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REVIEW ARTICLE

Emerging weed management techniques in agriculture: Harvest weed seed control, weed-tolerant cultivars and foam weed control

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ABSTRACT

Innovative approaches in weed management, namely harvest weed seed control (HWSC), weed-tolerant cultivars, and foam weed control, address the challenges posed by herbicide-resistant weeds and promote sustainable weed management. Firstly, HWSC offers a promising avenue for reducing weed populations and preserving the efficacy of herbicides. Methods such as chaff carts, chaff tramlining and chaff lining, narrow windrow burning, harrington seed destructor, and bale direct systems facilitate the collection and destruction of weed seeds at harvest. It disrupts the weed life cycle by destroying weed seeds before they return to the soil. Chaff tramlining and chaff lining, and narrow windrow burning are widely practiced in Australia and the USA due to their efficiency and economic feasibility. In contrast, bale direct systems and chaff carts may gain traction in developing countries where straw serves as livestock fodder. Secondly, weed-tolerant cultivars offer natural and sustainable weed control by leveraging rapid early growth, efficient canopy development, and allelo-chemicals to inhibit germination and suppress weed growth. However, these approaches pose challenges, including environmental specificity, trade-offs with crop yield, soil fertility, genetic diversity concerns, allelopathic effects, varietal selection challenges, and long-term stability. Thirdly, foam weed control enhances herbicide adhesion, reduces drift, and improves coverage. Mixing foam with hot water ensures efficient heat transfer to targeted plant tissues without dissipation into the atmosphere. However, its efficiency depends on factors such as the choice of foaming agent, foam concentration, foam persistence, water quality, application equipment, environmental conditions, weed species, growth stage, and application rate.

Keywords: Bale direct system, Chaff carts, Harrington seed destructor, Narrow windrow burning, Weed competitive cultivars, Weed suppressive cultivars

INTRODUCTION

In modern agriculture, the effective management of weeds is crucial for optimizing crop yield and sustaining agricultural productivity. Weeds significantly threaten crop yield and resource utilization by competing for essential resources such as water, nutrients, and sunlight (Saravanane *et al*. 2020, Ramesh *et al*. 2022). Among the pests, weeds cause maximum yield losses (Gharde *et al*. 2018), and the problem of weeds is exacerbated by modern farming practices, such as monoculture, fertilizer application, and the use of heavy machinery, which create ideal conditions for weed growth and spread (Gawêda *et al*. 2020). Traditional weed control methods often rely on herbicides, but their environmental impact and the evolution of herbicide-resistant weeds have made it difficult to control weed populations, further complicating this problem (Qasem 2013, Schütte *et al*. 2017, Bhullar *et al*. 2017). The phenomenon of herbicide-resistant weeds has exhibited notable and accelerating proliferation in recent decades. On a global scale, a total of 269 distinct herbicide-resistant weed species, further categorized into 154 dicots and 115 monocots, have been documented within 99 diverse crop types spanning 72 countries (Heap 2023).

Harvest weed seed control (HWSC) stands as a ground breaking concept in contemporary agriculture, offering a strategic and sustainable approach to weed management (Walsh and Powles 2014, Walsh 2018, Soni *et al*. 2020). The roots of the HWSC can be traced back to the late 20th century, emerging as a response to the alarming rise of herbicide-resistant weeds and escalating concerns regarding environmental sustainability (Bhullar *et al*. 2017). Australian agricultural researchers pioneered this concept, developing innovative strategies to target and eliminate weed seeds during the harvest process (Walsh 2018). The primary objective was to disrupt the weed life cycle by intercepting and destroying seeds before they could be returned to the soil, thereby curbing the propagation of herbicide-resistant weeds (Walsh and Powles 2014). By

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intercepting and either destroying or removing weed seeds during harvest, the HWSC disrupts the natural replenishment of the soil seedbank (Vijayakumar *et al*. 2022). This targeted approach has proven effective in mitigating herbicide resistance and reducing the overall reliance on chemical weed control methods, contributing to sustainable and environmentally conscious farming practices.

Another modern approach is the cultivation of weed-tolerant cultivars. Weed tolerance is the ability of a cultivar to maintain a high yield despite weed competition. In recent years, the focus has shifted toward exploiting the inherent abilities of certain cultivars that exhibit weed-competitive or weed-suppressive traits (Moukoumbi *et al*. 2011, Pooja *et al*. 2021a). These cultivars are specifically bred or selected for their ability to outcompete or suppress weed growth (Beckie *et al*. 2008, Chaudhari *et al*. 2014). This method harnesses natural processes to reduce weed pressure in fields and eliminates the need for synthetic herbicides, contributing to sustainable and ecologically responsible farming practices (Hoad *et al*. 2008, Moukoumbi *et al*. 2011, Pooja *et al*. 2021a). Thus, the screening process for identifying cultivars with superior weed competitiveness and suppression capabilities will play a pivotal role in enhancing agricultural resilience and fostering environmentally friendly farming systems (Langeroudi and Kamkar 2009).

Another approach to overcome the challenges of weeds in contemporary agriculture is foam weed control. Thermal weed control has emerged as an appealing alternative to chemical methods, and it is poised to play a crucial role in developing efficient and environmentally friendly weed management strategies (Mia *et al*. 2020). Flaming, hot water, and steaming are extensively investigated thermal methods, with a notable challenge being the dissipation of heat into the atmosphere rather than exclusively targeting weeds (Peerzada and Chauhan 2018). To address this, there is a growing interest in novel and more targeted thermal control methods. Foam weed control utilizes a mixture of foaming agents and hot water for targeted application. This approach minimizes heat loss to the surrounding air, ensuring effective weed control.

Several other techniques have been developed to control weeds in agriculture, including robotic weed control and unmanned aerial vehicles (UAVs). Numerous review articles are available on robotic weed control and precision weed control using UAVs. However, there are limited reviews available on HWSC, weed-tolerant cultivars, and foam weed control. The evolving nature of agriculture necessitates a continuous and comprehensive review of these promising methods and their outcomes. This will offer opportunities for the refinement and improvement of these technologies. Therefore, this review focuses specifically on these less-explored methods, HWSC, weed-tolerant cultivars, and foam weed control, emphasizing the potential benefits and associated challenges.

Harvest weed seed control

HWSC is a non-chemical method of weed control that involves the collection and/or destruction of weed seeds at harvest. This process involves a combination of cultural and mechanical management practices, all of which are designed to curtail the replenishment of weed seeds in the soil seedbank (Walsh and Powles 2014, Vijayakumar *et al*. 2022). This approach helps combat the resistance of weeds to non-selective herbicides. Herbicide-resistant weeds are the primary goal of the HWSC in Australia and North America (Walsh and Powles 2014). Tall and upright weeds that mature with crops and retain seeds until harvest are ideal targets for HWSC technologies. HWSC is applicable across a range of crops, with notable success in cereals, oilseeds, and pulses (Beam *et al*. 2019, Bitarafan and Andreasen 2020). The versatility of HWSC methods allows farmers to tailor the approach to specific crops, providing a targeted and effective means of weed control. The adaptability of the HWSC across different crops underscores its potential to become a standard practice in modern agriculture. HWSC encompasses various management practices, including the use of chaff carts, chaff tramlining and chaff lining, narrow windrow burning, the Harrington Seed Destructor (HSD), and the Bale Direct Systems (BDS). The fundamental principle behind the HWSC is that targeted weed species retain a significant proportion of their seeds at maturity. Research indicates that HWSC practices achieve substantial weed seed destruction, ranging from 75% to 99% at harvest (Walsh and Powles 2014).

Chaff tramlining and chaff lining: Directing chaff into narrow rows on specific wheel tracks during harvest is termed chaff tramlining, while directing chaff into thin rows between stubble rows is called chaff lining. These methods utilize a mulching effect to inhibit weed seed germination and emergence by concentrating the chaff material, creating an environment unsuitable for germination (Walsh *et al*. 2017). Instead of killing weed seeds, chaff lining condenses them into a much smaller area, reducing their presence in the field to less than 10% of its original extent. For these methods to be effective, the chaff lines must remain undisturbed by tillage or other field activities, as any disruption can allow weed seedlings to emerge. Walsh *et al.* (2020) reported that while chaff lines did not impact the survival of weed seeds, high quantities of chaff (>40,000 kg/ha) significantly restricted the emergence of weed plants. For every 1,000 kg/ha increase in chaff material, there was an approximately 2.0% reduction in the emergence of weeds, including rigid ryegrass, wild oat, annual sowthistle, and turnip weed, indicating a linear relationship. This relationship held true across different types of chaff from wheat, barley, canola, and lupin, suggesting that the amount of chaff, rather than its type, was the critical factor.

In contrast, Ruttledge *et al.* (2018) reported that wheat chaff had a greater suppressive effect on the emergence of annual ryegrass seedlings than barley chaff. This difference could be attributed to structural or chemical (allelopathic) variations between the chaff types. This method is most effective for crops that generate significant chaff or crop residue, such as wheat, rice, and corn, which typically produce more than 5 tons per hectare, as this method requires the concentration of large quantities of chaff material. Consequently, this technique may not be suitable for smaller-scale millers or for crops such as pulses that produce less chaff residue. Chaff lining and chaff tramlining have the potential to be widely adopted in northern Australia because they are relatively inexpensive and easy to implement. This is the second most commonly used HWSC method in Australia, following narrow windrow burning. It was recently estimated that 24% of Australian growers were using these techniques (Kondinin-Group 2020).

Narrow windrow burning: It is an efficient and cost-effective HWSC tactic. This approach employs a chute mounted on the rear of the combine, directing all the chaff into a narrow row, typically 16 to 18 inches wide. According to Lyon *et al.* (2016), the windrow width should be no more than 10% of the header width or 3 feet for a header that is 30 feet wide. These rows are subsequently burned with lower fire risks and fewer smoke issues compared to burning chaff heaps (Walsh and Powles 2022). The concentration of chaff in windrows results in higher temperatures and longer burning durations, leading to less residue loss and more effective weed seed destruction compared to burning the entire field (Walsh and Newman 2007, Lyon *et al.* 2016). The crop should be harvested close to the soil to increase the amount of crop residue that ends up in the windrow. In soybean, narrow windrow burning resulted in a 73% reduction in escaped *Amaranthus palmeri* and a 62% decrease in the soil seedbank over three years (Schwartz-Lazaro *et al.* 2017). Another study by Norsworthy *et al.* (2020) reported 100% control of Palmer amaranth, Johnson grass, barnyard grass, and pitted morning-glory seeds present in soybean crop residues. Most weed species can be killed when the windrow reaches 400°C to 500°C for 10 to 30 seconds; however, certain weeds, including crabgrass, can be killed when exposed to 85°C for 20 seconds (Hoyle and McElroy 2012, Walsh and Newman 2007).

This method has emerged as Australia's most popular HWSC system due to its high effectiveness and low cost (Walsh *et al.* 2017). The use of narrow windrow burning for weed seed control has significantly increased in Australia, with an estimated 30% of growers currently employing this technique. However, adoption rates are particularly high in Western Australia, reaching a notable 50% (Walsh and Powles 2022). This reflects a doubling of utilization since 2000 when only 21% of Western Australian growers used the method. This increasing popularity highlights the growing awareness of the effectiveness of narrow windrow burning for weed management. These systems exhibit a decline in performance when the moisture content of crop residues exceeds 12% (Schwartz-Lazaro *et al.* 2017). Similarly, cooler and damper post-harvest environmental conditions, along with stricter regulations on smoke hazards, restrict the use of narrow windrow burning systems. Before setting the fire, ensure that the windrow is dry and free of dew. Windy or dry days should be avoided because they pose a risk.

Bale direct systems: The BDS involves connecting a baler directly to the combine and transforming chaff expelled by the harvester into bales. This approach captures weed seeds without spreading them in the field, and the resulting bales can serve as fodder for livestock. Walsh and Powles (2007) demonstrated that the BDS method can effectively collect and remove up to 95% of annual ryegrass seeds from fields. However, this method has limitations, including a limited market for baled products and the potential risk of disseminating resistant weed seeds to other fields (Walsh *et al.* 2017).

Chaff cart: In this method, a chaff gathering and transfer system is connected to a combine harvester to direct weed seeds into a bulk collection container, enabling the simultaneous collection and extraction of both chaff and weed seeds from the field. The cart can be unloaded on the field edges once it has filled up. Afterward, farmers have the option of using the chaff for animal feed or burning the stacks of chaff to entirely eradicate the weed seeds. Given that crop residue is utilized as animal feed in Asia, this approach may be more suitable for Asia. However, if animals graze on chaff heaps, they may spread weed seeds (Vijayakumar *et al.* 2022). The chaff cart, which is attached behind the already sizable harvester, poses challenges in maneuvering within smaller fields. The challenge of managing large volumes of collected chaff has been the primary reason for the low adoption of this approach (Walsh *et al.* 2017). The burning of collected chaff to kill weed seeds carries a high risk of fires spreading beyond control. These slow-burning piles can be smolded for days, posing a significant fire hazard and creating severe smoke pollution (Walsh *et al.* 2022).

Harrington seed destructor: The HSD is a trailer-mounted cage mill equipped with chaff transfer systems developed by Australian agricultural experts, Ray Harrington, in 2005. It mechanically damages weed seeds at harvest. During commercial wheat, barley, and lupin crop harvest, HSD can kill up to 95% of the seeds of annual ryegrass, wild radish, and wild oats (Walsh *et al.* 2012; Walsh and Powles 2014). Studies in the US and Canada have confirmed that these machines can destroy more than 95% of seeds from major weed species, such as rice (barnyard grass and weedy rice), cereals and oilseeds (Italian ryegrass and wild oats), and soybean (Palmer amaranth and waterhemp) (Schwartz-Lazaro *et al.* 2017, Tidemann *et al.* 2017). Jacobs and Kingwell (2016) evaluated the economic value of the HSD within integrated weed management strategies. Their findings demonstrated that HSD provided greater returns than many other weed management strategies, particularly in scenarios involving non-selective herbicide resistance and large areas of high-yielding crops. The likely lower capital cost of HSD will enable its widespread adoption for weed control.

Constraints and challenges for the adoption of HWSC in Asia: The reasons for the selective adoption of the HWSC in Australia and the USA compared to Europe and Asia (Beam *et al.* 2019) are as follows.

Equipment requirements: HWSC typically requires specialized equipment, such as chaff carts, impact mills, or narrow-windrow burning systems, to effectively collect and destroy weed seeds. These machines are relatively expensive to purchase and maintain (Vijayakumar *et al.* 2022). Across Asia, farmlands are typically small and fragmented, which limits the potential for widespread mechanization. Mechanization in this region primarily targets tasks such as land preparation, planting, and harvesting (Vijayakumar *et al.* 2021a). Despite significant yield losses due to weeds, mechanized weed control has not gained much traction. The availability of cheap labour makes manual weeding the predominant practice. Although herbicide use is on the rise, herbicide resistance has not yet become a major concern. HWSC equipment has been primarily developed to address herbicide-resistant weeds. The lack of herbicide-resistant weeds, the high cost of HWSC equipment, the lack of suitable conditions on farms for easy movement, and the availability of human labour contribute to the lower adoption of HWSC in this region.

Cost-benefit ratio: Few studies have evaluated the cost-benefit ratio of HWSC in Australia, and no such studies are available for other regions, including Europe and Asia. Seed mills and narrow windrow burning are the most expensive options. Chaff carts are somewhat less expensive. Chaff lining is the least expensive option. Some studies have assessed the potential for HWSC in the USA and Europe, concluding that HWSC holds promise in specific cropping systems and regions within these countries (Akhter *et al.* 2023). The economic viability of the HWSC may vary depending on the specific farm and weed situation. The cost of implementing HWSC practices needs to be justified by the benefits gained in terms of weed seed reduction and long-term weed management. Currently, the implementation cost of HWSC is very high and cannot be justified by the benefits gained in terms of weed control in Asia (Vijayakumar *et al.* 2022). More research is needed to assess the economic feasibility of the HWSC in different cropping systems and regions.

Environmental impact: Burning crop residue has environmental impacts, resulting in concerns about air quality and the release of greenhouse gases (Vijayakumar *et al.* 2024). Additionally, frequent movement of these vehicles could create a hardpan in the soil and create problems for subsequent crops in the system. These factors contribute to its limited adoption in areas with strict environmental regulations.

Nutrient loss and fire risk: Burning crop residue leads to a loss of organic matter and nutrients. Most nitrogen is lost due to burning, while most potassium remains, albeit concentrated in a row (Vijayakumar *et al.* 2024). Windrow burning of crop residue may not be possible if the crop in the neighboring field is prone to fire or heat.

Alternate use of crop residue: In India and several other Asian countries, crop residues are commonly used as cattle fodder. Farmers without cattle often sell their crop residues to those who do, as straw commands a good price. However, the availability of dry fodder in the country is insufficient to meet the actual demand. Consequently, burning crop residue is neither viable nor economically feasible (Vijayakumar *et al*. 2021b).

Weed seed retention: High seed retention by a weed at harvest is a prerequisite for successful HWSC. Some weed species have mechanisms for seed shattering, making it difficult to collect and contain all weed seeds during harvest and reducing the overall effectiveness of HWSC (Schwartz-Lazaro *et al*. 2017). Seed production and retention by different weed species and their potential for HWSC are presented in **Table 1**.

Table 1. Seed production and retention by weeds and their potential for HWSC

Weed species	Seed retention (%)	Seeds/plant	HWSC potential	Reference
Secale cereale	49-61	-	Intermediate	Lyon *et al* (2019)
Bromus tectorum	25-87	10-6000	Low to high	
Lolium multiflorum	27-50	300	Intermediate	
Vulpia myuros	11-90	1000-1700	Low to high	
Aegilops cylindrica	>75	130-3000	High	Walsh (2018)
Avena fatua	69-84	250-500	High	Walsh and Powles (2014)
Bromus tectorum	<50	20,500-45,000	Intermediate	San Martín *et al* (2021)
Lolium perenne				
Lolium ssp. *multiflorum*				
Secale cereale	>50	485	Intermediate	
Bromus tectorum	75±2.9	10-6000	High	Soni *et al* (2020)
Secale cereale	90±1.7	485		
Aegilops cylindrica	76±4.3	130-3000		
Lolium multiflorum	63	5-10,000	Intermediate to high	(Walsh and Powles 2014)
Raphanus sativus	79			
Amaranthus palmeri	98	100,000-600,000	High	Schwartz-Lazaro *et al*. (2017)
Echinochloa crus-galli	41	31987	Intermediate	
Brassica napus	>95	543-14773	Very high	Tidemann *et al* (2017)
Echinochloa colona	42 to 56	394	Intermediate	Mahajan *et al* (2017)
Chloris virgata	67 to 75	90,030-143,180	High	
Ambrosia trifida	80	500-5,000	High	Goplen *et al* (2016)
Anagallis arvensis L.	61.6	293-428	Intermediate	Bitarafan and Andreasen (2020)
Capsella bursa-pastoris L.	52.7	1,460-7,444	Intermediate	
Chenopodium album L.	67.2	1876-4,910	Intermediate	
Geranium molle L.	58.4	117	Intermediate	
Persicaria maculosa	32.1	311-413	Low	
Polygonum aviculare L.	59.5	549-1,514	Intermediate	
Silene noctiflora L.	95.7	102-539	Very high	
Sonchus arvensis L.	23.5	460-1,954	Low	
Veronica persica	51.7	90-511	Intermediate	
Viola arvensis	33.9	22-203	Low	
Fallopia convolvulus	44	260	Intermediate	Bitarafan and Andreasen (2020a)
Sinapis arvensis	67	195	Intermediate	
Spergula arvensis	45	411	Intermediate	
Stellaria media	56	316	Intermediate	
Echinochloa crus-galli	75	31987	High	Vijayakumar *et al* (2023)
Lolium multiflorum	80	-	High	Broster *et al* (2015)
Kochia scoparia	99.8	100,000	Very high	Friesen *et al* (2009)
Galium spp.	74	300-400	High	Burton *et al* (2016);
Sinapis arvensis L.	70	2,000-3,500	High	Beckie *et al* (2017)
Polygonum convolvulus	82	12,000	High	Burton *et al* (2017)
Setaria viridis	94	34,000	Very high	Beckie *et al* (2017)
Sorghum halepense	96		Very high	Walsh (2018)
Amaranthus palmeri	91		Very high	
Amaranthus tuberculatus	88		High	
Kochia scoparia	100	14,600	Very high	Burton *et al* (2016); Tidemann *et al* (2017)
Lolium rigidum	85	-	High	(Walsh and Powles 2014)
Raphanus raphanistrum	99	160-1,875	Very high	

Integration with other practices: To achieve the best results, the HWSC should be integrated with other weed management practices, such as herbicide programs, crop rotation, and cultural practices. The adoption of HWSC practices requires education and training for farmers, as it represents a change in traditional harvest practices. Farmers need to understand the benefits and best practices associated with HWSC.

Weed tolerance cultivars

Weed tolerance in crops is achieved through two mechanisms, namely, weed suppressiveness and weed competitiveness.

Weed competitive cultivars: Weed competitive cultivars (WCCs) are specifically bred or selected for their ability to outcompete weeds for essential resources such as light, water, and nutrients (Ni *et al.* 2000, Phuhong *et al.* 2000, Norsworthy and Shipe 2006, Pooja *et al.* 2021a). These cultivars are designed to be taller and more vigorous than weeds to curtails their growth and competitive abilities. It leverages traits such as rapid early growth, efficient canopy development, and enhanced root systems to establish dominance in the early stages of crop growth, which in turn results in reduced weed establishment, competition, and improved crop yields (Ogg and Seefeldt 1999, Phuhong *et al.* 2000, Zhao *et al.* 2006, Zhao *et al.* 2007). Varieties that establish a canopy more quickly tend to occupy space first, reducing the impact of weed competition, as they suppress and weaken late-emerging weeds (Dass *et al.* 2017). Thus, the competitive advantage of WCCs stems from their ability to create a canopy that shades and suppresses weed growth, limiting their access to sunlight (Ni *et al.* 2000, Mwendwa *et al.* 2020). Additionally, the vigorous root systems of the WCC effectively compete for soil nutrients and water, further stalling weed proliferation. As a result, the need for additional weed control measures, including herbicides, is diminished, contributing to sustainable and cost-effective farming practices (Phuhong *et al.* 2000).

Weed suppressive cultivars: Weed suppressive cultivars (WSCs) are specifically bred or selected for their ability to suppress the growth of weeds through the production of allelochemicals that inhibit the growth of neighboring plants, including weeds (Khanh *et al.* 2007, Jamil *et al.* 2011). WSCs go beyond mere competition; they actively release substances known as allelochemicals into the soil, which hinder the germination and growth of neighboring weeds (Wicks *et al.* 2004, Shrestha *et al.* 2020). These allelopathic compounds can impede weed seed germination, root development, and overall growth, creating a weed-suppressive environment around the crop (Cheng and Cheng 2015). By directly inhibiting weed growth through chemical interactions, these cultivars offer an additional layer of defense against weed encroachment, complementing traditional weed control strategies (Kostina-Bednarz *et al.* 2023).

Attributes that contribute to weed tolerance in crops: For effective weed suppression, an ideal cultivar should possess several key traits, such as early and rapid establishment (seedling vigor), a large seed size that provides a food reserve, taller plant height, the ability to produce more tillers, strong root systems, a short growth duration, resilience to various biotic and abiotic stresses, and the production of allelochemicals (Zhao *et al.* 2006, Gibson *et al.* 2003). The rapid development of a large canopy with increased photosynthetic area, greater LAI, and improved root growth in terms of dry root weight, length, and volume are positively associated with the ability of crops to compete against weeds (Ni *et al.* 2000, Mason and Spaner 2006). High seedling vigor, which reflects the ability of plants to establish quickly and vigorously, plays a pivotal role in reducing the risk of weed seedling emergence and growth (Dass *et al.* 2017). Similarly, cultivars with greater root shoot characteristics have a competitive advantage in light, water, and nutrient resource acquisition, enabling them to attain greater height and grow faster.

The competition between crops and weeds becomes particularly intense when the root system, morphology, and growth pattern of weed species closely resemble those of crop plants. Moreover, crop germination and plant population significantly influence a cultivar's tolerance to weeds. Poor crop stands, often resulting from inadequate and uneven germination, lead to reduced soil coverage and increased weed pressure. The general rule is that the plant that germinates first in the field will occupy the most space by capturing the maximum amount of both below- and above-ground growth resources. Consequently, all management practices carried out in the field aim to ensure that crop plants germinate first and dominate the system. However, certain conditions, such as heavy rainfall immediately after sowing, poor or delayed seed germination due to poor seed quality or higher sowing depth, uneven land leveling, or poor irrigation management, can favor weed germination and growth over crop plant germination. Studies by Olsen (2012) and Marin and Weiner (2014) have shown that improving plant stand uniformity, in conjunction with increasing planting densities, significantly reduces weed biomass and enhances yields across several crops.

Weed-tolerant rice cultivars: Rice varieties with strong weed competitiveness have been identified in different regions. For example, in the Philippines, Apo and UPLRi-7 exhibit rapid seedling establishment and early accumulation of plant biomass, providing them with a competitive advantage against weeds (Zhao *et al.* 2006). In Latin America, *Oryzica sabana* 6 stands out due to its larger leaf area index (LAI) and higher tiller density, enabling it to intercept more light and compete more effectively with weeds (Fischer *et al.* 2001). In North America, M-202 exhibits a larger photosynthetic area and greater below-ground biomass, contributing to its ability to outcompete weeds (Gibson *et al.* 2003). In DSR, seedling vigor plays a crucial role in reducing crop-weed competition in favor of the rice crop, as it facilitates the early and robust establishment of rice plants. In dry DSR systems cultivated in rainfed and upland provinces of the tropics, greater seedling vigor in rice cultivars significantly limits weed growth and development (Hirao *et al.* 2008). Rice varieties exhibit rapid growth in the early seedling stage due to increased seedling vigor, rapid formation of a dense canopy, suppression of weeds, and increased yield by reducing the penetration of solar radiation through the leaf canopy (Fenner 1980). Thus, fast-growing rice cultivars have a distinct advantage in promoting ecological weed suppression and enhancing yields, particularly in rainfed regions (Kanbar *et al.* 2006).

Among the above-ground factors, competition for essential resources such as sunlight and CO_2 contributes to poor growth and lower yields in DSR (Fischer *et al.* 2001; Gibson *et al.* 2003, Ramesh *et al.* 2022). Weeds can reduce rice growth and yield through both shoot and root competition, with the latter resulting in 39-55% reductions in rice grain yield (Chauhan and Johnson 2010). The shading effect, primarily caused by excessive weed growth, significantly impacts the development of rice crop shoots, leading to a reduction in the production of dry matter and ultimately resulting in lower rice yields (Praba *et al.* 2004). Therefore, plant height is important for providing rice crops with advantages over weeds. However, there is a trade-off between plant height and lodging, with taller plants being more effective at suppressing weeds but also more prone to yield losses, especially in the case of transplanted rice. To suppress weeds in DSR, a relatively high seed rate is used (> 80 kg/ha to 200 kg/ha against 25 to 40 kg/ha for transplanted rice) in several countries, such as Cambodia, Vietnam, Laos, Thailand, Bangladesh, the Philippines, and India. However, there is a certain trade-off. For example, in the case of rice, farmers use seeds harvested from the previous season or year in their fields, which are of poor quality because they carry more weed seeds and a lower germination percentage. Higher seed rates also increase production costs, potentially exacerbating issues such as lodging, rodent damage, nitrogen deficiency, and insect and disease infection (Zhao *et al.* 2007).

Role of weed-tolerant cultivars in weed management: Crop rotation and intercropping systems that incorporate WCCs or WCSs enhance the resilience of agroecosystems (Gu *et al.* 2021). Farmers can strategically select and deploy cultivars that align with their specific weed management goals, creating a tailored and efficient approach. By diversifying plant species with varying weed management traits, farmers can disrupt weed life cycles and mitigate the development of herbicide-resistant weed populations. The use of WCCs and WSCs represents a compelling avenue for sustainable weed management. The global WCC and WSC reported for different crops are presented in **Table 2**.

Bottlenecks for the adoption of weed-tolerant cultivars: Although weed-competitive and weed-suppressive cultivars are environmentally friendly and economically viable alternatives to weed control, they may not be a one-size-fits-all solution (Ni *et al.* 2000, Fischer *et al.* 2001, Zhao *et al.* 2006). The feasibility of weed-tolerant cultivars may be limited when confronted with a wider range of weed species. WCC and WSC have demonstrated substantial control over specific weed species, but they may fall short in managing a broader spectrum of weeds in the field. Consequently, relying solely on weed-tolerant cultivars may not provide an optimal solution to weed management, but it can be one of several components of an integrated weed management strategy. Their success depends on various factors, including specificity, environmental conditions, crop yield trade-offs, management practices, crop type, cultivar, soil characteristics, seed rate or plant density, and timing and method of planting (Chauhan 2012).

Specificity: Agricultural fields often host a diverse range of weed species. Even if a cultivar is effective against one or a few weed species, it may not be able to manage the entire spectrum of weeds present in the field. Weeds that are not targeted by these cultivars can still thrive. Some weed species are highly competitive and may outcompete even the most competitive crop cultivars. In such cases, the crop may struggle to suppress or compete with other aggressive weed species for which the cultivar is not tolerant.

Yield trade-off: In some situations, highly competitive or suppressive cultivars may trade off some of their crop yield potential to achieve weed control (Moukoumbi *et al*. 2011, Chaudhari *et al*. 2014). Farmers may be unwilling to adopt these cultivars if they experience reduced crop yields.

Environmental factors: In addition, the effectiveness of these cultivars is influenced by environmental factors such as soil type, climate, and other local conditions. Effective weed control often requires a combination of methods, including cultural practices, herbicides, and mechanical control. Relying solely on weed-competitive or weed-suppressive cultivars may not be sufficient for comprehensive weed management.

Table 2. Weed competitive and suppressive cultivars reported globally in different crops

Crop	Cultivar	Target weed	Reference
Canola & mustard	Yellow mustard Hybrid Canola (InVigor 2663, SW5001, 45H21, InVigor5030)	Natural weed infestations	Beckie *et al* (2008)
	Baudin, Hamelin, and Flagship	Natural weed infestations	Paynter and Hills (2009)
	GT-50, Hyola 600RR, Hybrid Hyola	Natural weed infestations	Langeroudi and Kamkar (2009)
	Hybrid (Hyola-50, Hyola-571CL, 45Y77), Cultivar (AV-Garnet), *B. juncea* (Dune)	*Lolium multiflorum*	Lemerle *et al* (2011)
	Canola cultivar (Zarfam)	*Sinapis arvensis*	Mwendwa *et al* (2020)
Corn	Early-maturing, leafy reduced stature and Pioneer hybrid (‘P3979’)	*Chenopodium album, Amaranthus retroflexus*	Begna *et al* (2001)
	Sweet corn (hybrid Rocker, hybrid Cahill)	*Panicum miliaceum*	Williams *et al* (2008)
	Pioneer 3260’ hybrid with a horizontal leaf architecture	Natural weed infestations	Sankula *et al* (2004)
Cotton	CS-B22sh	*Amaranthus palmeri*	Fuller *et al* (2021)
	Deltapine 16	*Anoda cristata*	Chandler and Meredith (1983)
Wheat	Tallness, superior early-season growth, increased leaf area and high tillering capacity	Natural weed infestations	Mason and Spaner (2006)
Rice	*Oryzica sabana* 6	*Brachiaria brizantha, B. decumbens*	Fischer *et al* (2001)
	M-202, S-201	*Echinochloa oryzoides, Echinochloa phyllopogon*	Gibson *et al* (2003)
	Apo and UPLRi-7		Zhao *et al* (2006)
	CG20	Natural weed infestations	Moukoumbi *et al* (2011)
	R-1033-968-2-1 and Kakro	Natural weed infestations	Chaudhari *et al* (2014)
	IR 84899-B-183-CRA-19-1 and CR Dhan 40	*Echinochloa colona, Trianthema portulacastrum, Physalis minia, Cyperus rotundus and Fimbristylis miliacea*	Kumar *et al* (2016)
	PI312777, PI338046, and RONDO B2 and B81 (weedy rice accessions)	*Echinochloa crus-galli, Leptochloa panicoides*	Shrestha *et al* (2020)
	IR5 or IR442-2-58; Prabhat and Krishna Hamsa	Natural weed infestations	Shekhawat *et al* (2020)
	Hybrid PHB 71, Prabhat, PR-120, IR88633, and IR83927		Mahajan *et al* (2014)
DSR,	PR 115 (125 days duration)	Natural weed infestations	Singh and Bhullar (2015)
Aerobic rice	ADT 46		Pooja *et al* (2021b)
Upland DSR	Vandana, Kalinga-III and RR-151-3	Natural weed infestations	ICAR (2007)
Soybean	Sharkey and Biloxi	*Senna obtusifolia*	Shilling *et al* (1995)
	Late maturing cultivars	Natural weed infestations	Nordby *et al* (2007)
	Short statured cultivars	*Xanthium strumarium*	Jordan (1992)
	Pioneer 96B21 and SC00–883	Natural weed infestations	Norsworthy and Shipe (2006)
Wheat	HD 3086, PBW 677, PBW 725, HD 2967, PBW 621 and PBW 550	Natural weed infestations	Bhullar *et al* (2017)
	PBW 343		Mahajan *et al* (2014)
	Tall spring cultivars, NE 78742, NE 78743	*Setaria viridis*, Summer Annual Weeds	Blackshaw *et al* (1981); Wicks *et al* (1986)
	Turkey, Arapahoe, Jules, Pronghorn and Vista	Annual Weeds	Wicks *et al* (2004)
	Taller, soft winter cultivars	*Aegilops cylindrica*	Ogg and Seefeldt (1999)

In terms of crop type, African rice (*Oryza glaberrima*) varieties have shown superior weed-smothering capabilities compared to *O. sativa*, as they possess a downward-tilted leaf configuration and a high specific leaf area (Johnson *et al.* 1998). Additionally, African rice cultivars are taller in structure than *O. sativa*. However, the low yield potential of African rice makes it impractical for large-scale cultivation.

Planting pattern: Growing weed-competitive cultivars in a paired-row planting pattern can improve the yield potential of aerobic rice cultivars and DSR (Mahajan and Chauhan 2011).

Seed rate: Increasing seeding rates beyond the optimal level can enhance a crop's ability to suppress weed growth and minimize yield losses, particularly in weedy situations (Ahmed *et al.* 2014, Phuhong *et al.* 2000). Increasing the rice density to 400 plants/m^2 significantly reduces seed production in *Rottboellia cochinchinensis* (Clayton *et al.* 2014).

Crop management: Under soil conditions characterized by resource scarcity, such as limited moisture, root competition between weeds and crops has a more pronounced negative impact than does competition among above-ground shoots. Under such circumstances, fertilizers applied during the early stages of crop growth are more likely to be intercepted by weeds than by the crop itself, resulting in the crop experiencing root competition.

Knowledge and expertise: Additionally, the use of WSCs and WCCs for weed control requires significant knowledge and expertise, as it depends on a deep understanding of the underlying processes (Pooja *et al.* 2021a, 2021b).

Foam weed control

The application of hot foam, a modification of hot water weed control patented in 1995, involves the use of biodegradable foaming agents, such as plant extracts or renewable oils, to control weeds more efficiently (Cederlund and Börjesson, 2016; Martelloni *et al.* 2019). Hot foam has been successfully used for weed control along railways in Sweden (Cederlund and Börjesson 2016). The distinctive advantage of foam lies in its ability to isolate weeds during treatment, ensuring exclusive heat transfer to targeted plant tissues without dissipation into the atmosphere. This foam-induced insulation not only shields weeds but also enhances energy transfer, resulting in reduced hot water usage and increased overall efficiency (Cederlund and Börjesson 2016). Foam innovatively delivers herbicides. Mixing foam ensures better adhesion and absorption onto weed foliage, reduces herbicide drift and unintended damage, and improves coverage, especially under challenging conditions (Cederlund and Börjesson, 2016; Antonopoulos *et al.* 2023).

Compared to using hot water alone, foam incorporation leads to reduced hot water usage, increased resilience to weather changes, and prolonged heat transfer duration (Peerzada and Chauhan, 2018). Challenging-to-control weeds such as *Cynodon dactylon*, *Digitaria sanguinalis*, *Taraxacum officinale*, and other species within the initial weed populations experienced complete mortality at lower doses of hot foam compared to hot water. The incorporation of foam into hot water treatment led to at least a 2.5-fold reduction in the hot water dose compared to the use of hot water alone (Martelloni *et al.* 2021). The insulating characteristics of the foam played a pivotal role, resulting in higher peak temperatures and a more gradual temperature decay. Consequently, weed control was more effective with reduced treatment doses than with hot water alone. The efficacy of hot foam was found to be satisfactory across a diverse range of broadleaf weeds, including those challenging to control through conventional methods (Antonopoulos *et al.* 2023).

Kup and Saglam (2014) compared the effectiveness of hot foam in weed control, specifically by targeting *Cynodon dactylon* and *Glycyrrhiza glabra* in a cotton field, to traditional methods such as spraying and hoeing. The results indicated destruction rates of 94.3%, 84.1%, and 82.5% for *Glycyrrhiza glabra* with the hoeing, spraying, and hot foam methods, respectively. For *C. dactylon*, the destruction rate was 95.1% for both the hoeing and foam methods, while spraying yielded a rate of 94.5%. The close similarity in destruction rates between hot foam and spraying methods suggests that hot foam is a viable alternative to traditional spraying methods (Kup and Saglam 2014). In another study, where hot foam was applied at a rate of 13.33 L/m^2, weed biomass significantly decreased by 81%, 88%, 90%, and 96% compared to that in the mulching, mowing, pelargonic acid, and untreated control treatments, respectively. The overall performance of hot foam was comparable to that of glyphosate (at a rate of 1,440 g/ha), positioning it as an environmentally friendly and effective alternative for weed control in olive groves (Antonopoulos *et al.* 2023). Using hot foam as a desiccant in no-till field bands before transplanting high-value vegetable crops delays weed regrowth by up to 30 days, providing vegetable crops with an extended establishment period free from weed competition (Martelloni *et al.* 2021). On average, it took 26–27 days for 90% of the ground to recover after treatment with hot foam (Martelloni *et al.* 2020). Foam primarily affects the above-ground portions of plants and is more effective at damaging the meristems of weeds. However, certain weeds, such as perennial weeds, may regrow from their below-ground components. Therefore, repeated applications of thermal control may be necessary to effectively manage such weeds (Kup and Saglam 2014, Peerzada and Chauhan 2018).

Factors influencing the efficiency of foam weed control: Various factors influence the efficiency of weed control when employing foaming techniques. These factors include the choice of foaming agent, its concentration (Martelloni *et al.* 2019), water quality, application equipment, environmental conditions (De Cauwer 2015), foam density, viscosity (Machdar *et al*. 2023), weed species, growth stage (Kup and Saglam 2014), foam persistence, and application rate (Martelloni *et al.* 2021). Careful consideration must be given to selecting foaming agents with diverse properties to achieve the desired foam stability, persistence, and adherence to weed surfaces. The concentration of the foaming agent plays a pivotal role in creating a stable foam that adequately covers weed surfaces without becoming overly diluted or concentrated (Martelloni *et al.* 2019). Water quality, including hardness, pH, and impurities, also affects foam stability. The choice of application equipment influences coverage and efficacy, with properly calibrated equipment ensuring a uniform distribution of foam. Weather conditions such as wind and temperature impact foaming performance, inducing drift and influencing stability (De Cauwer 2015). The physical properties of foam, such as density and viscosity, affect adherence to weed surfaces, necessitating optimal consistency for thorough coverage (Machdar *et al.* 2023).

Different weed species and growth stages exhibit varying responses to foaming treatments, with young, actively growing weeds being more susceptible (Kup and Saglam 2014). The surface characteristics of weeds, such as waxy or hairy coatings, influence foam adherence and penetration, with foams adept at overcoming these surface traits tending to be more efficient. The duration of foam stability on weed surfaces is crucial for prolonged contact time and enhanced heat transfer efficiency (Cederlund and Börjesson 2016). The rate of foam application influences coverage and, consequently, weed control efficiency, necessitating an appropriate application rate to ensure that sufficient foam reaches the target (Martelloni *et al*. 2021, Antonopoulos *et al.* 2023). The effectiveness of foam weed control primarily depends on the heat dose applied. An appropriate dosage can significantly improve overall efficiency (Cederlund and Börjesson 2016). The requisite level of heat varies depending on factors such as the weed species, growth stage, water status, and presence of moisture on leaf surfaces (Melander *et al.* 2017). Treating weeds every three weeks was twice as effective and energy-efficient as treating them every six weeks. Compared with the afternoon treatments, the morning treatments showed approximately half the sensitivity. Most weed species are six times more sensitive at 98°C than at 78°C and 88°C, particularly during early growth stages (De Cauwer 2015).

Interventions for scale foam weed control: To scale foam weeding, research and development efforts are crucial to optimize technology, including developing new foaming agents and refining application equipment. Comprehensive training and education for farmers on foam weeding techniques are essential for successful implementation. Facilitating the transfer of technology from research institutions to farmers is crucial, along with investing in infrastructure to seamlessly support foam weeding operations. Supportive policies and regulations promoting foam weeding adoption are necessary. Market development, including creating markets for foam weeding services and products, can stimulate demand and encourage scaling.

Conclusion

Weeds have been a challenge in agriculture since the inception of crop cultivation. Over time, the weed species causing yield losses and the methods adopted for weed control have evolved significantly. The most notable shift has been from manual weed control to herbicidal weed management, driven by labor scarcity, high wages, and the effectiveness of herbicides on young weeds. However, this shift has led to issues such as herbicide resistance and environmental pollution. Thus, modern weed management approaches now emphasize precision, ecological safety, and economic viability. This review discusses three modern technologies: HWSC, weed-tolerant cultivars, and foam weed control. HWSC is effective at managing herbicide-resistant weeds, while foam weed control improves the efficiency of thermal and herbicidal weed management. However, HWSC is prohibitively expensive for small and marginal farmers. Therefore, there is a need to develop lightweight, inexpensive, and easy-to-replicate HWSC equipment. Similarly, the efficiency of foam is affected by the weed growth stage, the type of foam used, and its concentration, water quality, *etc*.

Weed-tolerant cultivars reduce the impact of weeds on crop yields by harnessing inherent traits to enhance resource use efficiency and support sustainable farming practices. Selecting the right cultivars requires a deep understanding of local weed species, environmental conditions, and specific crop requirements. Finding cultivars with the desired weed-competitive or weed-suppressive traits can be challenging, and the available options may not provide a universal solution. Overall, incorporating weed-tolerant cultivars, HWSC, and foam weed control into integrated weed management strategies holds promise for managing herbicide-resistant weeds, reducing reliance on synthetic herbicides, and promoting sustainable agriculture. However, addressing these challenges is essential for optimizing the benefits of these strategies in diverse agricultural contexts, particularly for managing herbicide-resistant weeds and ensuring sustainable weed management.

REFERENCES

Ahmed S, Salim M and Chauhan BS. 2014. Effect of weed management and seed rate on crop growth under direct dry seeded rice systems in Bangladesh. *PLOS ONE* **9**(7): e101919. https://doi.org/10.1371/journal.pone.0101919

Akhter MJ, Sønderskov M, Loddo D, Ulber L, Hull R and Kudsk P. 2023. Opportunities and challenges for harvest weed seed control in European cropping systems. *European Journal of Agronomy* **142**:126639. https://doi.org/10.1016/j.eja.2022.126639

Antonopoulos N, Kanatas P, Gazoulis I, Tataridas A, Ntovakos D, Ntaoulis VN, Zavra SM and Travlos I. 2023. Hot foam: Evaluation of a new, non-chemical weed control option in perennial crops. *Smart Agricultural Technology* **3**: 100063. https://doi.org/10.1016/j.atech.2022.100063

Beam SC, Mirsky S, Cahoon C, Haak D and Flessner M. 2019. Harvest weed seed control of Italian ryegrass [*Lolium perenne ssp multiflorum* (Lam.) Husnot], common ragweed (*Ambrosia artemisiifolia* L.), and Palmer amaranth (*Amaranthus palmeri* S. Watson). *Weed Technology* **33**: 627–632. https://doi.org/10.1017/wet.2019.46

Beckie HJ, Blackshaw RE, Harker KN and Tidemann BD. 2017. Weed seed shatter in spring wheat in Alberta. *Canadian Journal of Plant Science* **98**(1): 107–114.

Beckie HJ, Johnson EN, Blackshaw RE and Gan Y. 2008. Weed suppression by canola and mustard cultivars. *Weed Technology* **22**(1): 182-185.

Begna SH, Hamilton RI, Dwyer LM, Stewart DW, Cloutier D, Assemat L and Smith DL. 2001. Weed biomass production response to plant spacing and corn (*Zea mays*) hybrids differing in canopy architecture. *Weed Technology* **15**(4): 647–653.

Bhullar MS, Kaur N, Kaur P and Gill G. 2017. Herbicide resistance in weeds and its management. *Agricultural Research Journal* **54**(4): 436–444.

Bitarafan Z and Andreasen C. 2020. Seed retention of ten common weed species at oat harvest reveals the potential for harvest weed seed control. *Weed Research* **60**(5): 343–352. https://doi.org/10.1111/wre.12438

Bitarafan Z and Andreasen C. 2020a. Harvest Weed Seed Control: Seed Production and Retention of *Fallopia convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *Stellaria media* at Spring Oat Maturity. *Agronomy* **10**: 46. https://doi.org/10.3390/agronomy10010046

Blackshaw RE, Stobbe EH and Sturko ARW. 1981. Effect of seeding dates and densities of green foxtail (*Setaria viridis*) on the growth and productivity of spring wheat (*Triticum aestivum*). *Weed Science* **29**(2): 212–217.

Broster J, Walsh M, Aves C and Powles S. 2015. Harvest weed seed control: Ryegrass seed retention levels in south-eastern Australia wheat crops. In 17th Proceedings of the Australian Agronomy Conference (pp. 1-4). Australian Society of Agronomy. http://agronomyaustraliaproceedings.org/images/sampledata/2015_Conference/pdf/agronomy2015final00204.pdf

Burton NR, Beckie HJ, Willenborg CJ, Shirtliffe SJ, Schoenau JJ and Johnson EN. 2016. Evaluating Seed Shatter of Economically Important Weed Species. *Weed Science* **64**(4): 673–682.

Burton NR, Beckie HJ, Willenborg CJ, Shirtliffe SJ, Schoenau JJ and Johnson EN. 2017. Seed shatter of six economically important weed species in producer fields in Saskatchewan. *Canadian Journal of Plant Science* **97**(2): 266–276.

Cederlund H and Börjesson E. 2016. Hot foam for weed control—Do alkyl polyglucoside surfactants used as foaming agents affect the mobility of organic contaminants in soil?. *Journal of hazardous materials* **314**: 312–317. https://doi.org/10.1016/j.jhazmat.2016.04.061

Chandler JM and Meredith WR. 1983. Yields of three cotton (*Gossypium hirsutum*) cultivars as influenced by spurred anoda (*Anoda cristata*) competition. *Weed Science* **31**(3): 303–307.

Chaudhari P, Patel A, Saxena RR and Verulkar SB. 2014. Evaluation of the relative weed competitiveness ability in upland rice cultivars. *Journal of Progressive Agriculture* **5**(2): 90–94.

Chauhan BS and Johnson DE. 2010. Opportunities to improve cultural approaches to manage weeds in direct-seeded rice. In: 17th Australasian Weeds Conference. New Zealand Plant Protection Society, Christchurch, New Zealand, pp. 40e43.

Chauhan BS. 2012. Weed ecology and weed management strategies for dry-seeded rice in Asia. *Weed Technology* **26**(1): 1–13.

Cheng F and Cheng Z. 2015. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. *Frontiers in plant science* **6**: 1020.

Clayton WD, Govaerts R, Harman KT, Williamson H and Vorontsova M. 2014. World Checklist of Poaceae. Royal Botanic Gardens, Kew, Richmond, UK. http://apps.kew.org/wcsp/.

Dass A, Shekhawat K, Choudhary AK, Sepat S, Rathore SS, Mahajan G and Chauhan BS. 2017. Weed management in rice using crop competition-a review. *Crop protection* **95**: 45–52. https://doi.org/10.1016/j.cropro.2016.08.005

De Cauwer B, Bogaert S, Claerhout S, Bulcke R and Reheul D. 2015. Efficacy and reduced fuel use for hot water weed control on pavements. *Weed Research* **55**(2): 195–205. https://doi.org/10.1111/wre.12132

Fenner M. 1980. The inhibition of germination of *Bidens pilosa* seeds by leaf canopy shade in some natural vegetation types. *New Phyto*logist **84**: 95e101.

Fischer AJ, Ramirez HV, Gibson KD and Da Silveira Pinheiro B. 2001. Competitiveness of semidwarf upland rice cultivars against palisadegrass (*Brachiaria brizantha*) and signalgrass (*B. decumbens*). *Agronomy Journal* **93**(5): 967–973.

Friesen LF, Beckie HJ, Warwick SI and Van Acker RC. 2009. The biology of Canadian weeds. 138. *Kochia scoparia* (L.) Schrad. *Canadian Journal of Plant Science* **89**(1): 141–167.

Fuller MG, Saha S, Stelly DM, Jenkins JN and Tseng TM. 2021. Assessing the weed-suppressing potential of cotton chromosome substitution lines using the stair-step assay. *Plants* **10**(11): 2450.

Gawêda D, Haliniarz M, Bronowicka-Mielniczuk U and £ukasz J. 2020. Weed infestation and health of the soybean crop depending on cropping system and tillage system. *Agriculture* **10**(6): 208. https://doi.org/10.3390/agriculture10060208

Gharde Y, Singh PK, Dubey RP and Gupta PK. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107**: 12–18. https://doi.org/10.1016/j.cropro.2018.01.007

Gibson KD, Fischer AJ, Foin TC and Hill JE. 2003. Crop traits related to weed suppression in water–seeded rice (*Oryza sativa* L). *Weed Science* **51**(1): 87–93.

Goplen J, Sheaffer C, Becker R, Coulter J, Breitenbach F, Behnken L and Gunsolus J. 2016. Giant Ragweed (*Ambrosia trifida*) Seed Production and Retention in Soybean and Field Margins. *Weed Technology* **30**(1): 246–253. https://doi.org/10.1614/WT-D-15-00116.1

Gu C, Bastiaans L, Anten NP, Makowski D and van Der Werf W. 2021. Annual intercropping suppresses weeds: A meta-analysis. *Agriculture, Ecosystems & Environment* **322**: 107658.

Hirao K, Kubota F, Agata W and Song Fu X. 2008. Characteristics of leaf photosynthesis in Chinese F1 hybrid cultivar Shanyou 63. *Japanese Journal of Crop Science* **64**: 209e215.

Hoad S, Topp C and Davies K. 2008. Selection of cereals for weed suppression in organic agriculture: a method based on cultivar sensitivity to weed growth. *Euphytica* **163**: 355–366.

Hoyle J and McElroy J. 2012. Relationship between temperature and heat duration on large crabgrass (*Digitaria sanguinalis*), Virginia buttonweed (*Diodia virginiana*), and cock'scomb kyllinga (*Kyllinga squamulata*) seed mortality. *Weed Technology* **26**: 800–806.

ICAR. 2007. Vision 2025. NRCWS Perspective Plan. Indian Council of Agriculture Research, New Delhi, India.

Jacobs A and Kingwell R. 2016. The Harrington Seed Destructor: Its role and value in farming systems facing the challenge of herbicide-resistant weeds. *Agricultural Systems* **142**: 33–40.

Jamil M, Charnikhova T, Cardoso C, Jamil T, Ueno K, Verstappen F, Asami T and Bouwmeester H. 2011. Quantification of the relationship between strigolactones and *Striga hermonthica* in rice under varying levels of nitrogen and phosphorus. *Weed Research* **51**: 373e385.

Johnson DE, Dingkuhn M, Jones MP and Mahamane MC. 1998. The influence of rice type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*. *Weed Research* **38**: 207e216.

Jordan N. 1992. Differential interference between soybean (*Glycine max*) varieties and common cocklebur (*Xanthium strumarium*): a path analysis. *Weed Science* **40**(4): 614–620.

Kanbar A, Janamatti M, Sudheer E, Vinod MS and Shashidhar HE. 2006. Mapping QTLs underlying seedling vigour traits in rice (*Oryza sativa* L.). *Current Science* **90**: 24e26.

Khanh TD, Xuan TD and Chung IM. 2007. Rice allelopathy and the possibility for weed management. *Annals of Applied Biology* **151**: 325e339.

Kondinin Group. 2020. Harvest weed seed control: weed seed warriors. No. 121. Kondinin Group, Perth, WA, Australia. Available at https:// www.farmingahead.com.au/category/research-reports.

Kostina-Bednarz M, P³onka J and Barchanska H. 2023. Allelopathy as a source of bioherbicides: challenges and prospects for sustainable agriculture. *Reviews in Environmental Science and Bio/Technology* **22**: 471–504. https://doi.org/10.1007/s11157-023-09656-1

Kumar S, Mishra JS, Singh AK, Dwivedi SK, Singh SK, Singh SS, Haris AA, Mondal S, Bhatt BP, Singh S and Yadav A. 2016. Response of rice (*Oryza sativa*) genotypes to weed management in rainfed ecosystems of eastern India. *Indian Journal of Agronomy* **61**(1): 37–44.

Kup F and Saglam R. 2014. Weed destruction in cotton fields using hot foam method and its comparison to certain other methods. *ARPN Journal of Agricultural and Biological Science* **9**: 301–307. https://doi.org/10.1016/B978-0-12-809881-3.00002-4

Langeroudi AS and Kamkar B. 2009. Field screening of canola (*Brassica napus*) cultivars against wild mustard (*Sinapis arvensis*) using competition indices and some empirical yield loss models in Golestan Province, Iran. *Crop Protection* **28**(7): 577–582. https://doi.org/10.1016/j.cropro.2009.03.007

Lemerle D, Lockley P, Koetz E, Luckett D and Wu H. 2011. Manipulating canola agronomy for weed suppression. Proceedings of the 17th Australian Research Assembly on *Brassicas*. 181–183.

Lyon DJ, Huggins DR and Spring JF. 2016. Windrow burning eliminates Italian ryegrass (Lolium perenne ssp. Multiflorum) seed viability. *Weed Technology* **30**: 279–283

Lyon DJ, Michael JW, Judit B and Joan MC. 2019. "Harvest weed seed control: applications for PNW wheat production systems." https://hdl.handle.net/2376/16844

Machdar I, Abdullah A, Adisalamun A and Rinadi W. 2023. Foam Agent Synthesis For the Production of Foam-Based Concrete. *Journal of Applied Research* **10**(1): 17–23.

Mahajan G and Chauhan BS. 2011. Effects of planting pattern and cultivar on weed and crop growth in aerobic rice system. *Weed Technology* **25**: 521e525. https://doi.org/10.1614/WT-D-11-00025.1

Mahajan G, Poonia V and Chauhan BS. 2014. Integrated weed management using planting pattern, cultivar, and herbicide in dry–seeded rice in Northwest India. *Weed Science* **62**(2): 350–359. https://doi.org/10.1614/WS-D-13-00115.1

Mahajan G, Ramesha MS and Chauhan BS. 2014. Response of rice genotypes to weed competition in dry direct-seeded rice in India. *The Scientific World Journal*. 641589. https://doi.org/10.1155/2014/641589

Mahajan G, Walsh M and Chauhan B. 2020. Junglerice (*Echinochloa colona*) and feather fingergrass (*Chloris virgata*) seed production and retention at sorghum maturity. *Weed Technology* **34**(2): 272–276. https://doi.org/10.1017/wet.2019.109

Marin C and Weiner J. 2014. Effects of density and sowing pattern on weed suppression and grain yield in three varieties of maize under high weed pressure. *Weed Research* **54**: 467e474. https://doi.org/10.1111/wre.12101

Martelloni L, Frasconi C, Sportelli M, Fontanelli M, Raffaelli M and Peruzzi A. 2020. Flaming, glyphosate, hot foam and nonanoic acid for weed control: A comparison. *Agronomy* **10**(1): 129. https://doi.org/10.3390/agronomy10010129

Martelloni L, Frasconi C, Sportelli M, Fontanelli M, Raffaelli M and Peruzzi A. 2019. The use of different hot foam doses for weed Control. *Agronomy* **9**(9): 490. https://doi.org/10.3390/agronomy9090490

Martelloni L, Frasconi C, Sportelli M, Fontanelli M, Raffaelli M and Peruzzi A. 2021. Hot foam and hot water for weed control: A comparison. *Journal of Agricultural Engineering* **52**(3): 1–10. https://doi.org/10.4081/jae.2021.1167

Mason HE and Spaner D. 2006. Competitive ability of wheat in conventional and organic management systems: a review of the literature. *Canadian Journal of Plant Science* **86**(2): 333–343.

Melander B, Liebman M, Davis AS, Gallandt ER, Bàrberi P, Moonen AC, Rasmussen J, Van der Weide R and Vidotto F. 2017. Non chemical weed management. *Weed research: Expanding horizons*: 245–270. https://doi.org/10.1002/9781119380702.ch9

Moukoumbi YD, Sie M, Vodouhe R, Bonou W, Toulou B and Ahanchede A. 2011. Screening of rice varieties for weed competitiveness. *African Journal of Agricultural Research* **6**: 5446–5456.

Mwendwa JM, Brown WB, Weston PA, Haque KS, Preston C and Weston LA. 2020. Evaluation of selected commercial oilseed rape cultivars for early vigour, weed suppression and yield in southern New South Wales. *Weed Research* **60**(6): 450-463. https://doi.org/10.1111/wre.12451

Ni H, Moody K, Robles RP, Paller Jr EC and Lales JS. 2000. *Oryza sativa* plant traits conferring competitive ability against weeds. *Weed Science* **48**: 200–204.

Nordby DE, Alderks DL and Nafziger ED. 2007. Competitiveness with weeds of soybean cultivars with different maturity and canopy width characteristics. *Weed Technology* **21**(4): 1082–1088.

Norsworthy JK and Shipe E. 2006. Evaluation of glyphosate-resistant Glycine max genotypes for competitiveness at recommended seeding rates in wide and narrow rows. *Crop Protection* **25**(4): 362–368. https://doi.org/10.1371/journal.pone.0212700

Norsworthy JK, Green JK, Barber T, Roberts TL and Walsh MJ. 2020. Seed destruction of weeds in southern US crops using heat and narrow-windrow burning. *Weed Technology* **34**: 589–596. https://doi.org/10.1017/ wet.2020.36

Ogg AG and Seefeldt SS. 1999. Characterizing traits that enhance the competitiveness of winter wheat (*Triticum aestivum*) against jointed goatgrass (*Aegilops cylindrica*). *Weed Science* **47**(1): 74–80.

Olsen JM. 2012. How important are crop spatial pattern and density for weed suppression by spring wheat? *Weed Science* **60**: 501e509.

Paynter BH and Hills AL. 2009. Barley and rigid ryegrass (*Lolium rigidum*) competition is influenced by crop cultivar and density. *Weed Technology* **23**(1): 40–48. https://doi.org/10.1614/WT-08-093.1

Peerzada AM and Chauhan BS. 2018. Thermal weed control: History, mechanisms, and impacts. In Non-chemical weed control. pp. 9-31. Academic Press. https://doi.org/10.1016/B978-0-12-809881-3.00002-4

Phuhong H, Moody K, Robles RP, Paller EC and Lales JS. 2000. *Oryza sativa* plant traits conferring competitive ability against weeds. *Weed Science* **48**(2): 200–204.

Pooja K, Saravanane P, Nadaradjan S, Sundaravaradhan S, Muthukumarasamy S and Vijayakumar S. 2021a. Effect of cultivars and different weed management practices on yield, nutrient uptake and soil micro-flora in dry direct-seeded rice under coastal deltaic ecosystem. *ORYZA-An International Journal of Rice* **58**(1): 21–25. https://doi.org/10.35709/ory.2021.58.1.4

Pooja K, Saravanane P, Sridevi V, Nadaradjan S and Vijayakumar S. 2021b. Effect of cultivars and weed management practices on productivity, profitability and energetics of dry direct-seeded rice. *ORYZA-An International Journal of Rice* **58**(3): 442–447. https://doi.org/10.35709/ory.2021.58.3.11

Praba ML, Vanangamudi M and Thandapani V. 2004. Effect of low light on yield and physiological attributes of rice. *International Rice Research Notes* **29**: 71e73.

Qasem JR. 2013. Herbicide resistant weeds: The technology and weed management. Herbicides Current research and case studies in use. Publisher: *InTech Open*, 445–471. https://doi.org/10.5772/56036

Ramesh K, Vijayakumar S, Upadhyay PK and Chauhan BS. 2022. Revisiting the concept of the critical period of weed control. *The Journal of Agricultural Science* **159**(9-10): 636–642. https://doi.org/10.1017/S0021859621000939

Ruttledge A, Widderick M, Walsh M, Broster J, Bell K, Rayner A, Jalaludin A, Cooray O, Heuke L, Robilliard S and Chambers A. 2018. The efficacy of chaff lining and chaff tramlining in controlling problem weeds. Grains Research Update 26.

San Martín C, Thorne M, Gourlie J, Lyon D and Barroso J. 2021. Seed retention of grass weeds at wheat harvest in the Pacific Northwest. *Weed Science* **69**(2): 238–246. https://doi.org/10.1017/wsc.2020.91

Sankula S, VanGessel MJ and Mulford RR. 2004. Corn leaf architecture as a tool for weed management in two corn production systems. *Weed Science* **52**(6): 1026–1033.

Saravanane P, Poonguzhalan R, Vijayakumar S and Pooja K. 2020. Crop-weed competition in blackgram in coastal deltaic eco-system. *Indian Journal of Weed Science* **52**(3): 283–285, 2020. http://doi.org/10.5958/0974-8164.2020.00055.6

Schütte G, Eckerstorfer M, Rastelli V, Reichenbecher W, Restrepo-Vassalli S, Ruohonen-Lehto M, Anne-Gabrielle WS and Mertens M. 2017. Herbicide resistance and biodiversity: agronomic and environmental aspects of genetically modified herbicide-resistant plants. *Environmental Sciences Europe* **29**: 1–12. https://doi.org/10.1186/s12302-016-0100-y

Schwartz-Lazaro L, Green J and Norsworthy J. 2017. Seed Retention of Palmer amaranth (*Amaranthus palmeri*) and Barnyardgrass (*Echinochloa crus-galli*) in Soybean. *Weed Technology* **31**(4): 617–622. https://doi.org/10.1017/wet.2017.25

Shekhawat K, Rathore SS and Chauhan BS. 2020. Weed management in dry–direct seeded rice: A review on challenges and opportunities for sustainable Rice production. *Agronomy* **10**: 1264. https://doi.org/10.3390/agronomy10091264

Shilling DG, Brecke BJ, Hiebsch C and MacDonald G. 1995. Effect of soybean (*Glycine max*) cultivar, tillage, and rye (*Secale cereale*) mulch on sicklepod (*Senna obtusifolia*). *Weed Technology* **9**(2): 339–342.

Shrestha S, Sharma G, Burgos NR and Tseng TM. 2020. Competitive ability of weedy rice: Toward breeding weed–suppressive rice cultivars. *Journal of Crop Improvement* **34**: 455–469. https://doi.org/10.1080/15427528.2020.1733158

Singh M and Bhullar MS. 2015. Weed suppression ability of two rice varieties in aerobic rice. In: Proceedings of 25th Asian-Pacific Weed Science Society Conference on "Weed Science for Sustainable Agriculture, Environment and Biodiversity", Hyderabad, India during 13-16 October, p. 1.

Soni N, Nissen S, Westra P, Norsworthy J, Walsh M and Gaines T. 2020. Seed retention of winter annual grass weeds at winter wheat harvest maturity shows potential for harvest weed seed control. *Weed Technology* **34**(2): 266–271. https://doi.org/10.1017/wet.2019.108

Tidemann B, Hall L, Harker K, Beckie H, Johnson E and Stevenson F. 2017. Suitability of Wild Oat (*Avena fatua*), False Cleavers (*Galium spurium*), and Volunteer Canola (*Brassica napus*) for Harvest Weed Seed Control in Western Canada. *Weed Science* **65**(6): 769–777. https://doi.org/10.1017/wsc.2017.58

Vijayakumar S, Choudhary AK, Deiveegan M, Subramanian E, Joshi E, Goud BR and Kumar TS. 2022. The opportunities and challenges for harvest weed seed control (HWSC) in India: An opinion. *Indian Journal of Weed Science* **54**(1): 11–17. http://dx.doi.org/10.5958/0974-8164.2022.00002.8

Vijayakumar S, Gobinath R, Kannan P and Murugaiyan V. 2024. Optimizing potassium mining in rice-wheat system: Strategies for promoting sustainable soil health-A review. *Farming System* **2**(3):100099. https://doi.org/10.1016/j.farsys.2024.100099

Vijayakumar S, Jinger D, Saravanane P, Subramanian E and Govindasamy P. 2021b. Agricultural Waste to Wealth: Way for Sustainable Agriculture Development. *Indian Farming* **71**(5): 34–36.

Vijayakumar S, Saha S, Saravanane P, Subramanian E, Mahender Kumar R and Meenakshi Sundaram R. 2023. Barnyardgrass (*Echinochloa crus-galli*) seed production and shattering in response to its emergence time and transplanted rice geometry. *Indian Journal of Weed Science* **55**(2): 162–168. http://dx.doi.org/10.5958/0974-8164.2023.00029.1

Vijayakumar S, Subramanian E, Saravanane P, Gobinath R and Sanjoy Saha. 2021a. Farm mechanization in rice cultivation: Present status, bottlenecks and potential. Indian Farming 71(04): 04–07.

Walsh M and Newman P. 2007. Burning narrow windrows for weed seed destruction. *Field Crops Research* **104**: 24–30. https://doi.org/10.1016/j.fcr.2007.05.012

Walsh M and Powles S. 2014. High Seed Retention at Maturity of Annual Weeds Infesting Crop Fields Highlights the Potential for Harvest Weed Seed Control. *Weed Technology* **28**(3): 486–493. http://dx.doi.org/10.1614/WT-D-13-00183.1

Walsh M, Ouzman J, Newman P, Powles S and Llewellyn R. 2017. High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology* **31**(3): 1–7.

Walsh MJ, Harrington RB and Powles SB. 2012. Harrington seed destructor: a new nonchemical weed control tool for global grain crops. *Crop Science* **52**(3):1343–1347.

Walsh MJ, Powles SB and Rengel Z. 2022. Harvest weed seed control: impact on weed management in Australian grain production systems and potential role in global cropping systems. *Crop and Pasture Science* **73**(4): 313–324.

Walsh MJ, Rayner AE, Ruttledge A and Broster JC. 2021. Influence of chaff and chaff lines on weed seed survival and seedling emergence in Australian cropping systems. *Weed Technology* **35**(3): 515–521. https://doi.org/10.1017/wet.2020.142

Walsh MJ. 2018. Development of Harvest Weed Seed Control (HWSC) in Australian Cropping Systems. *Outlooks on Pest Management* **29**: 114-119.

Wicks GA, Nordquist PT, Baenziger PS, Klein RN, Hammons RH and Watkins JE. 2004. Winter wheat cultivar characteristics affect annual weed suppression. *Weed Technology* **18**(4): 988–998.

Wicks GA, Ramsel RE, Nordquist PT, Schmidt JW and Challaiah. 1986. Impact of Wheat Cultivars on Establishment and Suppression of Summer Annual Weeds 1. *Agronomy Journal* **78**(1): 59–62.

Williams MM, Boydston RA and Davis AS. 2008. Crop competitive ability contributes to herbicide performance in sweet corn. *Weed research* **48**(1): 58–67. https://doi.org/10.1111/j.1365-3180.2008.00602.x

Zhao DL, Atlin GN, Bastiaans L and Spiertz JHJ. 2006. Cultivar weed–competitiveness in aerobic rice: heritability, correlated traits, and the potential for indirect selection in weed–free environments. *Crop Science* **46**(1): 372–380.

Zhao DL, Bastiaans L, Atlin GN and Spiertz JHJ. 2007. Interaction of genotype x management on vegetative growth and weed suppression of aerobic rice. *Field Crops Research* **100**: 327–340.