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Weed management strategies for conservation agriculture: A review

Laxman Navi, NS Mavarkar, Kushal and Manjunath Madhukar Mopagar

Laxman Navi
Ph.D. Scholar, Department of Agronomy, University of Agricultural Sciences, GKVK, Bengaluru, Karnataka, India

NS Mavarkar
Department of Agronomy, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Kushal
Ph.D. Scholar, Department of Agronomy, University of Agricultural Sciences, GKVK, Bengaluru, Karnataka, India

Manjunath Madhukar Mopagar
Ph.D. Scholar, Department of Agronomy, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

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Abstract

Conservation agriculture (CA) represents an agricultural management approach characterized by minimal soil disturbance, the retention of residue for soil cover, and crop rotation at its core. In contrast, conventional agricultural practices involve intensive tillage, clean cultivation, and excessive agrochemical use, contributing to environmental deterioration and pollution. The main goals of implementing conservation agriculture practices include promoting agricultural sustainability, conserving resources and improving the biological functions of the agro-ecosystem, all achieved by minimizing mechanical interventions and using external inputs thoughtfully. However, the adoption of CA faces challenges in managing weeds due to alterations in tillage patterns, planting systems, and other management strategies. The key strategy for mitigating weed infestation in CA involves preventing field contamination. Various techniques, such as adjusting crop planting dates, increasing crop density, employing band placement of fertilizer, breeding competitive cultivars with allelopathic effects, retaining crop residue, practicing crop rotation, and utilizing the stale seed bed technique can be employed for effective weed control. Herbicides are considered as integral part of weed management in CA, can be used in conjunction with other options to optimize results. To enhance weed control efficacy in CA, it is crucial to integrate diverse weed management strategies, as no single method can provide the desired level of control. A comprehensive approach ensures a broader spectrum of weed control under CA practices.

Keywords: Conservation agriculture, weed management, tillage, cover crop, stale seedbed

Introduction

Over the past century, the global population has quadrupled, rising from 1.8 billion people in 1915 to a milestone of 8 billion people as of November 15th, 2022, according to the most recent estimate by the UN. Projections suggest that the global population is expected to reach around 9.7 billion by 2050 (Anon., 2022) [2]. The combination of population growth and increasing incomes in developing countries, leading to dietary changes such as higher protein and meat consumption, is driving up global food demand. Projections indicate that food demand is expected to increase by anywhere between 59 to 98 percent by the year 2050 (Anon., 2022) [2]. The current population of India stands at 1.42 billion and is expected to reach 1.5 billion by 2030 and 1.67 billion by 2050. Meanwhile, present food grain production in India is 330 million metric tons (MT), with a projected need to increase production to 400 MT to meet food requirements. Globally, the population is expected to reach 9.7 billion by 2050, necessitating a 60 per cent increase in food production from current levels to meet nutritional needs. Developing countries, experiencing the highest population growth, face significant challenges including socio-economic issues, food insecurity and poverty. Therefore, the agriculture sector must prioritize higher yields and increased food grain production. As the world's population continues to grow, per capita arable land decreases, underscoring the need to enhance food production efficiency both in terms of time and space to guarantee food and nutritional security. Since 1950-51, the Green Revolution has quadrupled food grain production through the adoption of High-Yielding Varieties (HYVs), intensive input usage, and extensive tillage practices. However, the intensive cultivation has resulted in the degradation of natural resources such as soil, water and vegetation. To address these challenges, there is a necessity to increase food production using less land, effectively harnessing natural resources and minimizing

Corresponding Author:
Manjunath Madhukar Mopagar
Ph.D. Scholar, Department of Agronomy, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

environmental impact. Achieving this goal can be facilitated by adopting conservation agriculture practices (Kassam *et al*., 2009; Lal, 2015) [29, 35].

Conservation Agriculture

If we look into conservation agriculture is basically a sustainable farming system defined as "a methodology for resource saving agricultural crop production, emphasizing on enhancement of natural and biological processes above and below ground" (FAO, 2019) [17]. It conserves the resources like Conserve the natural resources and Avoid degradation of land and other natural resources.

Origin of Conservation Agriculture

The Industrial Revolution, which began in the late 18th century, heralded the invention of numerous new technologies and machinery. This led to mechanization of work in all sectors. The efficiency of the work got increased as machines did not get tired like humans. Looking into that mechanization of agriculture began after the advent of tractors during 1900s. People felt that this can revolutionize agriculture by transforming it into commercial farming from subsistence farming. The capitalist mindset looked at it in a way to commercialize agriculture and earn profit from it. They started tilling the soil to get higher output. Over tilling and overgrazing had a drastic negative impact on agriculture leading to degradation of the tillage. Excessive tilling eroded the top layer and lead to the Dust Bowl in the United States. Drought leads to lack of moisture in the top soil layer increasing the friability of the soil particles. As the soil particles did not have anything to hold on to, so with wind it started to blow which affected the visibility and caused health issues. It rendered large hectare of land unproductive. All these problems led to the formation of new type of sustainable agriculture system i.e., Conventional Agriculture. It is the combination of ideas given by Mr. H.H. Bennet who is the father of soil conservation and Mr. Edward H. Faulkner who is the father of no-tillage.

Among the various countries, the USA holds top position in terms of area under conservation agriculture with 35.6 m ha followed by Brazil and Argentina. As of the latest available data, the total area under conservation agriculture worldwide is approximately 156.99 million hectares.

Table 1: Extent of implementation of Conservation agriculture in world wide

Country	Area (M ha)
USA	35.61
Brazil	31.81
Argentina	29.18
Canada	18.31
Australia	17.7
China	6.7
Russia	4.5
Paraguay	3.0
Kazakhstan	2.0
Others	8.18
Total	156.99

Principles of Conservation Agriculture

A resource saving technology based on three principles:

1. Minimal soil disturbances enabled through no-till/reduced tillage
2. Maximum soil cover/residues
3. Diversified crop sequences/rotations (spatial and temporal crop sequencing) (Hobbs *et al.*, 2008) [25].

Minimal soil disturbances: The importance of this principle is that it focuses on reducing the traffic in agriculture land. Due to inversion of soil, especially by primary tillage the soil aggregates break exposing the soil organic matter, which gets oxidized resulting in decreased soil fertility and increasing carbon footprint of agriculture by increasing GHGs. This will decrease land productivity in due course of time. The advantages of this principle are.

- Reduced water and wind erosion
- Reduction of fuel, time and labor costs
- Increasing Water infiltration and conserving soil moisture
- Decreasing the amount of fertilizer per hectare

Maximum soil cover/residues: It says that minimum 30 per cent of the land must be covered with residues. As presently we are facing the issue of residue management and residue burning, so by going for residue retention on the field in this method we can solve the problem. It also provides physical layer of protection for the top soil from wind erosion and water erosion. It also acts as a source of food for the microbes which will enhance the soil biodiversity. The other benefits are.

- Recycling of nutrients
- Organic matter accumulation and C sequestration
- Suppressing weeds

Diversified crop sequences/rotations: This will break the cycle of pest, disease and weeds which is associated with monocropping. Moreover, it will act as a contingent cropping planning during various weather vagaries by intercropping**.** Inclusion of legumes will enhance the nitrogen content of the soil as well. Other benefits include.

- Increase in water use efficiency
- Enhance the soil structure, diverse range of soil flora and fauna
- Reduction of pest populations and plant diseases
- Increase soil fertility and yield

Weed dynamics in Conservation Agriculture

Numerous studies have been undertaken to examine the direct and interactive effects of the three principles of Conservation Agriculture (CA) on weed dynamics (Chauhan *et al.,* 2012; Farooq *et al.*, 2011; Giller *et al.*, 2009) [10, 18, 22]. The principle of minimum soil disturbance, one of the three Conservation Agriculture (CA) principles, encompasses various tillage regimes that influence the vertical distribution of weed seeds. Studies have reported that seeds infiltrate the soil much more slowly in no-till soil compared to conventional tillage, leading to a concentration of weed seeds that make up about 60-90 per cent in the top 5 cm of the soil surface (Barberi *et al.*, 2001; Swanton *et al.*, 2000) [5, 54]. Under the Conservation Agriculture (CA) system, at least 30 percent of crop residue is maintained, which can be beneficial for improving soil quality. Nonetheless, it does not always result in a reduction in weed germination and emergence. (Liebman and Mohler, 2001) [36]. While crop residues can indirectly reduce weed seed production by limiting weed growth through mechanisms such as light interception, physical barriers and allelopathy, they can also lead to a higher accumulation of weed seeds due to the trapping of wind-dispersed weed seeds (Tuesca *et al.*, 2001) [57].

Problems associated with Conventional Agriculture: Traditional agricultural practices usually involve intensive tillage operations aimed at preparing a finely pulverized seedbed. These practices commonly include clean cultivation, which entails removing or burning all residues post-harvest, leading to nutrient loss from the soil profile. Moreover, leaving the soil bare without any cover increases moisture loss from the soil surface. Traditional agriculture relies heavily on the indiscriminate and excessive use of agrochemicals such as fertilizers and pesticides. This reliance results in reduced input use efficiency, lower factor productivity and environmental pollution. Conservation agriculture practices aim to promote agricultural sustainability through the implementation of sustainable management techniques that reduce environmental degradation and conserve resources while maintaining highly profitable systems. These practices also seek to enhance the biological functions of agro-ecosystems by minimizing mechanical interventions and using external inputs judiciously. Globally, innovations in conservation agriculture-based crop management technologies have demonstrated greater efficiency in addressing emerging agricultural challenges. (Gupta and Seth, 2007) [23].

Benefits of Conservation Agriculture

Conservation agriculture and its components have been associated with numerous benefits, including reductions in the cost of production, opportunities for crop diversification and savings in water, nutrients and soil quality (Jat *et al*., 2019; Somasundaram *et al*., 2019) [27, 53], increased yields, enhancing productivity (Page *et al*., 2019; Pradhan *et al*., 2018; Thierfelder *et al*., 2015) [42, 45, 56] environmental benefits (Montgomery, 2007) [39], resource improvement and reduced incidence of weeds.

Overall, Conservation Agriculture presents a holistic approach to sustainable farming that not only improves economic returns for farmers but also contributes to environmental conservation and the long-term viability of agricultural systems.

Importance of weed management

Weed management involves applying specific principles and suitable methods to enhance the vigor and uniformity of crop stands while discouraging weed invasion and growth. It covers prevention, eradication and control through regulated use, invasion restriction, growth suppression, prevention of seed production and complete destruction. And some of the harmful effect of weeds on crop plants like

- Decreased crop yields
- Diminished quality of agricultural produce
- Depletion of soil nutrients
- Rise in pest and disease occurrences
- Increased production costs
- Reduced efficiency of human labor and agricultural machinery

Weeds have long posed a challenge for crop production and successful agriculture. Globally, weed-related food losses amount to about 300 million tonnes, representing 11.5 percent of total food production. In India, weeds cause a monetary loss of about 2000 crores of Rupees.

Table 2: Estimated losses due to pests in India

Pest	Percent loss	Value (Rs. crores)
Weeds	33	1980
Insects	20	1560
Diseases	26	1200
Misc. pests	8	480
Stored pests	7	420
Rodents	6	360
Total	100	6060

The estimated yield losses due to weed infestation in India was 33 per cent and Rs. 1980 crores. Which was higher loss as compared to other crop losses.

Weed management strategies in conservation agriculture

Various approaches employed to successfully manage weeds in Conservation Agriculture (CA) systems include preventive measures and cultural practices such as tillage, using crop residue as mulches, intercropping, employing cover cropping and cultivating competitive crop cultivars. Additionally, the use of herbicide-tolerant cultivars and herbicides is also part of weed management strategies in CA systems.

Preventive weed management

Preventive weed management aims to hinder the introduction of new weed populations and minimize the overall emergence and spread of weeds in the field. This involves:

- Ensuring the use of crop seeds that are free from weeds.
- Employing practices to prevent the transfer of weed seeds or propagules between areas and crops, such as maintaining clean machinery, using screens to filter irrigation water, and controlling livestock movement.
- Utilizing well-decomposed manure or compost to avoid introducing viable weed seeds.
- Clearing weeds near irrigation ditches, fence rows, and other areas before they set seeds.
- Mechanically cutting the reproductive parts of weeds before they release seeds.
- Enforcing strict weed quarantine laws to prevent the introduction of invasive and harmful weed seeds or propagules into the country.

Cultural and other practices

A core long-term objective of sustainable and effective weed management is not merely controlling weeds in crop fields but establishing a system that reduces weed establishment and minimizes weed competition with crops. Given global environmental concerns, traditional weed management practices such as tillage, mulching, intercultivation, intercropping, cover crops, crop rotation/diversification and other agro-techniques, previously considered uneconomical or impractical-should be reconsidered and emphasized in weed management under Conservation Agriculture (CA). One of CA's key principles is maintaining ground cover with dead or live mulch, which limits the time available for weeds to establish during fallow or turnaround periods. Nonetheless, challenges persist under CA, including the emergence of recently produced weed seeds near the soil surface, difficulties in disrupting perennial weed roots, herbicide interception by thick surface residues, and shifts in the timing of weed emergence. Shrestha *et al*. (2002) [50] concluded that long-term changes in weed flora result from interactions among several factors, including tillage practices, environmental conditions, crop rotation, crop types and the timing and methods of weed management practices.

Stale seedbed Technique

The stale seedbed technique is founded on the principle of flushing out germinating weed seeds before crop planting, thereby reducing the seed bank in the soil's surface layer and minimizing subsequent weed seedling emergence. Stale seedbeds reduce weed populations in direct-seeded rice (Rao *et al.*, 2007) [47], and may be especially effective when combined with no till practices (Chauhan *et al.*, 2006) [8]. Pittelkow *et al.* (2012) [44] reported that while Zero Tillage (ZT) stale seedbed practice effectively reduces the population of sedges and grasses, it does not effectively control redstem weeds. This practice is very effective in ZT wheat in the north-western Indo-Gangetic Plains (Mahajan *et al.,* 1999) [37].

Tillage

Tillage, historically fundamental in conventional agriculture, remains a primary weed management method. Its impact depends on equipment choice and tillage depth, influencing weed seed dispersion in the soil profile and subsequent weed quantity in fields. Variations in seed distribution within soil profiles cause shifts in weed populations. Although deeply buried seeds may germinate, they struggle to emerge due to soil depth and suppressing weed seedlings. Tillage also triggers weed germination by exposing seeds briefly to light. Different forms of tillage practices are as follows

1. Conventional tillage: 2 ploughings + 1 harrowing + 2 inter cultivation at 25 and 50 DAS
2. Minimum tillage: 1 ploughing + 1 harrowing
3. Zero tillage: no tillage operation

Regardless of the weed species present, reduced tillage practices notably decreased the weed population compared to minimum tillage methods. Through soil inversion, reduced tillage facilitated the deeper burial of weed seeds, preventing their emergence and leading to a substantial decline in weed populations in wheat (Gangawar *et al.*, 2006) [20]. Conversely, minimum tillage, characterized by less soil disturbance and the retention of weed seeds on the soil surface, resulted in significantly higher weed population and dry weight compared to both reduced and conventional tillage methods in finger millet (Hatti *et al*., 2018) [24]. The effective weed control observed in reduced tillage treatments may be attributed to the stimulative effect of tillage on weed seed germination, as well as the greater concentration of weed seeds at the soil surface. Additionally, periodic plowing in reduced tillage treatments may contribute to the suppression of germinated weeds in finger millet (Vijaymahantesh *et al*., 2013) []. Zero tillage do not provide fine tilth condition which favor for weed germination and it not exposer of weed seeds to the upper soil layer to germinate and they remain in the lower surface of the soil in wheat. This might be due to different tillage practices significantly influenced weed population (Chhokar *et al*., 2007 and Chopra and Chopra, 2010) [13, 14].

Seed rate, spacing and plant population: Planting density and arrangement impact the structure of the crop canopy, influencing its efficacy in suppressing weeds. Narrow row spacing introduces variations in the microclimate, affecting factors such as light intensity, evaporation, and soil surface temperature. A more uniform and densely distributed crop, established through precise planting, optimizes the utilization of light and water resources, enhancing the crop's competitive ability. Crops grown in narrow rows engage in competition with weeds at an earlier growth stage than those in wider rows, achieving faster canopy closure and improved root distribution. Narrow row widths and higher seeding density help minimize the biomass of late-emerging weeds by reducing light availability beneath the crop canopy. Reports have shown reduced weed growth in rice due to increased population density and decreased spacing (Ghuman *et al.* 2008) [21].

Bullar and Walia (2004) [6] reported that increased wheat grain yields at higher seeding rate (150 kg ha^{-1}) are attributed to thick crop stand and the production of more effective tillers. The effective tiller numbers are negatively correlated with weed dry matter. So increased crop yields at higher seed rate (150 kg ha^{-1}) may also be attributed to reduced *P. minor* density and also reported that 15 cm row spacing recorded significantly lower panicle number and dry matter accumulation of *Phalaris minor* at harvest compared to 22.5 cm spacing in wheat. This might be due to the crowding effect of wheat plants in closer rows suppresses weeds and increased wheat grain yield by 10.8%. Reduced light interception by crop plants at wider row spacing might have become the limiting factor in the production of crop biomass and effective tillers. And the wheat canopy covered the ground more rapidly in closer rows than in wider rows, thus suppressing early weed growth.

Continuous drilling at 20 cm spacing suppressed 27-37 per cent of weed growth compared with 20-cm spacing. This might be due to narrowing plant-to-plant spacing in weedy or partially weedy environments may result in decreased weed growth. Reduced spacing between plants or rows enhances a crop's competitiveness with weeds by facilitating faster canopy cover and reducing light penetration through its leaves, leading to lower weed populations and higher rice yields (Joshi *et al*., 2016) [28].

Arvadiya *et al*. (2012) [4] reported that plant population, 1,11,111 plants ha^{-1} recorded significantly lower total weed population at 20 DAS (78.27 no m^{-2}) and dry weight of total weeds at harvest (206.66 kg ha^{-1}) in sweet corn as compared to lower plant population. The increased space in lower plant populations can lead to luxurious weed growth, resulting in higher dry matter accumulation by weeds. Conversely, higher plant populations have recorded the lowest weed dry weight due to a better crop stand, creating a smothering effect on weed growth.

Cultivar competitiveness: Crop species and cultivars exhibit varying abilities to compete with weeds, and this competitive advantage is greatly influenced by environmental conditions. The competitive strength of a crop variety depends on its capability to suppress weed growth and seed production, or withstand weed interference while still achieving high grain yields. Different genotypes of the same crop can vary in their competitive abilities against weeds due to differing morphological traits. While there is conflicting evidence on which crop characteristics contribute most to competitiveness, numerous studies highlight the significance of traits such as rapid germination and emergence, robust seedling growth, quick leaf expansion, prompt canopy development, extensive root systems, and the production of allelopathic compounds by the

crop. The enhanced competitiveness of a crop is primarily attributed to vigorous growth, which reduces both the quality and quantity of light beneath the crop canopy (Buhler 2002) [7].
Certain wheat varieties, such as 'PBW 154', 'WH 435', and 'PBW 343', exhibit higher competitiveness against little seed canary grass (Phalaris minor) compared to durum varieties like 'PBW 233' (Chauhan *et al.* 2001) [9]. This is likely due to the higher leaf area index (LAI) of the former varieties (Walia 2002) [60]. Likewise, the rice variety 'PR 108' demonstrated superior weed smothering ability compared to 'PR 114', 'PR 116', and 'PR 118' owing to its relatively higher leaf area index (LAI) (Ghuman *et al.* 2008) [21].

Crop residue and cover crops: The presence of crop residues on the soil surface can impact the germination and emergence of weed seeds by affecting sunlight availability, creating physical impediments and contributing to improved soil and moisture conservation as well as soil tilth. These residues exhibit considerable variations in dimensions, structure, distribution pattern, and spatial heterogeneity. The germination of weeds can be influenced by factors such as weed biology, quantity, position (vertical or horizontal, below or above weed seeds), and the allelopathic potential of crop residues (Chauhan *et al.* 2006) [8].
Utilizing cover crops is a fundamental and sustainable approach for weed management, optimizing natural resource use while mitigating water runoff, nutrient leaching, and soil erosion. Robust competition from cover crops can effectively hinder the growth of numerous annual weeds emerging from seeds. Aggressive cover crops also have the potential to significantly reduce the growth and reproduction of perennial weeds, which may emerge or regenerate from roots, rhizomes, or tubers, posing greater challenges for suppression. In Conservation Agriculture (CA), weed pressure can be minimized by incorporating short-duration legume crops such as mungbean, cowpea, green gram, Sesbania, etc., during the fallow period between wheat harvesting and rice planting. This practice promotes weed emergence during the legume period and helps decrease the weed population during the rice season (Kumar *et al.* 2012) [32].
Tarun *et al.* (2018) [55] reported that maintaining crop residue on the soil surface, creating a residue-laden condition can suppress weed seedling emergence, delay emergence timing and provide the crop with a competitive advantage, ultimately reducing the necessity for weed control in mustard. In the case of wheat productivity, in situ incorporation of residue proves beneficial when coupled with tillage operations, which are essential for effectively mixing the residue into the soil, facilitating its proper and timely decomposition (Gangwar *et al.*, 2006) [20].
Cowpea (*Vigna unguiculata* (L.) Walp), dolichos lablab (*Lablab purpureus* L.) and velvet bean (*Mucuna pruriens* (L.)) were assessed for biomass in Bergville. Lablab exhibited superior performance in weed suppression, consistently displaying the lowest weed biomass throughout all observation weeks. Despite the acidic nature of the soil, lablab rapidly developed a canopy cover compared to other cover crops, effectively suppressing weeds across all sampling periods. Lablab's tolerance to low soil pH provided it with a competitive advantage, enabling it to outcompete weeds for limited resources crucial for growth and development
Following closely was cowpea, which also demonstrated minimal weed biomass throughout the sampling times. With its prostrate growth condition, cowpea effectively smothered weeds. Known for its vigorous growth, cowpea is well-adapted to hot climatic conditions. However, herbicides did not exhibit effective weed suppression, largely attributed to suboptimal herbicide application methods (Mutondiwa *et al.*, 2018) [40].

Mulching and brown manuring: A critical element of Conservation Agriculture (CA) technology involves establishing ground cover with either dead or live mulch, reducing the window for weed establishment during fallow or turnaround periods. Singh *et al.* (2007) [52] confirmed that application of wheat residue mulch at 4 t ha^{-1} reduces the light penetration to ground surface and increases soil temperature reduces the weed seed germination and suppress the weed seedling emergences. Apart from this it reduces the evaporation and conserve moisture, plant take upper hand in utilizing the resources and reduces weed growth at initial stage. Few weeks after application of wheat residue, wheat straw leachates contain the allelochemical called hydroxamic acid which inhibit the weed seed germination and suppress the weed seedling emergences results in lower density and dry weight of weeds.
Ramachandran *et al.* (2012) [46] reported that application of Alachlor @ 1.0 kg a.i. ha^{-1} as Pre-emergence + Brown manuring (2,4-D @ 0.5 kg ha^{-1} at 35 DAS) recorded significantly lower weed density and higher weed control effiency, kernal yield and B:C ratio of maize. This could be attributed to the pre-emergence application of alachlor, which effectively controlled weeds during the early stages and maintained nearly weed-free conditions up to 30 days after sowing (DAS). Weed suppression continued thereafter due to the shade effect of daincha crop residue and the rapidly growing canopy of maize until harvest. Additionally, daincha serves as a green manure crop, fixing atmospheric nitrogen in the soil, which is efficiently utilized by crop plants, leading to increased growth and crop yield.

Intercropping: Intercropping is a cultivation method involving the growth of a suppressive crop between rows of the main crop to avoid competition for water or nutrients. This technique serves as an effective weed control strategy in Conservation Agriculture (CA) by pre-empting resources utilized by weeds and suppressing their growth. Intercropping short-duration, fast-growing and early-maturing legume crops with long-duration and widely spaced crops leads to rapid ground cover, exhibiting a greater overall weed-suppressing capability compared to sole cropping. For example, total weed growth decreased under intercropping combinations of chickpea + mustard compared to sole chickpea cropping, without compromising the productivity of the main crop (Rathi *et al.*, 2007) [48]. Similar observations were also recorded by Dubey (2008) [16] under a maize + cowpea intercropping system. The reduction in weed density and dry matter in maize-legume intercropping compared to sole cropping can be attributed to increased canopy cover and decreased light availability for weeds (Kumar *et al.*, 2010) [31]. Intercropping cowpea with maize under Conservation Agriculture (CA) had the most significant impact on weeding activities in the farmer's field, resulting in a 40 per cent increase in labor hours due to the additional precision required for weeding compared to maize-only fields (Lai *et al.*, 2012) [34].
Seema *et al.* (2019) [49] reported that maize + groundnut intercropping with 1:2 ratio recorded lower total weed density. This could be attributed to the groundnut intercrop suppressing weed emergence compared to sole maize cultivation. The inclusion of groundnut as an intercrop also provided ground cover, further suppressing weed infestation compared to sole maize. Intercropping with legumes has a smothering effect on weed emergence. Intercropping maize with groundnut offers the advantage of additional yield compared to sole maize

cultivation. The beneficial effects of intercropped legumes, such as nitrogen transfer to associated crops, could be a major factor contributing to yield enhancement in maize crops.

The allelopathic potential of sorghum, soybean, and sesame is well-documented. In soybean, rhizospheric soil compounds, including organic acids, acetone, aldehyde, naphthalene, phenyl and furan hydrocarbons, have been identified as allelochemicals affecting weed seed germination. When intercropped with cotton, these three crops may exhibit stronger competitiveness against purple nutsedge. It is also possible that both competition and allelopathy contribute to the suppression of purple nutsedge in these intercropping systems (Iqbal *et al*., 2007) [26].

Sequential cropping: Crop rotation entails the systematic alternation of different crops on the same parcel of land. This practice is effective in curbing the accumulation of weed populations and preventing shifts in weed composition, as certain weed species thrive in environments with similar growth requirements. Diversifying the system, even for a brief period, and intensifying practices by incorporating summer legumes or green manuring have proven effective in mitigating weed-related challenges (Singh *et al*., 2008) [51]. The superior performance of the rice-wheat-greengram sequence was primarily due to its occupation of the field for the maximum number of days compared to other crop sequences. Continuous cultivation of the rice-wheat system in north-western India has resulted in an increase in the population of sedges and grassy weeds. However, introducing system diversification, even for a brief period, and intensifying practices by incorporating summer green manuring have effectively reduced the weed-related challenges. Inclusion of greengram in the sequence which break the weed cycle results in lower density and higher yield (Singh *et al*., 2008) [51].

Mishra and Singh (2009) [38] reported that soybean - linseed sequential cropping system recorded lower total weed population and weed dry matter due to allelopathic potential of linseed crop residues resulting in lower weed dry matter production in succeeding soybean crop. Wheat - Sugarbeet sequential cropping system reduces the weed density due to broadleaf crops in rotation with narrow-leaf crops and also crops with different agronomic practices can reduce the weed seed bank density (Nassir *et al*., 2009) [41].

Allelopathy: The inhibitory response of certain plant species to their neighboring plants has been observed for a considerable period. Austrian botanist Hans Molisch coined the term "allelopathy" to describe this effect, attributing it to biochemical interactions between plants. An example of allelopathy can be found in rapeseed, mustard, and radish, which contain glucosinolates that break down into potent volatile allelochemicals known as isothiocyanates during residue decomposition (Uremis *et al*., 2009) [58].

Abdul *et al*. (2010) [1] reported that the application of crop residue from sorghum, sunflower, and brassica at a rate of 7.5 tons per hectare resulted in the inhibition of weed growth, likely attributed to the presence of various phytotoxins. Sorghum contains compounds such as gallic acid, protocatechuic acid, syringic acid, vanillic acid, p-hydroxybenzoic acid, p-coumaric acid, benzoic acid, ferulic acid, caffeic acids, phydroxybenzaldehyde and sorgoleone. Sunflower contains allelochemicals like chlorogenic acid, isochlorogenic acid, α-naphthol, scopolin and annuionones. Brassica contains several putative allelochemicals including simple phenolic acids such as phydroxybenzoic acid. These compounds collectively contribute to lower weed density and higher crop yield.

The application of Sorgaab reduces weed populations by either killing existing weeds or inhibiting weed germination through its allelopathic effect. Furthermore, the incorporation of sorghum stalks into the soil also leads to weed suppression, suggesting the release of sorghum allelochemicals into the soil reported by (Cheema and Khaliq, 2012 and Cheema *et al*. 2010) [11, 12].

Water and Nutrient management: Nutrients and water represent the primary inputs that not only impact crop growth and productivity but also influence weed infestation. Their interactions often affect each other's efficacy. Effectively managing nutrients and water is crucial for weed management in Conservation Agriculture (CA) systems. providing irrigation water at critical growth stages of the crop helps plant to absorb more amount of water and produces the more biomass and pose competition to the weeds reported by Das and Yaduraju (2007) [15]. Similarly, application of higher dose of nitrogen would have favoured the early growth and vigours growth of crop giving it a competitive edge over weeds results in lower weed population and higher yield of crop (Dubey, 2008) [16].

Chemical Weed management

The adoption of herbicides for weed management is gaining popularity due to their cost-effectiveness compared to traditional weeding methods, lower labour requirements, efficacy in controlling challenging weed species and the flexibility they provide in weed management strategies. Herbicides play a crucial role in weed management within Conservation Agriculture (CA). Pankaj and Angiras (2008) [43] reported application of atrazine 1.5 kg a. i. ha^{-1} which effectively control the weeds by interfering the photosynthesis of the weeds, which turns the green leaves to yellow leaves and finally death of the weed plants results in lower weed density and dry matter accumulation and similar results were reported by Kaur *at el.* (2008) [30].

Application of Clodinafop (60 g ha^{-1}) is a grassy weed killer whereas Metsulfuron (4 g ha^{-1}) is a broad leaf weed killer, with the broad spectrum of weed killer with the combination of the two herbicides control the complex weed flora result lower weed density and higher yield (Chopra and Chopra, 2010 and Kumar *at el*., 2015) [14, 33].

Integrated weed management

Given the diverse array of weed challenges in Conservation Agriculture systems, no single method of weed control. Whether cultural, mechanical or chemical can achieve the desired level of weed control independently. The Integrated Weed Management (IWM) system is not meant to replace selective, safe, and efficient herbicides; rather, it serves as a prudent strategy to encourage the judicious use of herbicides alongside other safe, effective, economical, and environmentally friendly control measures. Ganapathi *at el.* (2022) [19] reported that integrated weed management practices, IWM - pendimethalin 750 g ha^{-1} PE + hand weeding at 30 DAS reduces weed density and weed dry weight, due to which pendimethalin interfere the protein biosynthesis and weed plant leads to chlorosis and necrosis of plant, ultimately the death of plant upto 30 DAS. After that hand weeding 30 DAS which effectively control weeds and avoil crop weed competition and simillar results repored by Mishra and Singh (2008) [38].

Conclusion

Conservation Agriculture (CA) encompasses a range of efficient technologies that can achieve equal or higher yields compared to

Conventional Tillage (CT). Changes in tillage practices affect the depth of weed seeds in the soil, leading to shifts in weed species and influencing the effectiveness of control practices. Reduced tillage options increase reliance on herbicides, contributing to the growing problem of weed resistance to herbicides among Conservation Agriculture farmers worldwide, especially worsened by the use of Herbicide-Tolerant (HT) crops. However, ZT coupled with residue management offers advantages such as improved soil moisture, moderated temperature and enhanced weed control. Successful adoption of Conservation Agriculture relies on machinery, herbicides and effective management strategies. Therefore, integrating weed management practices involving both chemical and non-chemical methods (such as residue management, cover crops, and appropriate crop varieties) is crucial for long-term success in CA systems.

Future Line of Work

Advancements in weed management within conservation agriculture are likely to focus on precision technologies, innovative cover cropping strategies and the development of resilient crop varieties. Integration of artificial intelligence for targeted weed identification and robotic systems for precise weed control may enhance efficiency. Additionally, research on bio-based herbicides and tailored cover crop mixtures could offer sustainable solutions. Collaborative efforts among researchers, farmers and technology developers will play a crucial role in shaping the next frontier of weed management, ensuring that conservation agriculture continues to evolve as a sustainable and productive farming paradigm

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