species	[2]

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