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Weed Management in Conservation Agriculture: Integrated Strategies for Sustainable Agroecosystems

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Conservation Agriculture (CA), based on zero-tillage, permanent residue cover, and diversified crop rotations, helps reduce soil organic carbon loss, erosion, and input inefficiency. However, eliminating plowing removes mechanical weed control, making weed management a major challenge. Under zero-tillage, 60–90% of viable weed seeds concentrate in the upper 0–5 cm soil layer, intensifying early competition and favoring problematic grasses, perennial weeds, and herbicide-resistant biotypes. This article reviews weed dynamics across Transition, Stabilization, and Equilibrium phases, the physical and allelopathic suppression provided by heavy mulching (≥6 t/ha), microbial biocontrol interactions, and an Integrated Weed Management (IWM) framework suited to the Indo-Gangetic Plains and Eastern India's rice-fallow systems.

Foundations of Conservation Agriculture and the Weed Bottleneck

Conservation Agriculture (CA) is based on minimum soil disturbance, permanent soil cover (≥30%), and diversified crop rotations, improving soil health, reducing erosion and conserving resources (Jat et al., 2020). However, weed management remains a major challenge because eliminating tillage leaves weed seeds near the soil surface, promoting simultaneous emergence with crops and potentially causing 35–80% yield losses. Therefore, CA requires proactive, integrated weed management based on weed emergence, seed-bank dynamics and changing weed flora (Chauhan et al., 2012; Rao et al., 2017).

Physical and Cultural Weed Suppression Mechanisms

In Conservation Agriculture, physical and cultural practices provide the first line of weed management by reducing weed emergence and improving subsequent chemical and biological control. Surface residues (4–8 t/ha) suppress weeds through light interception (85–95% PAR reduction and altered R:FR ratio), hydrothermal buffering, and mechanical obstruction, resulting in reduced germination, seedling emergence, and pre-emergence mortality (Chauhan et al., 2012). The zero-till stale seedbed technique involves light irrigation or rainfall 10–15 days before sowing to stimulate weeds from the 0–5 cm layer, followed by knockdown control at the 2–3 leaf stage using glyphosate (1.0 kg a.i./ha) or paraquat (0.5 kg a.i./ha), before direct seeding with narrow-tine zero-till drills (Mishra & Singh, 2012; Kumar et al., 2016; Rao et al., 2017).

Crop diversification and smother cover crops such as cowpea (*Vigna unguiculata*), sunnhemp (*Crotalaria juncea*), and *Sesbania aculeata* during 60–70-day summer fallows rapidly close the canopy, reduce weed biomass by 60–80%, and contribute 40–80 kg N/ha, thereby suppressing weeds and improving soil fertility (Chauhan et al., 2012; Rao et al., 2017).

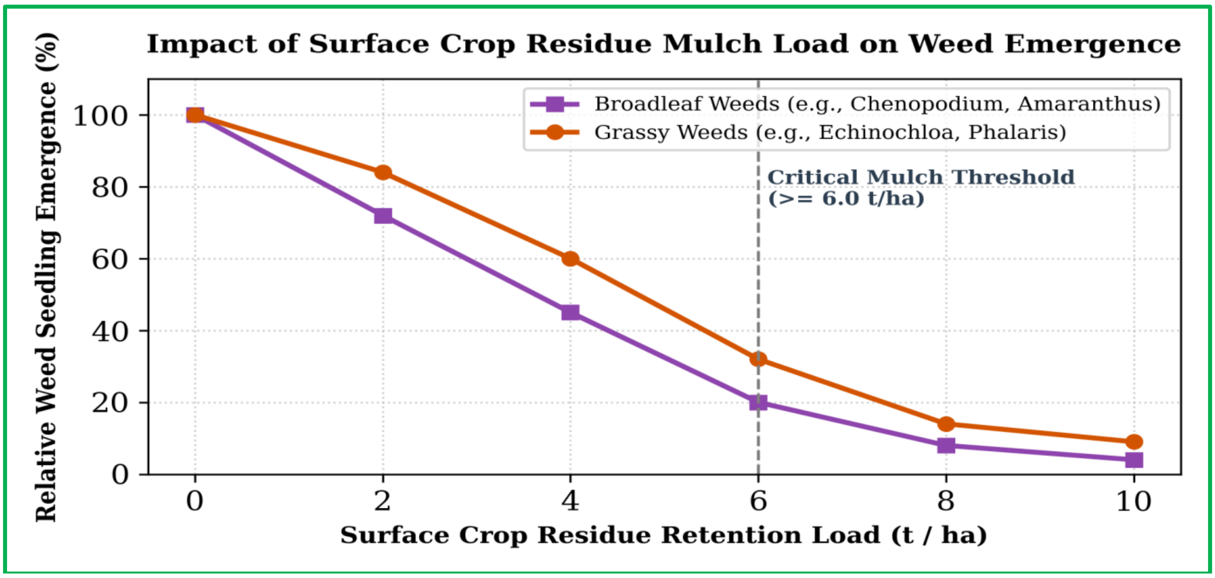

Figure 1: Impact of surface crop residue retention load (t/ha) on relative emergence of broadleaf vs. grassy weeds (Chauhan et al., 2012; Aušra, 2025).

Allelopathic Suppression and Soil Microbial Interactions

Conservation Agriculture enhances biochemical and biological weed suppression by maintaining organic root zones, residue-derived compounds, and diverse microbial communities. Allelopathic plants such as sorghum (*Sorghum bicolor*) release sorgoleone, which inhibits electron transport at PSII; sunflower (*Helianthus annuus*) residues release sesquiterpene lactones and phenolic acids that disrupt weed membrane permeability and mitosis; while Brassica residues produce glucosinolate-derived isothiocyanates (ITCs) through myrosinase activity, acting as natural biofumigants against weeds and soil-borne pathogens. Undisturbed soil also supports high microbial biomass carbon (MBC), with Deleterious Rhizobacteria (DRB) such as *Pseudomonas*, *Bacillus*, and *Streptomyces* producing HCN, phenazine-1-carboxylic acid, and 2,4-DAPG to suppress weed radicle growth. Additionally, Azotobacter, Azospirillum, PSB, and AMF enhance crop root growth and early N, P, and Zn uptake, accelerating canopy closure and suppressing weeds (Chauhan et al., 2012).

Chemical Weed Management and Herbicide Stewardship in CA

Table 1: Recommended Chemical Weed Management Schedule for Major CA Cropping Systems (Kumar et al., 2016; Rao et al., 2017; Soni et al., 2020).

Application Timing	Target Weed Flora	Herbicide Active Ingredient	Dose (a.i./ha)	Operational Specifics in CA
Pre-Plant Knockdown (Stale Seedbed)	Emerged annual grasses, sedges, perennials	Glyphosate 41% SL OR Paraquat 24% SL	1.0 – 1.5 kg 0.5 kg	Apply 10–14 days prior to seeding on active weed flushes; zero soil disturbance.
Pre-Emergence (PE) (0–3 DAS)	Annual grasses & small-seeded broadleaves	Pendimethalin 38.7% CS OR Atrazine 50% WP (Maize)	1.0 – 1.5 kg 1.0 kg	Use micro-encapsulated (CS) formulations to wash past surface residue layers.
Early post-emergence (15–20 DAS)	Mixed broadleaf weeds & annual sedges	Bispyribac-sodium 10% SC OR 2,4-D Ethyl Ester	25 g 0.5 – 0.75 kg	Target young weed seedlings (2–4 leaf stage); use flood-jet nozzles.
Post-Emergence (POE) (20–28 DAS)	Foliar grass weed escapes	Quizalofop-p-ethyl 5% EC OR Fenoxaprop-p-ethyl	50 g 100 g	Selective ACCase inhibitors for grassy weeds in zero-till legume/oilseed systems.
Sedgicide POE (20–30 DAS)	Specific sedge flushes (*Cyperus* spp.)	Halosulfuron-methyl 75% WG	67.5 g	Systemic control of underground nut-tubers in direct-seeded rice and maize.

In Conservation Agriculture, surface residues (5–8 t/ha) can intercept 30–60% of broadcast pre-emergence herbicides, while EC formulations may bind to straw lignin and reduce herbicide reaching the soil. CS formulations, such as pendimethalin 38.7% CS, are preferred because they resist photodegradation and move into the seed zone with 10–15 mm rainfall or irrigation. Effective resistance management requires rotating herbicide Sites of Action (SoA) between seasons, using multi-site tank mixtures such as pendimethalin + atrazine in maize and bispyribac-sodium + pyrazosulfuron in DSR, and integrating heavy residue mulch to reduce overall herbicide dependence (Bhullar et al., 2014; Rao et al., 2017).

Contextual Application in Odisha Agro-Ecologies

The Agro-Ecological Landscape of Odisha

Agriculture in Odisha spans three distinct agro-topographical zones: the Coastal Alluvial Plains, the Central Undulating Tablelands, and the Western/Southern Hilly Highlands.

Table 2: Customized CA Weed Management Schedule for Odisha Agro-Ecologies

Cropping System	Dominant Weed Challenges	Applied CA Weed Management Protocol	Agronomic & Economic Gain
Direct-Seeded Rice (DSR) (Kharif Season)	*Echinochloa colona, Digitaria sanguinalis, Cyperus difformis*	Stale seedbed + Glyphosate (1.0 kg) -> Sowing via ZT drill -> Pendimethalin 38.7% CS (1.0 kg) at 0–2 DAS -> Bispyribac-sodium (25 g) + Pyrazosulfuron (20 g) at 18–22 DAS.	Water saves 35% & Rs. 6,500/ha in labor; controls 92% of early weed flushes.
Rice–Zero-Till Pulse (Greengram / Blackgram) (Rabi Rice-Fallows)	*Cynodon dactylon, Physalis minima, Melilotus alba*	Direct drilling into standing rice stubble (4–5 t/ha) using Happy Seeder -> Stubble acts as moisture-conserving mulch -> POE Quizalofop-ethyl (50 g) at 20 DAS for grass escapes.	Utilizes residual moisture; straw mulch suppresses 75% of rabi broadleaf weeds.
Zero-Till Maize–Mustard (Western Odisha Plateau)	*Trianthema portulacastrum, Commelina, Cyperus rotundus*	ZT planting with residue -> Atrazine (1.0 kg) + Pendimethalin (0.75 kg) PE tank-mix -> Halosulfuron-methyl (67.5 g) for perennial sedge escapes.	Eliminates diesel tillage costs; enhances maize grain yield by 14–18%.

Mechanization: Turbo Happy Seeder & Super Seeder Integration

Adoption of Conservation Agriculture in Odisha and Eastern India depends on suitable direct-seeding machinery. The Turbo Happy Seeder cuts and lifts paddy straw, places seed and fertilizer, and redistributes residue as surface mulch, while the Super Seeder combines shallow strip tillage with precision seeding under heavy residue. Custom Hiring Centres (CHCs) improve smallholder access to zero-till drills and multi-crop planters at affordable costs, particularly in Sambalpur, Bargarh, Ganjam, and Balasore.

Multi-Tier Integrated Weed Management (IWM) Framework

Relying solely on chemical herbicides in CA is agronomically unsustainable and accelerates the evolution of resistant weed biotypes. Long-term success requires a multi-tier Integrated Weed Management (IWM) framework (Figure 4). Integrated Weed Management (IWM) combines preventive measures (weed-free seed, clean machinery, and weed-free channels/bunds), cultural and physical practices (5–8 t/ha mulch, stale seedbeds, competitive cultivars, and diverse rotations), biological and allelopathic approaches (sorghum, sunflower, Brassica residues, beneficial microbes, and *Zygogramma bicolorata*), and chemical stewardship through targeted herbicide use, suitable formulations, and rotation of herbicide modes of action to delay resistance.

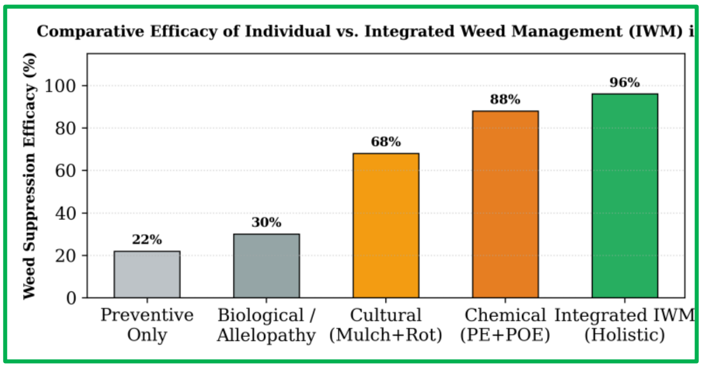

Figure 2: Comparative weed suppression efficacy of individual control strategies versus an integrated IWM approach in CA (Rao et al., 2017; Soni et al., 2020; Bhullar et al., 2014).

Operational Challenges, Policy Roadmap, and Future Horizons

While Conservation Agriculture (CA) offers major agronomic and ecological benefits, its adoption faces key challenges, including **competition for crop residues** used as fodder, fuel and thatching, **moisture and crusting problems** in light soils when residues are unevenly distributed, and **proliferation of perennial sedges** such as *Cyperus rotundus*, which may require targeted control. Wider adoption also depends on improving access to **zero-till drills, Happy Seeders and other precision equipment** through Custom Hiring Centres and Farmer Producer Organizations (FPOs).

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