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Advancing Future Weed Management Strategies through Weed Seed Bank Depletion: A Review

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Abstract

In recent decades, the demand for food production had increased due to the rapidly growing global population, exerting notable pressure on agricultural systems. Weeds had reduced the yield of crops by 34% due to which effective weed management is crucial. The pool of weeds is the reservoir of seeds which are viable within ground. Understanding the key factors influencing seed bank longevity, such as seed dormancy, environmental conditions, and human intervention, was essential for its effective management. Weed seed bank depletion could be achieved through various approaches that are cultural, biological, mechanical, chemical, biochemical, and integration of various strategies for management of weeds. The enhanced growth of herbicide resistant weeds led to the adoption of management strategies which addresses shifting weed dynamics. Various practices like crop rotation, cover cropping, mulching and other weed management methods can reduce the source of weeds in soil. Over time, systematic depletion of weed seed reserve could substantially lower weed pressure, reduce reliance on herbicides, and improve the effectiveness of long-term weed control strategies. Therefore, lowering the weed reserve forms a major component of sustainable management of weeds providing durable solutions for agriculture and land management.

Keywords: Weed, dormancy, tillage, predation, allelopathy, mulching, irrigation, flaming

1. Introduction

Over the past few decades, the need to increase food production has intensified due to rapid population growth, placing significant pressure on agricultural systems (Monteiro and Santos, 2022). By 2050, global food demand is expected to rise substantially, and with around 735 million people experiencing hunger in 2022 (Anonymous, 2023), enhancing crop productivity through sustainable intensification has become essential (Giller et al., 2021). At the same time, both intensified farming practices and climate change have improved the impact of weeds especially on crop yield and global food security (Storkey et al., 2021). Weeds contribute to loss of yield, with global reductions in major crops estimated at about 34% (Ghosh et al., 2023). In India, weeds alone contribute to approximately 37% of total annual crop losses, surpassing damage caused by insects (29%), diseases (22%), and other pests (12%) (Datta and Pilli, 2019). The competition among weeds and crops is usually for water, nutrients, light and above all weeds act as a host for the transmission of diseases and infestations by pests (Umurzokov et al., 2024). A key factor sustaining weed populations is the reservoir of dormant seeds that serves as the major source of future infestations for both annual and perennial weeds (Singh et al., 2012). In addition to storing seeds, soil seed banks preserve genetic variability, including traits like prolonged dormancy, irregular germination patterns, and varying responses to herbicides (Korres et al., 2018). The widespread emergence of herbicide-resistant weed species has further complicated management efforts (Hulme and Liu, 2022). The long-term outsourcing of seeds in the ground is contributed by multiple interacting factors such as cropping practices, environmental conditions, burial depth, microbial activity, and tillage operations (Barla and Upasani, 2022). Moreover, climate change is altering dormancy and germination dynamics, making weed control even more challenging (Mou et al., 2025). Typically, soil seed banks consist of three categories: dominant species that account for 70–90% of the seed bank and cause most yield losses; regionally adapted species contributing 10–20%; and a smaller proportion of persistent seeds remaining from earlier seasons (Sharshar et al., 2022). Soils contain thousands of weed seeds per square foot, along with its vegetative propagules (Menalled, 2013). The weed seed reserve effectively pronounce the history of cropping practices, and understanding its size and species composition helps farmers anticipate and manage future weed problems (Schwartz-Lazaro and Copes, 2019). Preventing the addition of new seeds-commonly referred to as seed rain-is considered the most effective long-term strategy for reducing weed pressure (Menalled, 2008). Techniques like harvest weed seed control (HWSC) limit seed return during harvesting and have proven effective in managing herbicide-resistant weeds (Shergill et al., 2020). Integrated weed management (IWM) strategies incorporating seed bank depletion have demonstrated considerable effectiveness, as evidenced in a six-year rice-wheat system where seed density declined by up to 51%, accompanied by reduced herbicide use (Zhang et al., 2021). Tillage practices also influence seed bank dynamics, with no-till systems reducing viable seed densities by 45–75% compared to conventional methods (Zamljen et al., 2024). Natural processes such as seed predation by animals (Daouti et al., 2022) and microbial degradation (Cheng et al., 2022) further contribute to the gradual decline of seed banks. When seed inputs are effectively controlled, seed banks can decline rapidly—for instance, annual ryegrass populations may decrease by 70–80% per year, while wild oat populations can drop by 80% in the first year (Peltzer and Matson, 2002). Therefore, a thorough understanding of seed bank dynamics, combined with integrated management strategies aimed at reducing seed reserves, is fundamental for achieving sustainable and effective weed control.

2. Weeds-Prolific Seed Producers

Weeds typically spread by seeds, while certain species can also proliferate through roots, bulbs, broken branches, and other plant parts. The seed production in weeds is heavy and it has a long dormancy span. For example, *Amaranthus retroflexus* produces around 1,17,400 seeds per plant and *Chenopodium sp.* about 72,450 seeds (Das, 2016). The soil seed reserve consists of viable weed seeds present on the soil surface as well as within different soil layers (Singh et al., 2012). It comprises both freshly shed and older seeds that remain viable for extended periods (Figure 1). In addition, this soil seed reserve also contains vegetative propagules such as tubers, bulbs, and rhizomes, which aid in the multiplication and persistence of perennial weeds. According to Santín-Montanyá et al. (2016), weed seed banks can be transient or persistent. A transient seed bank contains seeds that cannot survive beyond a single germination season, whereas a persistent seed bank has seeds that can be viable for several seasons. Weed scientists focus more on the persistent seed bank because they pose ongoing challenges for weed management (Schwartz-Lazaro and Copes, 2019). Understanding the soil weed seed reserve is crucial in analysing population dynamics and developing

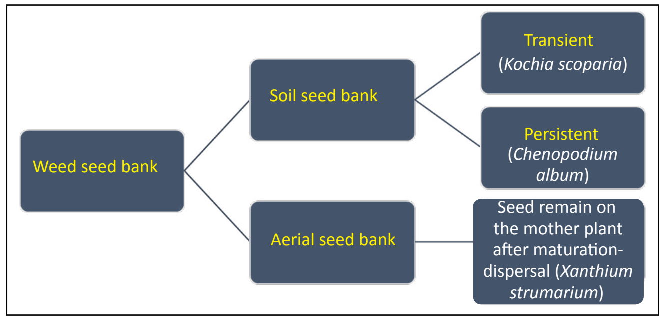

Figure 1: Types of weed seed reserve in soil

effective strategies for weed management. Even a minor effort in analyzing the weed seed bank can provide valuable information into the types of weeds that are expected to appear throughout a growing season, as well as their density and germination timing. Sharshar et al. (2022) reported that seed banks typically consist of three categories of species. The first category includes dominant species, which make up 70 to 90% of the total seed pool and are primarily responsible for most weed issues in cropping systems. The second category accounts for 10 to 20% of the seed bank and contains species that are adapted to the local environment but may not be suitable for present farming practices. The final group contains a small part of the total seeds, including recalcitrant seeds from previous crops' seed banks.

3. Longevity and Viability of Weed Seeds in Soil Systems

The longevity of weed seeds in the soil is affected by several aspects such as intrinsic dormancy, environmental circumstances (such as temperature, light, and moisture), and biological interactions (including predation and allelopathy). Tillage, for instance, lengthens the seed's life since buried weed seeds often survive longer (Hossain et al., 2021). Conversely, no-till decreases seed permanence by exposing them to diseases and predators. The long-term persistence of seeds of weeds is mainly due to seed dormancy (Schwartz-Lazaro and Copes, 2019). A seed, propagule, or any other vegetative propagating structure (tuber, bulb, corm, or bud) in a condition of suspended development is called dormancy. It is a phenomenon that allows a variety of plants and most weeds, to adapt to their surroundings, survive, and continue to exist on earth. There are three different types of dormancies in weed seeds: induced dormancy, enforced dormancy, and inherent dormancy (Das, 2016).

a) Primary or innate dormancy–dormancy is due to inherent characteristics of seeds, seed coats and embryos.

b) Secondary or induced dormancy–dormancy is induced by the unfavourable environmental conditions after seed shedding from the mother plants.

c) Enforced dormancy–dormancy is enforced due to sudden changes in the environment, position or status of seeds in soil after shedding from the mother plants.

4. Depletion Methods of Weed Seed Reserve

Weed seed bank depletion can be achieved by different methods (Figure 2). One way to deplete the weed seed bank is to stimulate the germination of weeds and destroy the emerged weeds later (Maqsood et al., 2020). Another effective method for depleting the weed seed bank is preventing the weed seeds from entering the soil seed reserve. Strategies for depleting weed seed banks encompass cultural, mechanical, biological, biochemical, chemical approaches, and integrated weed control (Das, 2016).

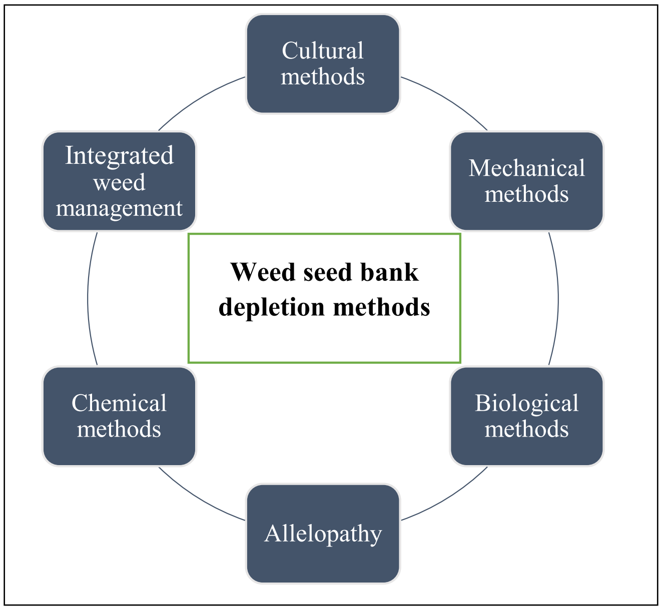

Figure 2: Methods of weed seed bank depletion

5. Cultural or Ecological Methods

5.1. Crop rotation

A key contemporary approach for managing weed seed bank is crop rotation, which constitutes around 75 % of the variance in soil seed banks that has been observed (Cardina et al., 2002). In the weed management scenario, crop rotations help in diversifying the weed management strategy (Rudeli et al., 2023). By introducing different crops, rotations can foster competition among plants, thereby aiding in weed control. Some of the modifications in the composition of weed species and its density is often due to the alteration in various practices of management of crops. Koocheki et al. (2009) examined significance of crop rotation and farming techniques on weeds and found that broadleaved weeds were higher in sugar beet-winter wheat rotation (55.2%). Approximately 90% of the weed community in continuously cultivated winter wheat plots consisted predominantly of sedges and grassy weed species. However, in sugar beet-wheat rotation, this percentage dropped to 43% of the overall weed density. Crop rotations incorporating species with different life cycles can provide added advantages in suppressing and reducing the weed seed reserve. According to Butkeviciene et al. (2021), rye monocultures in springtime had an average of 2.7 times more weed seedlings than rye crops in various crop rotations. The interplay between the crop sequence and the fertilizer/nutrients utilized had a noticeable effect on the soil seed bank. Crop rotation, while highly dependent on the nutrition source, generally had a good effect over time in reducing the bank of weed seeds (Saulic et al., 2022). The principal factor contributing to the expanding weed seed bank was identified as manure, which consistently resulted in the greatest weed seed population, irrespective of crop rotation practices. Hosseini et al. (2014) conducted a study comparing agricultural fields with non-agricultural lands to ascertain the impact of crop rotations on the soil seed bank. The crop rotation systems included continuous irrigated wheat, continuous dryland wheat, wheat–chickpea, and wheat–sugar beet. Apart from this, nearby orchards and pastures were also studied for comparison purposes. Seed bank density estimates were greater in pastures (52779 seed m^{-2}) than in cropped land.

5.2. Stale seedbed technique

Stale seedbed preparation, often referred to as false seedbed preparation, is a key technique for minimizing the weed seed bank (Kanatas et al., 2025). This method involves performing one or more seedbed preparations that promote the germination of weed seeds, but without subsequent crop planting. Following the removal of the emerging weed seedlings, agronomic disturbances are frequently performed mechanically (Benvenuti et al., 2021). Stale seedbeds (SSB) facilitate the leaching of germinal weed seeds from the soil's upper layer and inhibit the emergence of weed seedlings prior to crop planting.

The principles of stale seedbed technique include (Benvenuti et al., 2021);

a) Weed seed germination is accelerated by cultivation.

b) Very few seeds are non-dormant and it is able to germinate any time.

c) Most weeds primarily germinate from seeds located in the upper layers of the soil, particularly within the top 2.5 inches. Generally, they tend to emerge in substantial quantities from just the top one inch of soil.

According to Singh et al. (2018), stale seedbed treatments (using either shallow (5 cm) tillage or glyphosate 1 kg ha^{-1}) dramatically reduced the viable seed bank of *Dactyloctenium aegyptium* and *Echinochloa colona* to around 25 to 30% when compared to non-stale seedbed treatment. Subsequent to the rice harvest, both stale seedbed treatments exhibited a 13–33% reduction in seed bank compared to the non-stale seedbed treatment. Benvenuti et al. (2021) reported that improved soil aeration following ploughing enhanced oxygen availability, which stimulated seed germination and led to a marked decline in the weed seed reserve within the top 0–10 cm soil layer. They also observed a proportional relationship between the reduction in the weed seed reserve and the extent of soil fragmentation created by various tillage practices, with greater decreases occurring when finer soil aggregates were formed. Unnikrishnan (2023) found that the stale seedbed technique resulted in the minimum population and biomass of chocolate weed (*Melochia corchorifolia*) at 20, 40, and 60 days after sowing of sesamum, compared with plots where the stale seedbed practice was not adopted.

The stale seedbed technique is a useful tool for depleting the seed reserve of weedy rice in soil. Inorder to carry out depletion, the crop was forgone for one season and performed repeated stale seedbed operations (Anonymous, 2024). Dilipkumar et al. (2022) studied the applicability of stale seedbed technique for managing weedy rice in wet-seeded rice systems and observed that employing the stale seedbed technique with glyphosate application considerably lowered the dry weight of weedy rice by 12% as compared to the treatment without glyphosate.

5.3. Suicidal germination

Parasitic weeds like striga and orobanche depended on chemical signals from host roots to germinate (Nelson, 2021). Utilizing compounds that induce the germination of parasitic weed seeds in the absence of an appropriate host may reduce their seed bank. Once these seeds germinate, they cannot revert to dormancy and lack the ability to survive for extended periods without nutritional support from a host plant (Habimana et al., 2014), which is known as suicidal germination. Samejima et al. (2016) opined that when germination stimulant T-010 was applied at different rates, such as 0.1, 1, and 10 kg ha^{-1} to potted soil containing pre-conditioned striga seeds, there was a reduction in striga emergence in the range of 94 to 100%. Among the different chemical stimulants used in the study, MP16 resulted in the highest reduction of striga emergence (97%) in the greenhouse experiment. Conversely, under field conditions, Nijmegen-1 demonstrated notable effectiveness, leading to a 43% reduction in striga emergence in pearl millet and a 60% reduction in sorghum fields (Jamil et al., 2022). Rizk et al. (2022) reported that gibberellic acid and potassium nitrate can also be utilised for breaking dormancy and enhancing germination of weeds.

5.4. Cover cropping

Cover crops play a crucial role in weed control across different cropping patterns, as they effectively suppress weed growth (Fernando and Shrestha, 2023). A vigorously growing cover crop suppresses weeds through multiple mechanisms. The competition for resources lowers weed biomass and restricts seed formation, ultimately reducing the upgradation of new seeds. Weed suppression by cover crops also occurs through reduced seedling emergence, either due to shading that limits light penetration or through allelopathic interactions (Sturm et al., 2018). Additionally, cover crops can lower weed seed density in the soil and decrease the persistence of herbicide-resistant weed populations. Mirsky et al. (2010) reported that cover cropping completely eliminated the germinable seed reserve of *Setaria* spp., and reduced it by 85% and 80% for *Chenopodium album* and *Abutilon theophrasti*, respectively.

5.5. Application of fertilizers

Fertilizer application is the fundamental nutrient source for the cultivated crop, and an important indicator of both crop growth and soil nutrient status (Noulas et al., 2023). Continuous fertilizer application helped in maintaining the high soil fertility required for high crop growth and development. Additionally, the utilization of fertilizers significantly influenced weed populations in farms, which are crucial components of agricultural ecosystems (Wang et al., 2019). Weeds also respond well to the application of inorganic fertilizers, just like crops. Management practices, such as fertilizer application, can significantly influence the species composition, diversity, density, biomass and nutrient levels of weeds in agricultural fields. Consequently, it is crucial to thoroughly examine the effect of fertilizer application on soil weed seed reserve to enhance weed control and preserve biodiversity in farmland (Pan et al., 2020). The use of inorganic nitrogen, whether applied alone or in combination with potassium, significantly decreased weed species diversity in a rice-rice cropping system (Lal et al., 2016). In a study investigating the effects of prolonged fertilizer application on the weed seed bank within a wheat-soybean rotation, Pan et al. (2020) discovered that the diversity of weed species was markedly reduced in various fertilizer treatments relative to the control group. The total weed densities in the top 15 cm of soil ranged from 37,933 to 1,22,293 grains per square metre across different treatments, with a significant decrease observed in the following order: NPK >NP>NK>control>PK suggesting that PK treatment may be most effective for weed suppression. Zargar et al. (2023) observed that the incorporation of 40 t ha^{-1} of manure combined with nitrogen and phosphorus at 140 and 30 kg ha^{-1}, respectively, as well as 40 t ha^{-1} of manure together with NPK applied at 320, 120, and 210 kg ha^{-1}, respectively, led to a marked increase in weed density in brinjal by 23.7% and 32.5%, respectively. This increase in weed density corresponded to a rise in annual weed species by 35.2% to 47.7%.

5.5. Soil solarisation

Topsoil acts as a reservoir for weed seeds, often sheltered by parent plants from previous growing seasons (Srivastava and Singh, 2014). Under optimal soil moisture and temperature circumstances, these seeds develop in bursts, threatening crops for the essential resources in the rhizosphere. One effective method is soil solarisation which can reduce the sourcing of seeds. With the increasing global population in the 21st century, concerns about environmental quality are rising. As a result, practices like soil solarisation and other applications of solar energy are expected to become more significant. The hydrothermal treatment of soil known as "soil solarization," is practiced to eradicate weeds, insects, and diseases that are carried by the soil. Khan et al. (2012) reported that during the solarisation process, 85 to 95% of solar radiation is absorbed by clear mulch, effectively warming the soil. Soil solarisation is a non-chemical method that involves covering pre-soaked soil with a plastic film for 30 to 40 days before planting to manage soil-borne pests. This method harnesses the sun's heat to increase temperatures during the hot summer months (Shinde et al., 2023). Kanellou et al. (2023) reported that soil solarisation using clear plastic during the summer season resulted in significantly lower dry weight of weed biomass (74.42 g m^{-2}). Arora and Tomar (2012) assessed various approaches, including solarization, stale seedbed preparation, deep ploughing, green manuring, and mulching, for weed control and observed that the population of grasses, broad-leaved weeds, and sedges was minimum under solarized soil conditions. The temperatures measured in solarized plots reached 43.9°C and 43.8°C at depths of 10 and 15 cm, respectively, which contributed to the depletion of the soil weed seed reserve.

5.6. Mulching

Mulching involves covering the soil with various organic and synthetic materials to enhance conditions for plant growth and optimize crop yields. Additionally, mulching also contributes to lowering the seed reserve in the soil (Maqsood et al., 2020). Organic mulch, made up of decomposing materials, acts as a barrier between seeds and the soil surface. This practice often eliminates conventional tillage, allowing the soil surface to remain relatively undisturbed. This undisturbed habitat not only supports predators of agricultural pests, but also, insects, small birds, and rodents that feed on weed seeds, leading to a gradual reduction of weed seed reserve (Petrikovszki et al., 2020). Choudhary (2023) examined the effects of tillage and mulching on weed control, soil weed seed reserves, and crop yield in a maize–rapeseed cropping system. Results showed that both deep and reduced tillage combined with crop residue management reduced weed growth by 32.6 to 48.3%, decreased the active seed bank (0-5 cm) by 70%, and increased overall system productivity by 15.6 to 28.9% in the maize-rapeseed system. Hossain et al. (2021) reported that strip tillage combined with 50% mulch resulted in lower weed abundance and biomass, as well as fewer weed species, compared to conventional tillage without residue in intensive rice-based crop rotations. Furthermore, strip tillage combined with 50% crop residue showed greater seed bank diversity compared to conventional tillage without mulch. Under strip tillage, most of the seeds were concentrated in the 0–5 cm soil depth, at the same time, in conventional tillage they were mainly distributed in the 10–15 cm soil layer.

5.7. Irrigation

Irrigation also significantly affects the concentration of weeds in the soil (Khaffagy et al., 2022). Weed emergence is influenced by irrigation timing and technique; drip irrigation only wets a small portion of the soil near tree crops, alternate furrows reduce weed growth in dry furrows, and submergence suppresses a large number of weeds (Das, 2016). The seeds of aquatic plants, including salvinia, pistia, and water hyacinth, are frequently present in irrigation water (Koutika and Rainey, 2015). To avoid the entry of weed seeds into water bodies, weeds growing in and around reservoirs and irrigation channels should be effectively managed. Weed propagules can be intercepted and removed at the source by installing screens made of woven plastic fabric with mesh openings smaller than 1 mm, mounted on rigid metal frames of about 1.5 cm (Datta, 2009).

Schutte et al. (2016) examined how the timing of irrigation after soil disturbance influenced soil seed bank density and reported that disturbance of soil reduced the persistence of Palmer amaranth seeds, but did not significantly influence the persistence of jungle rice and yellow foxtail. The maximum decline in seed bank density following disturbance was observed when the soil was disturbed 0–3 days prior to flood irrigation. Fogliatto et al. (2010) observed that winter flooding led to over a 95% decline in viable weedy rice seeds on the soil surface, while fields kept dry between rice crops exhibited reductions ranging from 26% to 77%. Zhang et al. (2021) demonstrated that filtering irrigation water by trapping seeds at both entry and exit points, along with the use of nets to collect floating weed seeds during irrigation before rice sowing, helped in the reduction of weed to some extent. A quantitative evaluation of seed bank and weed population dynamics indicated that continuous adoption of this practice for six years reduced the overall weed seed bank density by 51% and lowered the density of dominant grassy weeds by 53% compared with the initial level. Ghosh et al. (2017) observed that maintaining water at a depth of 2 cm significantly decreased seedling emergence of the weedy rice strain JMP by 78%. Moreover, increasing the burial depth further reduced emergence, with the lowest emergence recorded at a depth of 10 cm. The findings indicated that the proliferation of weedy rice can be efficiently controlled using methods such as deep tillage, which buries seeds beyond their optimal emergence depth, and inundating fields to establish anaerobic conditions.

6. Mechanical Methods

6.1. Tillage

Tillage is another method in weed seed bank depletion that is widely adopted (Santín-Montanyá et al., 2016). The depth and timing of tillage operations impacted soil seed banks, influenced by weed characteristics like seed size and germination timing. Shallow tillage encourages the germination of recently dispersed seeds, whereas very small seeds may be incorporated into the soil seed bank through such practices (Pekrun and Claupein, 2006). Therefore, tillage strategies aimed at managing seed banks should carefully consider the specific seed traits of the target weed species.

According to Singh et al. (2015), in direct seeded rice under zero tillage, significant proportion of weed seeds, whether broad leaved (48-52%) or grassy (45-55%), remain concentrated in the top 2 cm layer of soil during crop sowing. On the other hand, conventional tillage tends to bury these seeds deeper, resulting in only 20 to 23% of broad leaved weed seeds and 16 to 20% of grassy weed seeds within 0-2 cm soil depth. Zhang and Wu (2021) evaluated the effects of different tillage practices and crop residue management on weed species composition and wheat yield in a wheat–maize double-cropping system. It was observed that retaining crop residues led to reductions in both weed density and species diversity, in both above-ground vegetation and the soil seed bank. In post-monsoon seasons following conventional tillage of rice, zero tillage led to reductions in weed seed density by 11%, 23%, and 13% compared to conventional tillage across crop rotations, specifically without residue, at depths of 0-7.5 cm, 7.5-15 cm, and 0-15 cm (Kumar et al., 2022). According to Ghosh et al. (2023), employing zero tillage with permanent broad or narrow beds, coupled with crop residue retention and applying full nitrogen, proved effective in decreasing weed density and improving crop productivity in maize-wheat-mungbean rotation.

6.2. Harvest weed seed control

Western Australia is considered a global hotspot for weeds which are resistant to herbicides because of the widespread occurrence of multiple resistant weed population (Peterson et al., 2018). This situation encouraged the development of alternative approaches aimed at restricting the entry of weed seeds into the soil seed bank, particularly for annual ryegrass (*Lolium rigidum*) in wheat systems, where conventional herbicides are no longer effective (Hartzler, 2018). Harvest weed seed control (HWSC) involves collecting seeds, during or immediately after crop harvesting (Walsh et al., 2017). Unlike conventional harvesting, where crop residues along with seeds remain on the soil surface and may germinate in the following crop, HWSC targets the removal of weed seeds at harvest (Borger et al., 2018). Different approaches used in harvest weed seed control include narrow windrow burning, chaff carts, the Harrington Seed Destructor, and the bale direct system. The success of harvest weed seed control largely depends on the proportion of seeds retained by the target weed species at crop maturity. This approach is particularly suitable for *Lolium rigidum*, as it retains a large portion of its seeds at the time of harvest. At the earliest harvest timing, up to 85% of seeds were retained above the cutting height and could be collected and destroyed by the harvester across nine locations in Western Australia. Even after 28 days, 63% of *Lolium rigidum* seeds were still retained on the plants (Walsh and Powles, 2014). In another investigation conducted in Queensland, *Echinochloa colona* retained approximately 42% to 56% of its seeds above harvest height in sorghum, whereas *Chloris virgata* retained about 67% to 75% of its seeds (Mahajan et al., 2020). Therefore, harvest weed seed control may be less efficient for managing *Echinochloa colona* due to its greater seed shedding, but it can contribute to reducing seed bank replenishment of *Chloris virgata*. Borger et al. (2021) found that after six years, the total weed seed bank of *Bromus diandrus* in the soil could be decreased by 46% by employing harvest weed seed control to eliminate 20% of the seeds each year during crop harvest. In the United States, at soybean maturity, barnyard grass retained 41% of its seeds, whereas Palmer amaranth retained as much as 98%; after one month, retention declined to 32% for barnyard grass and 95% for Palmer amaranth (Schwartz-Lazaro et al., 2017). In Western Australia, brome grass held onto 77% of its seeds at the time of wheat maturity, dropping to 41% a month later, while wild oats retained 84% initially and decreased to 39% after a month (Walsh and Powles, 2014). Tidemann et al. (2016) reported that reducing wild oat populations in Lacombe, Canada, would require controlling about 80% of the seeds at harvest. In contrast, a simulation study of a corn–soybean rotation in the United States showed that managing just 20% of *Amaranthus palmeri* seeds was sufficient to maintain a stable seed bank (Shergill et al., 2020). Bitarafen and Andreasen (2020) opined those weeds such as *Fallopia convolvulus* (black bindweed), *Sinapis arvensis* (wild mustard), *Spergula arvensis* (corn spurrey), and *Stellaria media* (chickweed) in oats produced an average of 260,195,411 and 316 seeds per plant, respectively. During the harvest of oats by a combine harvester, these weeds retained approximately 44%, 67%, 45%, and 56% of their seeds on average.

6.3. Seed flaming

Flaming is a common technique for eradication of young weed seedlings, apart from killing weed seeds that are present on the soil surface following seed rain (Bolat et al., 2017). Achieving high levels of weed seed mortality requires relatively slow tractor speeds along with substantial propane application. To assess how tractor speed influences seed mortality during flaming, experiments were conducted in Germany. The treatments consisted of one flaming pass at 1.6 miles per hour (mph), 0.8 mph, 0.36 mph, and a control where seeds were not exposed to flame. A considerable proportion of weed seeds were destroyed when the tractor operated at speeds below 0.8 mph. Additionally, flaming at 1.6 mph was moderately effective in controlling hairy galinsoga, resulting in about 50% mortality compared to the control. Seeds subjected to the 0.8 and 0.36 mph treatments were frequently observed to be charred or “popped.” Birthisel and Gallandt (2014) documented these findings. Furthermore, Horesh et al. (2019) evaluated propane flaming as an innovative approach for managing invasive Mediterranean weed species. A broadcast method was used in the study, administering multiple applications of a single dose of 2.5 kg propane per km to combat *Cyperus rotundus, Sorghum halopense,* and *Ecballium elaterium.* The findings revealed that three applications were sufficient to achieve significant control (up to 90%) of all perennial species tested. Furthermore, the treatments impacted the seed and flower production of *Sorghum halapense* and *Ecballium elaterium*, suggesting potential effects on their seed banks and offering promise for long-term management strategies.

7. Biological Methods

7.1. Seed predation

Another strategy for controlling weed seeds is to arrange crops spatially. Entomologists investigating 'push-pull' methods to keep the insects away from crops and move them to areas which are not meant for agricultural crops. It was observed that an insect that repels *Desmodium uncinatum* hindered the spread of *Striga hermonthica* propagules. This technique could be extended to influence soil root chemistry as well as weed seeds by means of improved insect predation. By providing favourable conditions for insect habitat, granivorous insect promotion may be able to decrease the addition of soil seed banks (Shiferaw et al., 2018). Scientists studying weeds may also consider altering the habitat to encourage the growth of microorganisms that break down weed seeds. Compared to insect predation, microbial seed degradation is still a developing field of study, although both mechanisms are mostly underutilized in agricultural weed management. Methods involving the consumption of weed seeds by insects or microbes may apply primarily to large-seeded crops that can withstand predation. Innovative approaches in managing weed seed banks could significantly advance integrated weed management strategies (Muller-Stover et al., 2016).

Blubagh and Kaplan (2016) found that seed predators caused a 38% decrease in seedling emergence and an 81% decline in weed biomass of *Chenopodium album* in fallow plots after simulated weed dispersal. Additionally, Daouti et al. (2021) highlighted that predation by carabid beetles on weed seeds contributed to a reduction in the population growth of the herbicide-resistant weed *Alopecurus myosuroides* in wheat fields.

8. Allelopathy

Allelopathy, as defined by Inderjit (2003) is a significant mechanism in ecological interactions that allows specific plant species to dominate or influence plant communities through the chemical suppression of competitors. Through the synthesis of chemical molecules known as allelochemicals, which are released into the environment and have an impact on the entire agro ecosystem, allelopathy plays a significant role in plant-to-plant contact and its surroundings (Figure 3). There are various forms of allelopathy, including weeds versus crops, crops against weeds, and weeds against weeds (Weston and Duke, 2003). Allelopathy represents another approach for reducing the weed seed bank in soil. Scavo et al. (2019) found that the allelopathic properties of *Cynara cardunculus* (globe artichoke, including both cultivated and wild cardoon) contributed to a decline in the soil weed seed bank. Similarly, Abbas et al. (2017) showed that allelopathic

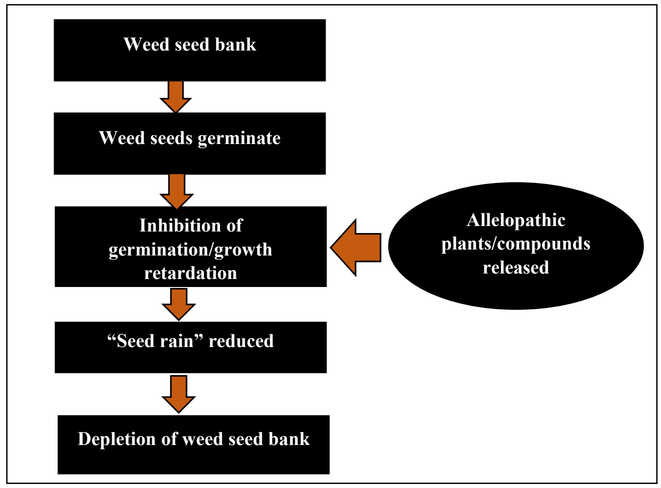

Figure 3: Role of allelopathy in weed seed bank depletion

mulches derived from rice, maize, sorghum, and sunflower significantly lowered the soil seed bank of *Phalaris minor* in wheat by 23–52%.

9. Chemical Methods

9.1. Herbicide application

Herbicides remained the dominant and effective form of control of weeds in the 21st century. According to Hossain et al. (2014), the quantity of weeds and the number of seeds added to the soil seed reserve can be highly reduced with the help of herbicides (Table 1). Organic management systems typically have higher weed seed bank densities than herbicide-dependent systems (Menalled et al., 2001), while this isn't always the case because crop rotation and other factors can also have a pronounced reflection on weed seed output. In agricultural systems relying heavily on herbicides for weed management, seed bank densities typically range from 1000 to 4000 seeds per square meter (Blackshaw et al., 2004). The use of herbicides which are tolerant to crops had eventually made the seed reserve to be at the lower end of this spectrum. Even when seed bank densities are reduced under such systems, considerable weed seedling emergence may still occur in following seasons. Pre-harvest application of glyphosate can limit seed production and reduce seed viability in late-flowering weed species; however, its relatively slow mode of action requires implementation well before seed dispersal at crop maturity. Raj and Syriac (2018) reported that post-emergence use of herbicide mixtures such as penoxsulam+cyhalofop-butyl (125 or 135 g ha^{-1}) is effective for managing the weed seed bank in wet direct-seeded rice. Ali et al. (2022) observed that two applications of fluroxypyr+MCPA reduced the broad-leaved weed seed bank by 70.1% compared to the untreated control, while double applications of metsulfuron methyl+tribenuron methyl, bromoxynil+MCPA, aminopyralid+fluroxypyr, and one-time hand weeding reduced the soil weed seed bank by 69.17%, 69%, 61.39%, and 45.18%, respectively. Arya and Syriac (2018)

Table 1: Appropriate herbicides for depleting the weed seed bank in crops/cropping systems

Herbicide	Crop/cropping system studied	Reference
2,4-D+fenoxaprop-p-ethyl for barley and 2,4-D+MCPA for corn	Corn-barley rotation system	Ovaisi et al. (2006)
Pendimethalin *fb* imazamox+ imazethapyr	Groundnut	Gohil et al. (2016)
Penoxsulam plus cyhalofop butyl	Rice	Raj and Syriac (2018)
Flucetosulfuron	Rice	Arya and Syriac (2018)
Pendimethalin plus imazethapyr	Maize-wheat cropping system	Susha et al. (2018)
Glufosinate ammonium, paraquat dichloride or glyphosate (by novel wiper device) for depleting the seed bank of weedy rice	Rice	Jose et al. (2020)
Isoproturon followed by fenoxaprop-ethyl	Wheat	Zhang et al. (2021)

found that applying flucetosulfuron in wet-seeded rice at 10–12 and 18–20 days after sowing significantly lowered the weed seed bank compared to application at 2–3 days after sowing. Furthermore, Susha et al. (2018) demonstrated that tank-mix application of pendimethalin and imazethapyr, with or without potassium nitrate, significantly reduced the weed seed bank during both rainy and winter seasons, as well as overall seed bank, compared to the untreated control in a maize–wheat system of the northwestern Indo-Gangetic plains.

10. Integrated Weed Management

Integrated weed management combines many strategies, encompassing cultural, mechanical, biological, and chemical approaches to efficiently diminish the weed seed reserve in soil (Table 2). According to Ameena et al. (2013), the stale seedbed preparation combined with pre-plant application of glyphosate 1.5 kg ha^{-1} (before sowing okra) and subsequent polythene mulching proved effective in significantly reducing nutsedge tuber production with lower tuber viability. According to a study by Norsworthy et al. (2016), the herbicide systems are amalgamated with harvest weed seed control to combat glyphosate-resistant palmer amaranth in soybean cultivation. The results emphasized the importance of managing crop residues; such as chaff removal, cover crop implementation, or seed incorporation during bed preparation, in conjunction with a robust pre and post emergence residual herbicide strategy. Schleich et al. (2023), reported that incorporating a cereal rye cover crop led to a significant 90% reduction in waterhemp seed production compared to without cover crop. These findings underscored the effectiveness of cover crops and harvest weed destruction as viable strategies to minimize water hemp seed bank inputs.

Table 2: Successful integrated weed management strategies for weed seed bank depletion

Integrated weed management strategy adopted	Reference
Winter cover crops like grazing vetch and oats, as well as fertilizer application in a maize-based conservation agriculture system	Dube et al. (2012)
Stale seedbed combined with pre-plant application of glyphosate 1.5 kg ha^{-1} (before sowing okra) followed by polythene mulching for depleting nutsedge tuber production	Ameena et al. (2013)
Integration of herbicides like paraquat, glyphosate or atrazine plus hand hoe weeding along with conservation agriculture in maize-soybean rotation	Muoni et al. (2014)
Weed seed wizard integrating harvest weed seed control for destructing *Lolium rigidum*	Borger et al. (2018)
Wheat residue incorporation followed by soil solarisation in groundnut or integration of suicidal germination and herbicide application	Gohil et al. (2016)
Application of 50% mefenacet+3% bensulfuron-methyl in rice season and application of isoproturon followed by fenoxaprop-ethyl in wheat fields as well as seed interception measures by nylon nets in rice-wheat system	Zhang et al. (2021)
Stale seedbed technique with glyphosate application (@ 850 g ha^{-1}) for weedy rice control	Dilipkumar et al. (2022)
Crop rotation, in contrast to continuous corn cultivation, along with adjustment in row spacing and integration of herbicides for controlling *Amaranthus tuberculatus*	Soltani et al. (2023)
Conservation agricultural practices in maize-wheat-mung bean rotation	Ghosh et al. (2023)

11. Emerging Technologies for Weed Seed Bank Depletion

11.1. Ryegrass integrated management

Ryegrass integrated management (RIM) is an Australian-developed software tool that enables users to explore various combinations of weed management strategies and their expected effects on ryegrass population, crop yield, and long-term economic results (Tidemann et al., 2016). It includes a broad range of both chemical and non-chemical treatment options, allowing for the identification of effective substitutes as certain herbicides become ineffective due to resistance (Anonymous, 2010).

11.2. Weed seed wizard

The weed seed wizard is an interactive software system developed in Australia that offers insights into the concealed weed seed bank and aids in the strategic long-term management of weeds (Borger et al., 2018). This tool allows users to simulate various paddock or weed management strategies, demonstrating how these choices affect both the current and projected seed bank and weed population. In contrast to Ryegrass Integrated Management, the weed seed wizard encompasses a broader array of weed species, offers a more comprehensive representation of dormancy and weed ecology, and enables predictions based on real weather data and soil information for specific seasons (Anonymous, 2010).

11.3. Gene drive

Weed scientists can look to other fields for innovative seed management strategies. For example, entomologists employ gene drives to spread recessive sterility traits within mosquito populations; a comparable strategy could be adapted for weeds to reduce their overall fitness. Although gene drives have been suggested as a means to increase herbicide sensitivity (Conner and Jacobs, 2025), they may also be utilized to induce seed sterility, thereby decreasing the number of viable seeds in the soil seed bank. Additionally, gene drives could enable the inheritance of traits that make weed seeds more visible to robots. Focusing on seed dormancy genes presents a viable strategy to reduce seed fitness (Kumar et al., 2025). The use of CRISPR/Cas9 to target these genes thereby integrating them into gene drives, it may be possible to reduce the weed seeds' ability to germinate under favourable conditions. Additionally, targeting genes responsible for seed shattering could be effective, as this trait distinguishes wild plants from domesticated ones (Dong and Wang, 2015). Eliminating the seed-shattering trait could significantly help in curbing the spread of weeds in agricultural areas. Yu-Liang et al. (2022) opined that modifying either the sh4 or qSH1 shattering genes, or both, significantly decreased the seed shattering capability of the weedy rice line (C9) that initially exhibited strong shattering. This approach could effectively disrupt the abundance of the weed seed bank.

11.4. Nanotechnological interventions

A significant use of nano pesticides is the reduction of the weed seed reserve (Adarsh et al., 2024). Bindu et al. (2023) reported that, carbon nanotubes effectively destroy weed seeds rather than targeting seedlings. These nanotubes create cracks in the seed coat, facilitating the entry of water and chemicals, which breaks seed dormancy and accelerate germination, often cutting the germination period in half. Additionally, nano herbicides help combat perennial weeds by targeting their underground structures, like rhizomes and tubers, which are essential for their rapid propagation. The use of encapsulated glyphosate combined with iron oxide, silver, and titanium oxide nanoparticles effectively inhibited the secondary tuber formation of *Cyperus rotundus* over a 40-day observation period (Viji and Chinnamuthu, 2015).

Nanotechnology is an advanced technique for depleting the weed seed bank even in rainfed ecosystems (Chinnamuthu and Boopathi, 2023). The nano-encapsulated herbicides can be released in a controlled manner so that the weed competition can be mitigated successfully. These formulations distribute more efficiently under adequate moisture levels in rainfed environments. The release of Pend-CuCts (Pendimethalin-Copper Chitosan) nanoparticles was highest in an acidic medium with a pH of 5.5, while the lowest release occurred in a neutral pH of 7 (Itodo et al., 2017).

12. Conclusion

The weed seed bank acted as a reservoir of seeds within soil layers, enabling weeds to persist and germinate under favourable conditions. Effective management required integrated strategies such as tillage, mulching, herbicide application, etc., which reduced seed accumulation in the soil. Sustainable approaches like cover cropping and crop rotation suppressed weed germination and improved crop productivity. However, their implementation required strong agroecological knowledge. Minimizing the seed bank can facilitate enduring weed management and diminish the likelihood of herbicide-resistant weed biotypes.

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