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REVIEW ARTICLE

Weed management in conservation agriculture systems under changing climate scenario

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ABSTRACT

Conservation agriculture (CA) improves crop-water and energy productivity, profitability, environmental quality, and preserves natural resources for future food security and poverty reduction. However, weeds are a major challenge for large-scale CA adoption. Changes in tillage and planting systems in CA shift weed populations, favouring small-seeded and perennial grasses. Weeds like *Trianthema portulacastrum* and *Cyperus rotundus* in direct-seeded rice, and *Rumex dentatus*, *Medicago denticulata*, and *Avena ludoviciana* in wheat, become more common, though *Phalaris minor* declines. Weed management, especially early in CA adoption, heavily relies on herbicides like paraquat, glufosinate ammonium, and glyphosate. However, crop residues can reduce herbicide efficacy, and overuse can lead to herbicide resistance. These problems are further exaggerated under the changing climatic scenario which requires deeper knowledge and understanding. Since C_4 weeds are more competitive, therefore, would be dominant under elevated temperatures and pose yield penalties. Under changing climatic scenarios such as increased temperature, delayed or late onset of rainfall, prolonged drought and elevated CO_2 levels are major concerns for weed management and crop production. Therefore, sustainable CA requires integrated weed management using both chemical and non-chemical approaches.

Keywords: Conservation agriculture, Crop diversification, Crop residue retention, Tillage, Weed management

INTRODUCTION

India's rapidly growing population is expected to reach 1.5 billion by 2030, making it the most populous country. To feed this population, 345 million tons of food grains will be required (Mishra *et al.* 2021). Meeting this demand will be challenging due to limited resources, current agricultural practices, and growing threats like climate change, water scarcity, and shrinking farm sizes. Abiotic and biotic stresses also limit production, with weeds being the top biotic stressor, causing up to 37% yield loss—greater than losses from pests (29%), diseases (22%), and others (12%) (Mishra and Choudhary 2022). Weed severity is influenced by management practices like tillage, crop rotation, row spacing, fertilization, herbicide use, and soil and environmental conditions. Conventional agriculture, heavily reliant on intensive tillage, faces land degradation and climate variability challenges. While tillage offers short-term benefits like improved soil tilth, aeration, and weed control, it is unsustainable in the long term, leading to soil degradation, erosion, reduced water infiltration, and higher production costs. Intense tillage accelerates organic matter breakdown, particularly in warmer climates, degrading soil health over time. Rising atmospheric levels of carbon dioxide (CO_2) and increasing temperatures are anticipated to have both direct and indirect effects on agricultural production, sustainability, water availability, and ultimately, food security (Chauhan *et al.* 2014). The greenhouse gases (GHG; CO_2 and methane) are at an unprecedented high, posing significant ecological challenges in the present context. Climate change with intensive cropping systems would reduce crop yields and soil organic carbon under future climate (Zhang *et al.* 2022). Globally, to meet the food demand, intensive farming (excessive irrigation, fertilization and tillage) has been widely adopted to enhance crop productivity. These practices reduce the soil organic carbon (SOC) and degrade soil quality and also change the weed flora (Waqas *et al.* 2020, Choudhary 2024). Crop straw burning is another problem associated, this releases large amounts of CO_2 and minimizes the potential for sustainable crop production (Zhang *et al.* 2021). Elevated levels of GHG will certainly influence the geographic range expansions, alterations in species life cycle and weed shift dynamics. Similarly, this change will alter the structure and composition of weed communities.

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Peters *et al*. (2014) categorized shifts in weedy vegetation into three primary types: range shifts, niche shifts, and trait shifts, which manifest across different scales, including landscape, community, and population levels. Climate change is expected to influence weed biology, ecology, and competitive dynamics, leading to complex interactions between crops and weeds that will require the implementation of alternative adaptive strategies. There is widespread agreement that climate change is likely to result in divergent growth patterns between crops and weeds, particularly because many prevalent weeds utilize the C_4 photosynthetic pathway, enhancing their competitive advantage. Nevertheless, the situation is nuanced, shaped by the diverse adaptive mechanisms exhibited by weedy species (Ramesh *et al.* 2017). There is a need for technologies that can conserve resources and also mitigate the impact of climate change. Under the circumstances, conservation agriculture (CA) is a potential option. CA can buffer the negative effects of climate change and secure crop yields in some regions (Zhang *et al.* 2022). In CA no-tillage and straw retention are effective measures to mitigate the impact of climate change, they reduce GHG emissions, sequestrate carbon, conserve biodiversity and provide ecosystem services (Pathak *et al.* 2021), it also optimizes soil properties, minimize runoff, restrict soil erosion and provides a sustainable growing environment for crops (Wang *et al.* 2020). Similarly, using herbicides has reduced the need for tillage, paving the way for no-tillage or CA systems (Chhokar *et al.* 2021). The comparison between conventional and conservation agriculture has been given in **Table 1**.

Conservation agriculture focuses on reducing soil disturbance and conserving soil moisture to enhance crop production. It is based on three core principles: (1) minimal soil disturbance, (2) permanent soil cover with previous crop residues, and (3) diversified crop rotations. CA has been recognized globally as a sustainable farming practice that can increase yields. Despite its benefits, weed control remains a significant challenge for CA adopters (**Table 2**). CA alters tillage, crop establishment methods, and management practices, which in turn affect the microclimate, leading to changes in weed flora. These changes influence weed emergence patterns, seed bank composition, distribution, dispersal mechanisms, and competition dynamics, making weed management more complex compared to conventional systems (Mishra *et al.* 2022, Choudhary 2023). Weeds can cause significant

Table 2. Tangible and non-tangible benefit of conservation agriculture at scale

Parameters	Impact at scale
Tangible	
Tillage	Saving of 3 tillage /season; total pass of tractor (60-75%)
Fuel consumption	Saved 60-75%
Water use	Saved 25-30%
Electricity consumption	Saved 25-30%
Soil erosion	>90% saving
Labour requirement	Reduction of 25-30%
Production cost	Saving of Rs. 8000/season, Rs. 24000/per year
Weed severity	20-35% less
Seed rate	Saving of 10-15%
Nutrient saving	Continuous retention of crop residues may lead to savings of 20% N fertilizer
Yield	Improved 10-12%
Net returns	Higher by Rs. 32000-45000/ha
Energy productivity	Improved 10-15%
Saving of time	10-12 days each season, 20-22 d in a year
Carbon stock	Saving of 2-4.5 Mg C/ha
Earthworm population	Significantly increased
Quality of harvested produce	Improved
Non-tangible	
Soil compaction	Decreased
Infiltration rate	Improved
Crop residue burning	Completely stopped
Environment	Positive (Air quality index improvement)
Water quality	Improved
Groundwater recharge	Improved
Non-point pollution	Drastically reduced
Eutrophication	Reduced

Table 1. A comparison of some issues between conventional tillage and conservation agriculture

Issues	Conventional agriculture (CT)	Conservation agriculture (CA)
Soil disturbance	High	Low
Soil surface	Bare surface	Permanent cover
Erosion	High soil and wind erosion	Low soil and wind erosion
Water infiltration	Low	High
Diesel use and costs	High	Low
Production costs	High	Low
Timeliness	Delayed operation	Timeliness of operation more optimal
Yield	Lower (where delayed planting)	Same or higher (if planted on time)
Weeds	Less perennial weeds but trigger germination	Early-stage weed problem, but decreased with time

yield losses, ranging from 25-79%, depending on weed aggressiveness (Mtambanengwe *et al.* 2015, Nandan *et al.* 2020, Chhokar *et al.* 2021). Since there is an inverse relationship between weed pressure and crop yield, effective weed management in CA is crucial to achieving optimal yields. Therefore, effective weed management in CA is important to obtain good crop yields.

Effect of conservation agriculture principles on weeds

Effect of zero tillage (ZT) on weed seed bank: In conventional tillage, weed seeds are buried deep in the soil, with many found up to 50 cm below the surface. These buried seeds often have lower germination rates due to limited access to light, moisture, and nutrients, and may remain dormant for years (Santín-Montanyá *et al.* 2016). However, once these seeds reach the surface, they can compete with crops. In ZT, most weed seeds remain on the soil surface due to the absence of tillage (Choudhary 2023). Seeds closer to the surface may germinate sooner in favourable conditions but are also more vulnerable to weather and predation, leading to higher mortality rates (Choudhary 2016). Herbicides can effectively control these surface-level weeds, reducing crop-weed competition (Nichols *et al.* 2015). Tillage also influences the timing and synchronization of weed seed emergence. Depending on factors like soil moisture and temperature, some tillage practices can either accelerate or delay weed emergence. Repeated tillage can deplete the seed bank by promoting germination and exhausting viable seeds over time, whereas in ZT systems, the seed bank is typically three times smaller. However, perennial weeds are more common in ZT systems (Feledyn-Szewczyk *et al.* 2020). Improper tillage can also bring buried seeds back to the surface, replenishing the seed bank. Studies show that 67.1-164.8% more weed seeds germinate from the soil surface than from deeper layers, though this varies by weed species. Conventional tillage (CT) tends to distribute weed seeds more evenly throughout the soil profile. The adoption of specific cultural practices can exert selection pressure on certain weed species, potentially altering the composition of the soil seed bank over time (Mashavakure *et al.* 2020, Winkler *et al.* 2022).

Predation of weed seeds (natural enemies) and desiccation: In ZT systems, the absence of tillage and the retention of crop residues create a favourable environment for beneficial insects like field crickets and black ants. These insects feed on weed seeds that remain on the soil surface, gradually reducing the weed seed bank, unlike in CT (Carbonne *et al.* 2023). They particularly prefer older seeds from species such as *Echinochloa* spp., *Chenopodium album*, and *Amaranthus viridis*. Additionally, in ZT, weed seeds left on the soil surface are more exposed to desiccation due to weather extremes, which can alter their viability and reduce their emergence by affecting moisture, light exposure, and microbial activity (Singh *et al.* 2015, Travlos *et al.* 2020). This helps to reduce crop-weed competition.

Limited weed seed wash-off: In ZT systems, with higher soil organic matter and crop residues, promote better infiltration and percolation, minimizing runoff. This limits the wash-off of weed seeds from the field, helping to prevent weed seed dispersal and reducing the spread of weeds to nearby fields. Consequently, the weed seed bank may be enriched in ZT, but the spread of weeds is restricted.

Effect of tillage on weeds

Switching from intensive tillage to reduced or ZT significantly alters weed population dynamics (Chhokar *et al.* 2021). Reduced tillage favours the establishment of perennial weeds due to undisturbed root systems, and small-seeded annual weeds become more problematic as they remain on the soil surface (Choudhary *et al.* 2016). While ZT combined with crop rotation generally suppresses weeds more effectively than CT, the retention of crop residues can encourage weed establishment. For instance, *Convolvulus arvensis* populations in reduced-tilled fields increased by 11.2-39.1% in soybean, 0.9-4.2% in wheat, and 11.9-24.4% in maize, with 77% of seeds concentrated at a 0-10 cm depth (Rusu *et al.* 2015). Despite these changes in weed populations, yields remained similar across tillage systems. Sepat *et al.* (2017) observed the highest weed density and biomass in soybean under ZT with a flatbed, though over time, CT with a flatbed showed higher weed severity. In continuous ZT, wild oats (*Avena ludoviciana*) and *Chenopodium album* populations decreased, though the seed bank was concentrated at a 0-20 cm depth in the rice-wheat system (Mishra and Singh 2012). Rotational tillage resulted in lower weed density compared to continuous ZT. While ZT systems saw increased densities of *Rumex dentatus*, they had fewer *Phalaris minor* (Chhokar *et al.* 2007, Shyam *et al.* 2014).

ZT tends to increase the density and biomass of both annual and perennial weeds due to the presence of weed propagules from the previous season, allowing them to establish earlier in favourable conditions, making control more difficult later (Choudhary and Kumar 2019). Minimum tillage (MT) recorded higher densities of dicot weeds compared to CT, though overall weed densities (both monocot and dicot) were lower in MT than CT (Choudhary and Kumar 2014). On the other hand, CT displaces most weed seeds and propagules, leading to lower weed density and biomass. Rotational tillage has been shown to significantly reduce the density of weeds like *Cyperus iria*, *Avena ludoviciana*, *Medicago hispida*, *Solanum sarrachoides*, and *Amaranthus powellii* compared to continuous MT and ZT (Peachey *et al.* 2006). An absence of weed control grasses and sedges tended to dominate in ZT-DSR and broadleaves in puddled TPR. However, herbicide and manual weeding significantly dominance of sedges over broadleaves and grasses in ZT-DSR, underscoring the need for specialized weed control methods in these systems (Hossain *et al.* 2020).

Effect of tillage on productivity: Crop yields are generally higher under CT compared to conservation tillage (MT and ZT), largely due to more effective weed control. However, despite the lower production costs associated with MT and ZT, the economic yield may not always offset these savings due to severe weed pressure. For instance, Panasiewicz *et al.* (2020) observed a 75% decrease in cereal yields, which significantly reduced the adoption of MT and ZT. In contrast, Chaghazardi *et al.* (2016) found that wheat and chickpea performed better under MT and ZT, suggesting that these practices can be efficient for achieving higher yields while conserving soil and water. Chhokar *et al.* (2014) noted that rice yields are consistently higher in transplanted conditions compared to direct-seeded rice (DSR), primarily due to water stagnation, the early head start of seedlings, delayed weed emergence, and more effective weed control. Yield losses due to weeds in DSR can reach up to 97%, while losses in transplanted rice are typically capped at 33%.

Effect of crop residue on weeds

Retention of crop residues on the soil surface reduces light penetration, preventing the germination of photoblastic weed seeds, and lowering weed pressure by 15-20% (Sahu *et al.* 2022). A thick, uniform layer of crop residue effectively suppresses weed germination, delays weed emergence, and promotes crop vigour. Weed management can be further enhanced by optimizing the amount of crop residue applied to the soil surface (Chauhan *et al.* 2012). Crop residues release allelochemicals and block light transmission to the soil, aiding in weed suppression. However, in some cases, crop residues can stimulate weed germination, complicating weed management in ZT systems. Prolonged retention of crop residues increases soil organic matter, maintaining optimal moisture and moderate soil temperatures, which may favour certain weed species. For instance, Chauhan and Abugho (2012) observed that weeds like *Echinochloa crus-galli* and *Cyperus iria* could escape control under ZT and MT when crop residues were present. However, applying 6 t/ha of crop residues significantly reduced the populations of *Chenopodium album* by 83%, *Rumex dentatus* by 88%, and *Phalaris minor* by 45% compared to bare soil (Kumar *et al.* 2013, Sharma and Singh 2014). While herbicides are effective at controlling weeds, their efficacy is reduced when residues are loose rather than anchored.

Effect of crop residues on seed bank: The presence of crop residues alters the weed seed bank. Plots with retained crop residues showed a reduction in weed seed density by 22% in the rainy season, 29.8% in winter, and 30.3% in summer at a soil depth of 0-15 cm compared to bare land. Retaining 50% of crop residue in potato fields significantly reduced the weed seed bank, with further reductions observed as the residue layer thickened (Jalali 2013). The thickness and uniform application of crop residues regulates soil temperature, delaying the germination and emergence of small-seeded annual weeds while creating favourable conditions for crops (Chauhan *et al.* 2012, Choudhary and Kumar 2019). As mulch, crop residues can suppress weed biomass by 20-40.5% compared to bare soil, reducing herbicide usage and leading to a 70% suppression of weed density in CA (Mtambanengwe *et al.* 2015).

As crop residues decompose, they release nutrients that enhance crop growth over weeds, further reducing weed competition (Choudhary and Bhagawati 2019). Over time, crop residue retention improves soil organic matter (SOM), promoting the build-up of soil microbes and flora in CA systems, as supported by higher SOM levels (Oliveira *et al.* 2024). In ZT, crop residue retention reduces evaporative water loss, conserving 10-15% more water and potentially saving 1-2 irrigations. However, crop residues can interfere with pre-emergence herbicides, reducing their effectiveness (Chauhan *et al.* 2012, Singh *et al.* 2022). In ZT, the lack of weed seed burial and poor incorporation of soil-applied herbicides further diminish their efficacy, leaving most weed seeds on the soil surface. This requires special attention to control established, particularly perennial, weeds. Certain crop residues, such as wheat straw, release chemicals like hydroxamic acid, which inhibit the germination of other weed species on the surface. Additionally, other residues can block light penetration, reducing weed germination by 15-45% (Scavo and Mauromicale 2021).

Effect of crop diversification on weed dynamics

Crop rotation disrupts weed life cycles by creating unfavourable conditions for weeds adapted to specific crops. Different crops have unique growth habits, rooting depths, and canopy structures that help suppress weed growth (Derksen *et al.* 2002). Some crops release allelopathic chemicals that inhibit weeds, while cover crops act as living mulch, suppressing weeds during fallow periods. Vigorous crops with dense canopies can also outcompete weeds for light, water, and nutrients. Crop diversification reduces weed resistance to herbicides and improves soil health, promoting stronger crop growth, which further aids weed control. In contrast, monoculture with uniform management practices allows specific weed species to dominate, potentially becoming tolerant or resistant to frequently used herbicides (Khamare *et al.* 2022, Nath *et al.* 2024). These issues can be addressed by adjusting the sowing window, seed rates, row spacing, and herbicide application methods to minimize weed pressure. Crop diversification, including cereals, pulses, and oilseeds, can reduce herbicide usage, while cover crops and perennial forages provide additional benefits for weed management (Choudhary *et al.* 2016).

Effect of cropping systems on seed bank and weed severity

Weed seed banks and dynamics are influenced by crop rotation and management practices. The seed bank variation is greater in the upper soil layers and reflects the effectiveness of weed management. Poor management leads to an increase in the seed bank, complicating future control efforts. Effective input management reduces weed densities; for example, medium-input systems had 15 species and 145 plants/m², while high-input systems had 11 species and 66 plants/m² (Koocheki *et al.* 2009). Proper herbicide use at the right dose and time can deplete weed seed banks by preventing reproduction (Norris *et al.* 2001).

Effect of crop rotation on weeds

Including competitive crops in the system and modifying weed management strategies can inhibit weed seed germination and growth. Allelochemicals released from roots further suppress weed germination. Using a mix of annuals, perennials, and diverse herbicides is effective for weed control (Nichols *et al.* 2015). While cover crops may not have a major impact, delaying termination and using competitive species can reduce weed density by over 75% in CA systems (Alonso-Ayuso *et al.* 2018; Sahu *et al.* 2022). Rotating diverse crops also modifies herbicide use and traffic patterns, effectively controlling weed composition (Izquierdo *et al.* 2020).

Effect of cropping systems on productivity

The cereal-cereal cropping system is vital for food security in South Asia, but declining productivity threatens its sustainability (Kumar *et al.* 2021). To meet growing population demands, urgent efforts are needed to enhance productivity. Diversifying and intensifying cropping systems by incorporating green manuring, legumes, pulses, and oilseeds, especially in summer, is essential. Crop diversification alters weed emergence patterns, sustains or boosts yields, improves soil health, preserves natural resources, and optimizes resource use (Jat *et al.* 2012, Ghathala *et al.* 2014).

Weed management in CA under climate change

Preventive methods

This method includes practices to prevent weed entry into fields, such as using clean equipment, fully decomposed manure, weed-free seeds, cleaning irrigation canals, restricting livestock movement from infested areas, maintaining clean right-of-ways, cutting reproductive weed parts before seed dispersal, and enforcing strict weed quarantine laws to block invasive species. These measures aim to keep weeds out of crops.

Cultural methods

Sustainable weed management focuses on reducing weed establishment and competition, not just control. Practices like tillage, mulching, intercropping, and crop rotation, though challenging, are essential in CA. Using crop residues as mulch in CA limits weed germination, but the non-inversion of soil and micro-climate changes can encourage weed emergence, requiring sustainable strategies to manage weed establishment and competition (Sims *et al.* 2018).

Tillage: Tillage practices have varied effects on weed emergence and establishment. The CT disrupts perennial weeds but promotes annual weed germination. In contrast, ZT reduces *Phalaris minor* infestation but encourages *Avena ludoviciana* and perennial weed establishment. The differences in weed populations between ZT and CT largely depend on the weed seed bank and previous cropping systems (Mishra and Singh 2012). Continuous ZT with effective weed management is more profitable and energy-efficient, especially in soybean-wheat systems (Mishra and Singh 2009).

Stale seed bed: Eliminating established weeds significantly reduces future weed problems. In ZT systems with stale seedbeds, weed control in CA is effective. Under irrigated conditions, watering the field 10–15 days before planting encourages weed germination, allowing them to be killed using non-selective herbicides like glufosinate ammonium or paraquat. This practice reduces the weed seed bank and minimizes future weed issues by up to 80%, giving crops a competitive advantage (Pittelkow *et al.* 2012).

Competitive crop cultivars: The inclusion of fast-germinating, early-vigour crop cultivars helps cover the ground quickly, limiting empty spaces where weeds can grow. This reduces crop-weed competition for resources like moisture, light, CO_2, space, and nutrients. Compared to traditional varieties, competitive crop varieties typically reduce weed pressure by 25-30%.

Crop residues: Use of previous crop residues, either loose residues (as mulch) or anchored residues covers the soil and provides effective weed management. These residues delay the germination and emergence of the weeds by the time the crop becomes competitive. However, thickness and material type are also important. Uniform application with optimum thickness decreases weed growth and favours crop. While, a thin layer or sparsely distributed crop residue may stimulate the emergence of certain weeds, like wild oats (Chauhan and Abugho 2012, Choudhary and Bhagawati 2019). Under CA, delayed emergence of weeds less impacted the crop yield and only a few weeds could reach the reproductive stage and contribute to the weed seed bank. It also restricts the evaporative loss and conserves 10-15% in soil moisture. However, this is not the only solution to control weeds, additional herbicide use may be necessary for season-long weed management.

Intercropping: The inclusion of short-duration, fast-growing legumes with long-duration, wide-spaced crops effectively suppresses weeds. Intercropping provides early ground cover and competes with emerging weeds by reducing light availability, similar to the effect of cover crops. Selecting suitable intercrops like cowpea, blackgram, greengram, or soybean is crucial to balance light, water, and nutrient needs, ensuring optimal resource use without reducing main crop yields (Choudhary *et al.* 2016). Although intercropping increases labour requirements for weeding, as seen in maize-cowpea systems, it remains a valuable technique for weed suppression in diverse cropping systems (Lai *et al.* 2012).

Cover crops: In CA, growing and incorporating short-duration legumes like mungbean, cowpea, blackgram, sesbania, and sunhemp during fallow periods can significantly reduce weed pressure (Kumar *et al.* 2012). These legumes encourage weed emergence during their growth, creating a stale seedbed effect that reduces weed populations for future seasons (Anderson 2005). In India, Sesbania cover crops, producing up to 30 t/ha in 60 days, have effectively controlled most weeds (Mahapatra *et al.* 2004).

Crop diversification: Planting crops in rotation on the same land disrupts weed species that thrive in monoculture systems, restricting weed buildup. Varying management practices can break weed growth cycles and prevent the dominance of a single species. Crop rotation introduces diverse competition for resources, soil disturbance, mechanical damage, and allelopathic effects, creating an unstable environment for weeds (Chhokar and Malik 2002). In rice-wheat systems, rotating non-rice crops significantly reduces *Phalaris minor* infestations in wheat. Including crops like Egyptian clover, potato, sunflower, or annual rape for 2-3 years also helps reduce *Phalaris minor* infestations in wheat.

Mechanical measures

Land levelling and Happy Seeder: In CA, laser land levelling ensures uniform moisture distribution, promotes seed germination, and enhances crop growth while reducing weed infestation. In contrast, uneven fields often lead to patchy crop growth and higher weed densities. Jat *et al.* (2003) found that precisely levelled wheat fields had a weed density of 200/m², compared to over 350/m² in non-leveled fields. Precision levelling can reduce labour requirements for weeding by up to 75%.

The ‘Happy Seeder’ is an advanced no-till seed drill designed for sowing seeds in standing crop residue. It integrates stubble mulching with seed and fertilizer application, cutting the crop residue in front of the sowing tines, opening slits, and drilling fertilizers and seeds at the desired depths. Seeding with this machine conserves moisture, controls weeds, and also retains organic matter. Adoption of the Happy Seeder can decrease weed density by 26.5% compared to rotavator sowing and by 47.7% compared to conventional practices (Singh *et al.* 2013).

Herbicide-based weed management

Herbicides are essential in CA due to their cost-effectiveness, affordability, low labour requirements, and ability to control difficult weeds. However, concerns over herbicide resistance and non-point pollution are significant. To mitigate these issues, it is important to adopt herbicide rotation and include other reliable weed management strategies. Non-selective herbicides can be applied to eliminate emerging weeds before or after planting but before crop emergence. The presence of crop residues can reduce herbicide efficacy, so early post-emergence herbicides combined with need-based hand weeding have proven effective for weed management (Choudhary *et al.* 2016). Nevertheless, over-reliance on herbicides and continuous use of similar types can shift weed populations from easily controlled species to more resilient ones, leading to the development of herbicide-resistant biotypes. This shift can make weed management particularly challenging in the early years of CA adoption (Vahid 2014). A list of recommended herbicides for various crops suitable for use in CA is provided in **Table 3**.

Integrated weed management

Weeds pose a significant threat in CA, a problem that is exacerbated by issues such as herbicide resistance and shifts in weed flora when relying solely on one management method. The adoption of multiple strategies—referred to as "many little hammers" in integrated weed management (IWM)—creates conditions that favour crops. Successful and effective IWM strategies include preventive approaches, false seedbed practices, appropriate row spacing and sowing windows, competitive crop cultivars, crop residue retention, allelopathic intercropping, cover crops, crop rotation, efficient water and nutrient management, and the need-based use of pre- or post-emergent herbicides alongside manual weed removal before seed set. Additionally, innovative methods such as strategic tillage and harvest weed seed control can be explored to manage weeds effectively. Integrating these practices can enhance crop competitiveness and develop sustainable weed management strategies within CA-based cropping systems. Lessons learned in weed management related to cropping systems are presented in **Table 4**.

Conclusions

In modern agriculture, while food production has significantly increased, the natural resource base is at risk, production costs have risen, and environmental pollution has become a major concern. The CA offers an alternative that addresses these issues, but it faces challenges, particularly with weed management during the initial years of adoption.

Table 3. List of promising herbicides for weed control in different crops (pre-emergence: 0-3 DAS; post-emergence: 18-22 DAS) (Source: DPPQS, 2023)

Weed management in rice

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Pendimethalin 30% EC	1000-1500 g/ha	3300-5000 ml/ha	PE	Annual grasses and some BLWs
Azimsulfuron 50% DF	35 g/ha	70 g/ha	PoE	Broad-spectrum weed control
Bispyribac-sodium 10% SC	20-25 g/ha	200-250 ml/ha		Broad- spectrum weed control
Carfentrazone-ethyl 40% DF	25 g/ha	62.50 g/ha		BLWs and sedges
Cyhalofop-butyl 10% EC	75-80 g/ha	750-800 ml/ha		Grasses only
Florpyrauxafen- benzyl 2.7% EC	21.25-37.5 g/ha	1250-150 ml/ha		Broad spectrum weed control
Metamifop 10% EC	100 g/ha	1000 ml/ha		Grasses
Propanil 80% DF	2000-3000 g/ha	2500-3750 g/ha		Broad-spectrum weed control
Ready mix				
Pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG	600 + 15 g/ha	2000 g/ha	PE	Broad-spectrum weed control
Bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG	20+15 g/ha	100 g/ha	PoE	Broad-spectrum weed control
Bispyribac-sodium 38% + chlorimuron-ethyl 2.5% + metsulfuron methyl 2.5% WG	43 g/ha	100 g/ha		Broad-spectrum weed control
Florpyrauxifen-benzyl 1.31 + penoxsulam 2.1% OD	15.63+25 g/ha	1250		Broad-spectrum weed control
Florpyrauxifen-benzyl 2.13 + cyhalofop butyl 10.64% EC	150 g/ha	1250 ml/ha		Broad-spectrum weed control
Penoxsulam 1.02% + cyhalofop-butyl 5.1% OD	120-135 g/ha	2000-2250 ml/ha		Broad-spectrum weed control
Triafamone 20% + ethoxysulfuron 10% WG	44+22.5 g/ha	225 g/ha		Broad-spectrum weed control

However, strict adherence to three fundamental principles—minimal soil disturbance, permanent soil cover, and crop diversification—can help minimize weed problems. In CA, most weed seeds remain on the surface, potentially leading to severe infestations; however, these seeds are also vulnerable to desiccation, predation, and effective weed management practices. To ensure CA is effective, productive, profitable, and sustainable, controlling weed flora in the early years is crucial. Additionally,

Weed management in maize

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Atrazine 50% WP	0.5–1.0 kg/ha	1000-2000 ml/ha	PE	BLWs and grasses
Pyroxasulfone 85% WG	127.5 g/ha	150 g/ha		Grasses and BLWs
Halosulfuron-methyl 75% WG	67.5 g/ha	90 g/ha	PoE	Sedges
Tembotrione 34.4% SC	120 g/ha	286 ml/ha		Broad-spectrum weed control
Topramezone 33.6% EC	25.2-33.6 g/ha	75-100 ml/ha		Broad-spectrum weed control
Mesotrione 2.27%+ atrazine 22.7%	875	3500 g/ha		Broad-spectrum weed control
2,4-D-amine salt 58% SL	500 g/ha	860 ml/ha		BLWs and sedges
2,4-D-sodium salt 80% SL	500.3 g/ha	1250 g/ha		BLWs and sedges
2,4-D-ethyl ester 38% SL	900 g/ha	2650 ml/ha		BLWs and sedges
2,4-D-ethyl ester 20% WP	900 g/ha	5000 ml/ha		BLWs and sedges
Ready mix				
Halosulfuron-methyl 5% + atrazine 48% WG	56.25+540 g/ha	1125 g/ha		Broad-spectrum weed control
Mesotrion 2.27% + atrazine 22.7% SC	875 g/ha	3500 ml/ha		Broad-spectrum weed control
Topramezone 1% + atrazine 30% SC	775 g/ha	2500 ml/ha		Broad-spectrum weed control

Weed management in soybean

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Clomazone 50% EC	750-1000 g/ha	1500-2000 ml/ha	PE	Grasses and BLWs
Diclosulam 84% WDG	22-26 g/ha	26.2-30.9 g/ha		BLWs and sedges
Flumioxazin 50% EC	125 g/ha	250 ml/ha		Grasses and BLWs
Metolachlor 50% EC	1000 g/ha	2000 ml/ha		For grasses
Metribuzin 70% WP	350-500 g/ha	500-750 g/ha		Grasses and BLWs
Pendimethalin 30% EC	700-1000 g/ha	2500-3300 ml/ha		Grasses and some BLWs
Pendimethalin 38.7% EC	580-677 g/ha	1500-1750 ml/ha		Grasses and some BLWs
Pyroxasulfone 85% WG	127.5 g/ha	150 g/ha		Grasses and BLWs
Sulfentrazone 39.6% SC	360 g/ha	750 ml/ha		Grasses and BLWs
Ready mix				
Pendimethalin 30%+imazethapyr 2% EC	900+60 g/ha	3000 ml/ha		Grasses and BLWs
Sulfentrazone 28%+ clomazone 30% WP	350+375 g/ha	1250 ml/ha		Broad-spectrum weed control
Sole application				
Bentazone 480 g/l SL	960 g/ha	2000 ml/ha	Early PoE	2-3 leaf stage of weeds, BLWs
Chlorimuron-ethyl 25% WP + surfactant	9 g/ha	36 g/ha	3-15 DAS	Controls BLWs and sedges
Clethodim 25% EC	120-180	500-700 ml/ha	PoE	For grasses
Fenoxaprop-p-ethyl 9.3% EC	100 g/ha	1111 ml/ha		Grasses
Fluazifop-p-butyl 13.4% EC	125-250 g/ha	1000-2000 ml/ha		Grasses
Fluthiacet-methyl 10.3% EC	13.6 g/ha	125 ml/ha		Grasses and BLWs
Haloxyfop-R-methyl	108-135 g/ha	1000-1250 g/ha		Grasses
Imazethapyr 10% SL	100 g/ha	1000 ml/ha		Grasses, sedges and BLWs
Imazethapyr 70% WG + surfactant	70 g/ha	100 ml/ha		Grasses, sedges and BLWs
Propaquizafop 10% EC	50-75 g/ha	500-750 ml/ha		Grasses
Quizalofop-ethyl 5% EC	37.5-50 g/ha	750-1000 ml/ha		Grasses
Ready mix				
Fomesafen 12% +quizalofop-ethyl 3% SC	180+45 g/ha	1500 ml/ha		Broad-spectrum weed control
Fluazifop-p-butyl 11.1%+fomesafen 11.1% SL	250 g/ha	1000 ml/ha		Grasses and BLWs
Fluthiacet-methyl 2.5%+quizalofop-ethyl 10% EC	12.5+50 g/ha	500 ml/ha		Grasses and BLWs
Imazethapyr 35% + imazamox 35% WG	70 g/ha	70 g/ha		Grasses and BLWs
Propaquizafop 2.5% + imazethapyr 3.75% ME	50+75	2000 ml/ha		Grasses and BLWs
Quizalofop-ethyl 7.5%+ imazethapyr 15% EC	32.5+65.6 g/ha	437.5 ml/ha		Grasses and BLWs
Quizalofop-ethyl 10% EC+ chlorimuron-ethyl 25% WP (twin pack) + surfactant	37.5+9 g/ha	375 ml/ha + 36 g/ha		Grasses and BLWs
Sodium-acifluorfen 16.5% + clodinafop-propargyl 8%	165+80 g/ha	1000 ml/ha		Grasses and BLWs

Weed management in greengram and blackgram

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Fenoxaprop-p-ethyl 9.3% EC	56.25-67.5	625-750 ml/ha	PoE	Controls most grasses
Imazethapyr 10% SL	75-100	750-1000 ml/ha		Grasses and BLWs
Quizalofop 5% EC	50	1000 ml/ha		Grasses only
Clodinafop-propargyl 12.5% EC	125	1000 g/ha		Grasses only
Propaquizafop 10% EC	75-100	750-1000 ml/ha		Grasses only
Ready mix				
Imazethapyr + imazamox	70	100 ml/ha		Grasses and BLWs
Propaquizafop 2.5% + imazethapyr 3.75% ME	50 + 75	2000 ml/ha		Grasses and BLWs
Fomesafen 17.5% + clodinafop-propargyl 12.5% ME	175+125	1000 ml/ha		Grasses and BLWs

Weed management in sugarcane

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Atrazine 80% WDG	2000	2500 g/ha	PE	BLWs & grasses
Atrazine 50% WP	500-2000	1000-4000 g/ha		BLWs & grasses
Diuron 80% WP	1600-3200	2000-4000 g/ha		Broad-spectrum weed
Ametryne 80% WDG	2000	2500 g/ha		Broad-spectrum weed control
Metribuzin 70% WP	1050-1400	1500-2000 g/ha		Broad-spectrum weed control
Metribuzin 70% WG	1400-2000	2000-3000 g/ha		Broad-spectrum weed control
Sulfentrazone 39.6% SC	720	1500 g/ha		Control of BLWs and sedges
Clomazone 50% EC	750-1000	1500-2000 ml/ha		BLWs & grasses
Clomazone 22.5% + metribuzin 21% WP	563+525	2500 ml/ha		BLWs & grasses
Hexazinone 13.2% + diuron 46.8% WP	1200	2000 g/ha		Broad-spectrum weed control
Ready mix				
Amytrin 73.1%+ trifloxysulfuron-sodium 1.8% WG	937.5-1125	1250-1500 g/ha		Broad-spectrum weed control
Sulfentrazone 28% + clomazone 30% WP	700+750	2500 g/ha		BLWs and sedges
Sole application				
Halosulfuron-methyl 75% WG	60-67.5	80-90 g/ha	PoE	Sedges
Metsulfuron-methyl 20% WP and WG	6	30 g/ha		BLWs and sedges
2,4-D-amine salt 58% SL	3500	6300 ml/ha		Broad-spectrum weed control
2,4-D-sodium salt 80% WP	2000-2600	2500-3250 ml/ha		Broad-spectrum weed control
2,4-D-ethyl ester 38% EC	1200-1800	3530-5290 ml/ha		Broad-spectrum weed control
Ready mix				
Halosulfuron-methyl 12% + metribuzin 55% WG	54+247.5	450 g/ha		Grasses and sedges
Mesotrione 2.27% + atrazine 22.7%	875	3500 g/ha		BLWs and grasses
Topramezone 1% + atrazine 30% SC	930	3000 g/ha		BLWs and grasses
2,4 D-sodium salt 44%+ metribuzin 35% + pyrazosulfuron-ethyl 1% WDG	1320+1050+30	3000 g/ha		Broad-spectrum weed control

Weed management in cotton

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Diuron 80% WP	750-1500	1000-2200 g/ha	PE	BLWs and sedges
Pendimethalin 30% EC	750-1250	2500-4165 ml/ha		Grasses and some BLWs
Pendimethalin 38.7% CS	580.5-677.25	1500-1750 ml/ha		Grasses and some BLWs
Ready mix				
Pyrithiobac-sodium 3.1% + pendimethalin 34% ZC	650-742	1752-2000 ml/ha		For BLWS and grasses
Sole application				
Fenoxaprop-p-ethyl 9.3% EC	67.5	750 ml/ha	PoE	For control of grassy weeds
Propaquizafop 10% EC	62.5	625 ml/ha		For control of grassy weeds
Fluazifop-p-butyl 13.4% EC	125-250	1000-2000 ml/ha		For control of grassy weeds
Quizalofop-ethyl 5% EC	50	1000 ml/ha		For control of grassy weeds
Pyrithiobac-sodium 10% EC	62.5-75	625-750 ml/ha		BLWs
Glufosinate-ammonium 13.5% SL	375-450	2500-3300 ml/ha	PoE (directed spray)	For broad-spectrum weed control
Paraquat dichloride 24% SL	300-500	1250-2000 ml/ha	PoE (directed spray)	For broad-spectrum weed control
Ready mix				
Pyrithiobac-sodium 6% + quizalofop-ethyl 4% EC	75+50	1000-1250 ml/ha	PoE	For broad-spectrum weed control

Weed management in wheat

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Pendimethalin 30% EC	1000-1500	3300-5000 ml/ha	PE	Controls grasses and some BLWs
Pyroxasulfone 85% WG	127.5	150 g/ha		Controls mostly grasses and some BLWs
Ready mix				
Pendimethalin 35% + metribuzin 3.5% SE	875+87.5	2500-3000 ml/ha		BLWs & grasses
Sole application				
Isoproturon 50% WP	1000	2000 ml/ha	PoE (30–35 DAS)	Grassy weeds
Isoproturon 70% WP	1000	1330 ml/ha		Grassy weeds
Metribuzin 70% WP	175-210	250-300 g/ha		Grasses and BLWs
2, 4-D-amine salt 58% SL	500-750	860-1290 ml/ha		BLWs & sedges
2, 4-D-sodium salt 80% WP	500-840	625-1000 ml/ha		BLWs & sedges
2, 4-D-ethyl ester 38% EC	450-750	1320-2200 ml/ha		BLWs & sedges
Metsulfuron-methyl 20% WP	4	20 g/ha		BLWs & sedges
Pinoxaden 5.1% EC	40-45	800-900 ml/ha		Grassy weeds
Carfentrazone-ethyl 40% DF	20	50 g/ha		BLWs & sedges
Clodinafop-propargyl 15% WP and DF	60	400 g/ha		Grassy weeds
Sulfosulfuron 75% WG	25	33.3 g/ha		Controls both grasses and BLWs
Fenoxaprop-p-ethyl 10% EC	100-120	1000-1200 ml/ha		Grassy weeds
Ready mix				
Carfentrazone 20% + sulfosulfuron 25% WG	20+25	100 g/ha		BLWs & grasses
Metsulfuron-methyl 10% + carfentrazone-ethyl 40% DF	25	50 ml/ha		BLWs & sedges
Mesosulfuron-methyl 3% + idosulfuron-methyl-sodium 0.6% WG	12+2.4	400 ml/ha		BLWs & grasses
Sulfosulfuron 75%+ metsulfuron-methyl 5% WG	30+2	40 g/ha		BLWs & grasses
Clodinafop-propargyl 15%+metsulfuron-methyl 1% WP	60+4	400 g/ha		BLWs & grasses
Metribuzin 20% + clodinafop-propargyl 9% WP	120+54	600 g/ha		BLWs & grasses
Metribuzin 42% + clodinafop-propargyl 12% WP	210+60	500 g/ha		BLWs & grasses
Fenoxaprop 7.77%+ metribuzin 13.6% EC	100+175	1250 ml/ha		BLWs & grasses
Halauxifen-methyl 20.8% + florasulam 20% WG	12.76	31.23 g/ha		BLWs

Table 4. Lesson learned in weed management under conservation agriculture

Particulars	Constraints /Changes	Possible solution
Weed shift	Annual to perennial weeds	De-establishment of perennial weeds
Tough to kill weeds	Weed escape or not being controlled	Manual removal of escaped weeds
Late emergence of weeds	Retention of crop residues prolonged weed emergence	Strategic weed management, change in weed management practices
Weed seed bank	Enrichment of weed seed bank	Encourage seed predation or weed seed harvest
Mono-tonus weed management	Overreliance on herbicides	Integrated weed management to be practiced
Over-reliance on herbicides	Continuous use of non-selective herbicides	As per the weed flora herbicide needs to be applied/rotated
Use of a similar mode of action of herbicide	Use of similar herbicides for a prolonged period	Herbicide rotation with different modes of action is required
Crop cultivars	Similar types of crop cultivars	Selection of weed-competitive cultivars
Non-efficacy of pre-emergence herbicides	Use of less spray volume	As per crop residue load, spray volume may be increased
Herbicides formulation	EC formulation of herbicides	Use of granular or CS formulation of pre-emergence herbicides under optimum moisture condition
Herbicide efficacy	Poor efficacy of herbicides	Use of at least 500 L/ha of spray volume for pre-emergence and 375 L/ha for post-emergence herbicides
Nozzle	Use of hollow cone nozzles	Flat-fan or flood-jet nozzles to be used
Sprayer	Gun sprayer for large area spraying	Due to high pressure so much drift takes place and the desired quantity of herbicide cannot reach to target site, hence, avoid gun sprayer for herbicide application
Herbicide	Similar types of herbicides	Use of low dose high potency herbicides for broad-spectrum weed control and the least environmental hazards
Ineffective control of broad-spectrum weeds	Use of similar kinds of herbicides	Use of pre-mix/ready mix or tank mix application of compatible herbicide for broad-spectrum weed control
Mono-tonus use of days old herbicides	Continuous use of recommended herbicides	Smart selection of herbicides, based on weed flora

depleting the weed seed bank can reduce weed severity. Essential strategies for effective and sustainable weed management in conservation agriculture include using non-selective herbicides before seeding, applying pre-and post-emergence herbicides with appropriate competitive cultivars, incorporating cover crops between rows, and utilizing other non-chemical approaches.

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