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REVIEW ARTICLE

Pulse crops as effective living mulches: An eco-conscious weed management approach

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Abstract

The evolution of weed management strategies from basic cultural techniques to novel, integrated approaches reflects technological advancements that promise further improvements in weed management strategies, fostering more efficient and eco-friendly farming practices. Using legume crops as living mulches for weed suppression has gained considerable attention in agricultural systems. This method involves strategically planting leguminous cover crops as intercrops to inhibit weed growth and improve soil health, potentially boosting crop yields through reduced weed pressure and enhanced nutrient availability. The successful implementation of living mulches requires careful selection of crop species, optimal planting density, and appropriate management practices. Choosing compatible legumes, optimizing planting geometry and employing suitable termination methods are essential for maximizing the weed-suppressing and soil-enhancing benefits of living mulches. The efficacy of intercropping systems in controlling weeds largely depends on intercrop components' growth rate and duration. Weed management strategies rely on understanding plant interactions, including the competitive ability of main crops at various growth stages to inhibit weed expansion. While intercropping shows promise for enhancing crop dominance over weeds, weed control efficiency varies among different intercrops due to factors affecting the intercrop-weed relationship. Smallholder farmers find this practice appealing for improving labour productivity and land use through intensification and resource utilization for maximum yield. Research on developing genotypes suitable for weed suppression and studies on combined herbicide applications and optimal dosage determination for effective control of mixed weed flora is necessary. The shift towards integrating pulse crops as a cornerstone in weed management strategies presents a promising avenue for research and application. The comparative analysis underscored in this review showcases the capacity of legumes to offer a viable alternative to synthetic herbicides and mechanical controls, paving the way for their increased adoption in diverse farming systems.

Keywords

cover crop; intercrop; legumes; living mulch; sustainable weed management

Introduction

Agriculture is vital for economic stability and food security in developing nations, driving socio-economic growth by feeding populations and supporting rural economies. However, crop productivity is severely hindered by weeds competing with crops for essential resources. Effective weed control is critical for maintaining sustainable agriculture and ensuring food security in these regions (1, 2) since weeds compete with crops for sunlight, water and nutrients and reduce yield and quality. They disrupt farming practices, making operations less efficient and more labour-intensive. These issues affect both immediate crop yield and long-term soil health. Weeds also host pests and diseases, further complicating farmer's challenges (3). Effective weed management is crucial for maintaining agricultural productivity and sustainability, especially in developing countries. This requires a multifaceted approach that includes mechanical, chemical and biological control methods tailored to each agroecosystem's needs. Research shows that weeds can cause up to 34% crop yield losses, significantly higher than insects and diseases (8-10%) (4). This underscores the importance of proper weed management.

The evolution of weed management strategies has been marked by a shift from traditional methods to more innovative approaches. In the 1960s, research into using living mulches began, growing progressively throughout the 1970s and 1980s. Significant advancements have been made in the past decade as the focus on sustainable agricultural systems has intensified (5). This shift paved the way for adopting new agro strategies into cropping practices, with the spotlight turning to innovative solutions. One such solution is the use of Cover Crops (CCs), with major emphasis laid on live mulches that leverage the inherent properties of certain crops. Cropping systems incorporating ground covers have progressed significantly for various agricultural systems. These include orchards, vineyards and conventional agronomic crops such as maize, minor millets and forage crops (6). This progression represents a significant step forward in weed management strategies, combining the benefits of traditional innovative methods with sustainability as the mainstay.

Current Strategies and Challenges in Weed Management

In conventional arable farming and most of the agroecosystems, weed control heavily relies on synthetic herbicides followed by mechanical practices. Still, their widespread use raises concerns about human health risks, environmental pollution, additional costs incurred and the emergence of herbicide-resistant weeds (7). However, using herbicides for weed control has not effectively managed long -term weed seedbanks (8). The overreliance on chemical solutions has contributed to developing herbicide-resistant weed species, posing a significant challenge to farmers and researchers. Also, various weed management tactics are likely to increase the production costs. In addition to dealing with weeds, implementing weed control measures presents various challenges and difficulties (Fig. 1, 2). This realization has sparked a renewed interest in exploring alternative, non-chemical methods to effectively manage weeds while promoting ecosystem health.

Fig. 1. Challenges arising from weeds.

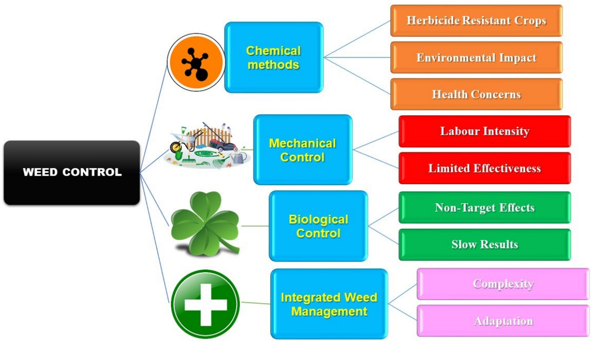

Fig. 2. Challenges associated with weed control measures.

Non-chemical weed control methods, developed to minimize chemical inputs, are generally less cost-effective than chemical alternatives due to their labour-intensive nature. Techniques such as thermal weed control require slow application speeds to ensure proper weed suppression and prevent regrowth, leading to higher labour and fuel costs (9, 10). Unlike chemical treatments, which may require fewer applications, non-chemical approaches often demand more frequent interventions. Mechanical weed control, including tilling, mowing and hand weeding, is commonly employed in conventional and organic farming, especially on small farms where chemical use is restricted. However, these methods can lead to soil compaction, erosion and degradation, ultimately reducing soil fertility and productivity (11, 12). The labour-intensive nature of mechanical weeding makes it impractical for large-scale farming, particularly in areas with limited labour availability (13, 14). Perennial weeds further complicate management due to their regenerative capacity, and weeds within crop rows often evade control, causing significant yield losses (15, 16). Repeated mechanical interventions can also negatively affect soil structure and long-term efficiency (17). Bioherbicides, which include organic agents like phytotoxins, pathogens, fungi and bacteria, have been explored for weed control since the 1980s (18). Over 100 bacterial and fungal agents have been studied for this purpose. While bioherbicides offer several advantages, such as preventing weed seed germination, being environmentally friendly, reducing pollution, ensuring user safety and posing a low risk of resistance, they remain primarily confined to laboratory research and a few minor field sites. The main challenge lies in creating bioherbicide products that are efficient, stable, eco-friendly and free from long-term side effects (19).

The Emergence of Pulse Crops as Live Mulches

The terms living mulch and undersown crops can be used synonymously. Live mulches are defined as cover crops interplanted or undersown with a main crop, intended to serve the purposes of a mulch, such as weed suppression and regulation of soil temperature. These living mulches grow concurrently with the main crops over an extended period, unlike traditional cover crops, which are typically incorporated into the soil or terminated with herbicides (20). The primary functions of live mulches include suppressing weed growth (21), protecting soil from erosion due to water and wind (22), improving soil structure, nitrogen fixation and soil fertility enhancement (23), soil water preservation and enhancing the populations of soil fauna and also natural enemies of crop pests (24).

Pulses are integral to global cropping systems and daily dietary practices (25). Pulse crops are indispensable in a cropping system, as they can fix atmospheric nitrogen, which is crucial for the main crop, recycling soil nutrients and enhancing soil nutrient availability. This reduces the dependency on chemical fertilizers and various tillage practices and supports sustainable agricultural practices. Unlike traditional cover crops, which are typically terminated before the main crop is planted, live mulches are maintained throughout the growing season, providing a continuous ground cover and competing with weeds for resources.

Pulse crops, such as lentils, chickpeas, and peas, have gained attention due to their potential to serve as live mulches in cropping systems (26, 27). Furthermore, the role of pulse crops extends to improving soil structure and health. They increase water infiltration, help in assimilating excess nitrogen and sometimes aid in carbon storage, thereby improving the overall fertility and health of the soil (28). Compared to no cover crop, cover crops can reduce weed seedling emergence by lowering soil temperature, decreasing light availability and trapping nitrogen, making it less available to weeds (29). Actively growing cover crops, like hairy vetch, reduce light penetration, affecting small-seeded weeds more due to their limited resources (30). Additionally, cover crops lower soil temperature fluctuations, helping maintain weed seeds in dormancy or delaying their emergence (31, 32).

Mechanisms for Enhancing Weed Control Efficiency

Pulse-based live mulches can effectively decrease weed infestations through various mechanisms (20). Legumes utilized as living mulch effectively manage weeds, particularly when planted densely (33). This effectiveness of legume cover crops in weed suppression primarily arises from their strong competitive advantages, particularly in terms of light and habitat utilization compared to weeds (34). With their rapid growth and extensive canopy, legumes can outcompete weeds for light and space, thereby suppressing weed growth. However, perennial species are less favoured in dryland systems due to their higher water requirements and the potential for resource competition (35). Pulse crops exhibit competitive growth and shading effects that suppress weed growth. Their dense canopies shade the soil, limiting the light available for weed germination and growth, thereby reducing weed infestation (36). Moreover, the broad-leaved legumes with horizontal leaf orientation cover the soil faster than narrow-leaved cereals, making them more effective at suppressing the weeds.

Pulse crops also possess allelopathic properties, which release biochemical compounds that inhibit weed germination and development. These allelochemicals have been demonstrated to suppress the growth of various weed species, contributing to effective weed control (36). Pisatin, an allelopathic compound isolated from pea plants (*Pisum sativum* L.), has been shown to inhibit the growth of cress (*Lepidium sativum* L.) and lettuce (*Lactuca sativa* L.) seedlings (37). Similarly, spring vetch (*Vicia sativa* L.) exhibits allelopathic effects that suppress weeds like *Chenopodium album* L., *Matricaria chamomilla* L. and *Stellaria media* (38). In velvetbean, the allelopathic effect is attributed to L-DOPA, which is exuded from leaves and roots, inhibiting radicle elongation in *Amaranthus hypochondriacus* L. and barnyard grass (*Echinochloa crusgalli*) (39, 40). Hairy vetch (*Vicia villosa*) and cowpea (*Vigna unguiculata*) also exhibit allelopathic properties, with their aqueous extracts reducing germination and radicle growth in various weeds such as pitted morning glory, wild mustard and Italian ryegrass. These effects were most pronounced at higher extract concentrations (41).

Allelopathic cover crops show great promise in utilizing allelopathy to control weeds and decrease reliance on synthetic herbicides (42). The allelochemicals diffuse through the soil and affect the growth of neighbouring vegetation. These naturally occurring compounds can be as complex as synthetic herbicides and offer a wide range of selectivity for weed control (43, 44). Sun et al. (45) identified o-coumaric acid as a key allelochemical in hairy vetch, inhibiting alfalfa root growth at a concentration of 1.6 mg/ml. The weed-suppressing impact of *M. sativa* cultivars was found to correlate with the presence and potency of growth inhibitors, mainly phenolic compounds, which exhibit allelopathic solid activity. Therefore, the ability of legume crops to suppress weeds may correspond to the intensity of their allelopathic properties (46).

The light interception is a primary way that living mulches to control weeds. The quantitative aspects of light, such as its intensity and amount intercepted by plants, determine the efficiency of canopy photosynthesis. Concurrently, the qualitative properties of light determine plant shape and morphology. In a crop-weed competition scenario, both aspects of light change compared to situations where the crop or weed canopy exists alone. Under mixed crop-weed circumstances, mutual shading between leaves decreases available photosynthetically active radiation (PAR), lowering photosynthetic rates (47). When used as living mulches, legumes create physical barriers that inhibit weed emergence. This suppression occurs as the dense foliage of legumes shades the soil and reduces the light available for weed seed germination and growth (48). Early light interception by the living mulch positively correlates with weed suppression, sustained by a strong negative correlation between cumulative light interception and weed biomass across various weed species (49).

Furthermore, the diversification of crop rotations with pulse crops disrupts weed life cycles and reduces weed populations' buildup over time. This strategic integration of pulse crops into crop rotations contributes to sustainable weed control in agricultural systems. Perennial legumes are more effective if grown over a year in crop rotation (50).

Selection of Suitable Pulse Crops

The botanical classification of cover crops influences agroecosystem benefits and cultivation suitability. The morphological and physiological characteristics of the component species are key predictors of intercropping yields (51, 52). Among these, fast-growing species are often preferred for cover crop intercropping due to their ability to quickly establish a canopy that suppresses weed growth and conserves soil moisture (53). In weed management, legumes are particularly suitable as cover crops. Furthermore, legumes typically have different growth periods than many weed species, which helps to minimize resource competition. This temporal complementarity ensures that the legume cover crops can thrive without depriving the main crops of essential resources like light, water and nutrients (51, 54). When legumes are combined with other species with different growth habits and resource needs, they can effectively cover the soil, suppress weeds and contribute to biomass productivity. This integrated approach enhances weed control and promotes overall agroecosystem health by improving soil structure, enhancing biodiversity and increasing resilience against pests and diseases.

The inter sowing of crops with living mulches has yielded mixed results, with the effectiveness of weed control often hinging on strategic crop selection (55). Critical traits for effective weed suppression in crops include rapid germination, early growth vigour, tillering capacity, height, leaf area development, growth rates, shading ability (56), allelopathy (57) and early light interception (21). When selecting cover crops, prioritizing those with faster growth and shorter vegetation periods is crucial to minimize resource competition (58).

Fujii evaluated 53 cover crops, including 26 leguminous species, at SNAES in Japan, finding hairy vetch to be the most promising for weed control. Hairy vetch demonstrated an 80% inhibition rate in the Plant Box Method and achieved up to 100% weed control in field trials. Additionally, it improved subsequent rice yield (42). Hairy vetch enhances soil structure, water infiltration, nitrogen availability and overall soil productivity. Maize, often the dominant crop in smallholder farming systems, pairs well with legumes to enhance productivity. However, the benefits of intercropping with cover crops must surpass any potential resource losses, particularly water, to be deemed advantageous (59). Hence, a dense, early-season ground cover provided by leguminous crops is recommended to prevent weed establishment effectively (38).

Self-seeding annual legumes are more suitable for no-till strip crop systems, as they can establish quickly and provide adequate ground cover without replanting every season (60).Timely termination of annual leguminous cover crops is crucial to prevent them from becoming volunteer plants, which can compete with the main crops in subsequent seasons (61). This requires careful management to balance the benefits of weed suppression and soil enhancement against the potential drawbacks of resource competition and the risk of cover crops becoming pests themselves. According to Gaudin *et al*. (62), forage legume species that produce a high yield of above-ground mass are considered effective competitors for local resources but depend on the size of their seeds, sowing rate and sowing time (63).

Global research has explored various legumes as live mulches, consistently highlighting their efficacy in reducing weed biomass. Gerhards (64) found significant reductions in weed biomass when using leguminous cover crops as both living and dead mulches, noting that short-growing cultivars have minimal impact on cereal grain yields. Suwarto and Aish (65) tested three legume cover crops with cassava varieties, finding *P. javanica* the most promising for improving cassava cultivation. Despite the extensive research, identifying the ideal legume for living mulch across diverse ecosystems remains challenging due to the variability in environmental and management factors.

Twin Benefits of Pulse as Live Mulches

Legume cover crops contribute to increased carbon inputs which, combined with reduced tillage, elevate soil organic carbon levels and enhance soil health. The improvement in soil quality is evident through increased microbial biomass, enzyme activity and overall soil organic matter, which are essential for sustainable soil management (66). The enhanced soil structure and increased organic matter create an environment less conducive to weed growth, further aiding weed suppression. Fabaceae cover crops, such as clover and vetch, substantially contribute to soil carbon and nitrogen levels through their plentiful post-harvest residues and root exudates. These compounds serve as the primary energy source for soil microorganisms (67). The rich organic matter from legume residues promotes a healthy and active soil microbial community, critical in nutrient cycling and soil fertility. This microbial activity can also help break down weed seeds and suppress weed germination.

A critical factor in maintaining soil fertility and productivity is including a diverse crop rotation strategy with cover crops (68). Leguminous cover crops play a crucial role in this category by enhancing soil fertility through nitrogen fixation and improving soil structure. Maintaining cover crops during autumn and winter is vital for reducing nutrient losses and erosion, particularly in light soils with low fertility (69). These cover crops help to stabilize the soil, thereby preventing degradation from wind and water erosion, which are severe threats to agricultural fields. Leguminous cover crops, such as sunn hemp, have shown a pronounced effect on improving soil moisture levels. During maize harvest, soil moisture at depths of 0-15 cm and 15-30 cm increased by 1.63 -2.91% due to live mulching, with sunn hemp demonstrating more significant benefits compared to other mulching materials (70). This improvement in soil moisture not only supports the growth of primary crops but also creates unfavourable conditions for weed germination and growth.

Field experiments conducted by Bhaskar et al. (71) in 2012 and 2013 across four locations in Vidarbha explored the feasibility of introducing four selected living mulches (gliricidia, sesbania, sorghum sudan grass and sunn hemp) in monoculture cotton farming. The results indicated that during dry years, the growth of living mulch negatively impacted cotton yield due to competition for limited water resources. This suggests that leguminous living mulches can be successfully integrated into cotton cultivation in environments with sufficient moisture, offering effective weed control and maintaining acceptable cotton yields. Utilizing cover crops as living mulch also decreased the maximum soil temperature by about 5°C at a depth of 5 cm compared to leaving dead mulch on the soil surface (72). This temperature moderation helps in creating a more favourable microclimate for crop growth and can inhibit weed seed germination.

Intercropping of Pulse Crops: Enhancing Weed Suppression

Pulse crops utilized as living mulches in intercropping systems should establish quickly, reaching peak growth as early weeds emerge. This peak growth phase must not coincide with the main crop's growth period. An effective living mulch suppresses weed growth during the critical period when emerging weeds could potentially reduce crop yield (73). The timing and rate of interseeding pulses are crucial factors determining the success of crop-living mulch intercropping systems (Fig. 3) (20). Higher densities of living mulch have shown superior weed control compared to lower densities (74, 75).

Research indicates that cover crops containing legumes enhanced subsequent crop yield by an average of 13%, while those without legumes reduced main crop yield by an average of 4% (76). Mas-Ud *et al*. (77) reported higher grain and stover yields in maize plots interseeded with cowpea mulch than plots without mulch. Experiments at the International Institute of Tropical Agriculture demonstrated that interplanting *Centrosema pubescens* and *Psophocarpus palustris* as legume living cover between maize resulted in very low weed populations. Despite having lower biomass accumulation compared to rye, Hungarian vetch may offer superior weed management in potato farming due to its reduced competitiveness with the main crop (78). Hungarian vetch also outperformed common vetch and grass peas, which suppresses weed growth while enhancing potato yields.

Banik et al. (79), found that intercropping wheat and chickpeas with 20 cm row spacing decreased weed biomass by 69.7% and reduced weed population by 70% compared to monocropping. Choudhary et al. (80) observed that a maize-cowpea intercropping system with a 1:5 ratio reduced the density of grasses (34 m^{-2}) and sedges (15.2 m^{-2}) compared to pure maize stands, possibly due to lower nutrient uptake by weeds. Similarly, Midya *et al*. (81) reported that intercropping upland rice with black gram (20 cm) effectively suppressed grassy weeds like *Echinochloa colonum*, *Digitaria sanguinalis* and *Digera alternifolia* due to the smothering effect of black gram hindering weed germination.

A long-term study by Sharma *et al*. (70) in Selakui, Dehradun from 2001 to 2004 investigated the impact of in situ grown live mulches using legumes such as sunnhemp, dhaincha and cowpea in a maize-wheat cropping system. The results showed that maize productivity increased by 5.6 -8.8% with legume mulching applied 30 days after planting compared to no mulching. Additionally, wheat yields increased by 13.3-14.0% in the subsequent season due to legume mulching in maize, benefiting from improved soil moisture and nutrient retention. Mathukia *et al*. (82) reported that in the pearl millet + black gram (1:1) intercropping system, there was significantly reduced density and dry weight of weeds as compared to sole cropping thus recorded higher weed control efficiency (65.8%) and weed smothering efficiency (52.0%) over sole cropping.

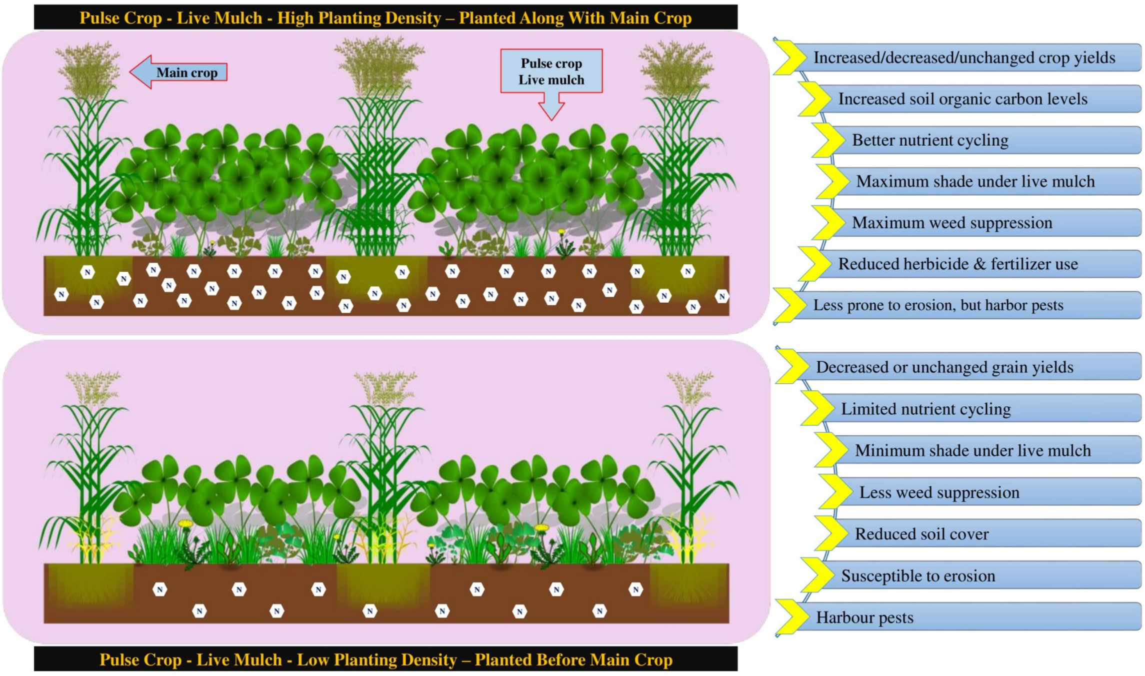

Fig. 3. Dual possible benefits (weed and soil health management) when pulse crops are grown as live mulch in intercropping systems with varied planting time and density.

Adopting leguminous green manure intercrops in rice-based cropping systems can suppress the weeds with their fast growing canopy (83). Goswami *et al*. (84) reported that live mulching with sesbania decreased total weed density and dry weight compared to non-mulched treatments, recording the highest weed control efficiency at the harvest stage. Growing daincha as an intercrop and incorporating it 30 days after sowing resulted in higher nutrient uptake, weed suppression and improved soil fertility in aerobic rice cultivation (85). Intercropping as live mulching with daincha and cowpea in aerobic rice improved weed control efficiency over dead mulching with coirpith and shredded coconut waste at 5 tonnes per hectare (86). Pulses are more compatible in intercropping with cereal crops. So, numerous studies have investigated the impact of interplanting pulses as living mulches on cereals grain yields and associated weed growth (Table 1). The findings are variable, influenced by soil conditions and dynamic environmental factors.

Comparison with Dead & Synthetic Mulches

Living mulches have proven to be more effective at suppressing weeds than cover crop residue and synthetic mulches. This superiority stems from their active growth and ability to compete for essential resources such as water, nutrients and light. In contrast, dead mulches, including cover crop residue and synthetic options, do not consistently suppress weeds as effectively (87). A study on globe artichoke plots further supports this finding, showing that biodegradable film mulch resulted in more abundant weed populations than plots using living mulch (88).

The weed-suppressing ability of living mulches varies across different stages of weed development. It is particularly high during weed germination and early growth stages, while remaining moderate during seed production, seed survival and perennial structure survival phases. On the other hand, dead mulches show a different pattern of effectiveness. Their weed-inhibiting capacity is moderate during germination and emergence, low during growth and seed production phases and almost non-existent for seed survival and perennial structure survival stages (20).

Synthetic mulches, including plastic and landscape fabrics, are widely used for their longevity and effective weed suppression. Polythene mulching significantly reduced weed dry matter by inhibiting weed emergence (89). However, these materials often prove expensive and require regular replacement, diminishing their long-term economic viability. Additionally, synthetic mulches pose substantial environmental concerns, particularly regarding soil health and ecosystem balance, including issues of persistence and disposal (90). Synthetic options like plastic mulches elevate soil temperature, potentially harming microbial life and nutrient cycles. They also impede water and air exchange between soil and atmosphere, negatively impacting plant health and soil organisms (91).

Table 1. Effect of various pulse crops in intercropping as live mulch

Main crop	Live mulch	Grain yield (tons ha^{-1})	Weed dry weight (g m^{-2})	Weed ecology	Study area / Reference
Spring wheat & Spring barley	No living mulch - Early sown	6.9	45.4	*Stellaria media*,	(64)
	No living mulch - Late sown	6.8	45.1	*Veronica persica*,	
	Perennial ryegrass - Early sown	6.6	23.1	*Lamium purpureum*,	
	Perennial ryegrass - Late sown	6.8	20.3	*Galium aparine*,	
	White clover - Early sown	6.7	24.1	*Chenopodium album*,	
	White clover - Late sown	6.7	26.7	*Poa annua*	
Maize	Cowpea (7 plants m^{-2})	10.3	--	*Amaranthus retroflexus L.*, *Chenopodium album L.*	(75)
	Cowpea (15 plants m^{-2})	10.9			
	Cowpea (22 plants m^{-2})	11.5			
	Cowpea (30 plants m^{-2})	10.9			
Maize	Hairy vetch (Planting rate (kg ha^{-1})) 0	9.7	240.8	*Sorghum halepense*, *Xanthium strumarium*, *Glycirrhiza glabra*, *Convolvulus arvensis*	(103)
	25	10.4	159.0		
	50	10.8	118.2		
Maize	Cowpea mulching at 30 days	2.61	--	--	(70)
	Cowpea mulching at 45 days	2.39			
	Sunnhemp mulching at 30 days	2.69			
	Sunnhemp mulching at 45 days	2.55			
	Dhaincha mulching at 30 days	2.72			
	Dhaincha mulching at 45 days	2.53			
Winter wheat	No living mulch (Weed free control)	2.756	--	--	Zurich, Switzerland (104)
	White clover	0.324			
	Subclover	0.337			
	Birdsfoot trefoil	0.507			
	Strong-spined medick	0.637			
	No living mulch (Weed free control)	4.817	**--**	--	Lucerne, Switzerland (104)
	White clover	0.745			
	Subclover	1.483			
	Birdsfoot trefoil	0.300			
	Strong-spined medick	1.853			

Nevertheless, synthetic plastic mulch, especially silver mulch, demonstrated the highest water use efficiency compared to other mulch types (92). Still then, in India's Eastern plateau and hill region, a major pulse-producing area, using polythene mulch with drip irrigation every two days is recommended to enhance water productivity (93).

Over time, synthetic mulches degrade, releasing unwanted chemicals into the soil (94). In contrast, organic mulches, including legumes as live mulches, offer a more sustainable and cost-effective alternative. These improve soil health and decrease reliance on synthetic inputs, ultimately enhancing crop plant performance without additional expenses for pesticides or other weed control methods (95). These findings highlight the dynamic nature of weed suppression by living mulches that offer a more comprehensive and long-lasting solution to weed management, particularly in the critical early stages of weed development.

Cost of Living mulching of Legumes

Legume intercropping proves cost-effective by significantly reducing the necessity for chemical weed control, thereby saving farmers expenses on herbicides and other chemical inputs. This approach not only fosters sustainable agricultural practices but also mitigates the emergence of herbicide-resistant weeds, which are a critical concern in modern farming (36). While the initial stages of intercropping may require additional labour for planting and maintenance, the subsequent reduction in labour-intensive activities such as manual weeding and herbicide application can lead to substantial cost savings and potentially enhance overall farm productivity.

Furthermore, integrating live mulches within arable crops presents a valuable opportunity to decrease labour hours and associated expenses related to weed management, concurrently bolstering economic returns (96). Over time, the reduced reliance on herbicides and other chemical inputs leads to significant cost savings and ensures the long-term economic sustainability of legume intercropping systems. Additionally, adopting living mulches can yield savings in machinery costs, which is particularly advantageous in organic farming systems where reduced ploughing is an added benefit. The information on cost-effectiveness of utilizing pulses as live mulches are presented in Table 2.

Overcoming Challenges and Optimizing Pulse-Based Weed Management

Living mulches have necessitated the adoption of novel cropping techniques and innovative strategies for weed control (97). While pulse-based live mulches offer numerous advantages, they also present their own set of challenges. These challenges include potential competition with the main crop and the need for careful management to avoid yield losses. Legume cover crops contribute to atmospheric nitrogen fixation, which indirectly promotes conditions more conducive to weed growth than other types of cover crops (98).

Table 2. Economics of pulse based live mulching

Live Mulch	Main Crop	Reference	Cost of cultivation per ha	Net returns per ha	B:C ratio
Cowpea - 30 days	Maize	(70)	Rs. 11500 (Maize) + Rs. 1500 (legume mulching) Total = Rs. 12500	Rs. 6740	0.539
Cowpea - 45 days				Rs. 5070	0.406
Sunnhemp - 30 days				Rs. 7060	0.565
Sunnhemp - 45 days				Rs. 5940	0.475
Dhaincha - 30 days				Rs. 7310	0.585
Dhaincha - 45 days				Rs. 6000	0.480
Sesbania (brown manuring)	Transplanted rice	(105)		Rs. 53926	3.33
Hairy vetch	Soybean	(106)	146 USD	-30 USD	
Crimson clover			175 USD	-84 USD	
Subterranean clover			241 USD	-176 USD	
Chickpea - 20 cm - no weeding	Wheat	(79)	192 Euro	82 Euro	
Chickpea - 20 cm - one weeding			225 Euro	181 Euro	
Chickpea - 20 cm - two weeding			269 Euro	343 Euro	
Chickpea - 30 cm - no weeding			186 Euro	107 Euro	
Chickpea - 30 cm - one weeding			218 Euro	200 Euro	
Chickpea - 30 cm - two weeding			262 Euro	385 Euro	
Cowpea	Maize	(107)	1080.9 USD	417.4 USD	1.58
Crotalaria			1124.7 USD	686.7 USD	1.92
Green gram			1025.6 USD	744.0 USD	2.07
Groundnut			1097.6 USD	389.7 USD	1.52
Desmodium			1390.8 USD	1157.8 USD	2.20
Beans			1115.9 USD	414.6 USD	1.11

This dual nature of legume cover crops is beneficial for soil health but potentially problematic for weed management, which requires a nuanced approach to their use in agricultural systems. In main crop cultivation, any unwanted plant, regardless of its ecological benefits, is classified as a weed. This classification extends to the self-seeding of legume cover crops in subsequent crops, which can pose significant challenges. This is especially true for species that compete strongly with main crops. Managing these self-seeding legumes can be particularly difficult, especially when dealing with perennial species. These perennials often proliferate, produce numerous seeds and exhibit resilience to abiotic stresses (36).

Interestingly, living mulch has shown a minimal impact on perennial weeds (99), suggesting that alternative strategies may be necessary for controlling these persistent plants. Timing of interseeding of intercrops as living mulches for weed management should coincide with appropriate timing. For example, while snail medic (*Medicago scutellata* (L.) Mill) and burr medic (*Medicago polymorpha* L.) proved effective against weeds, they also competed strongly with corn for resources. This competition significantly reduced corn yields from 15% to 21%, primarily due to competition for nutrients and moisture (100). However, not all legume-corn interactions lead to yield reductions. Caamal-Maldonado *et al*. (40) demonstrated a promising strategy to lessen interaction effects. By delaying the sowing of velvet beans as a living mulch by 20 days after planting corn, they effectively reduced weed biomass by 68% while maintaining corn yield. This finding highlights the importance of timing in implementing living mulch systems.

To optimize legume-based weed management, carefully select compatible species and adjust planting timing to reduce competition. Implement efficient irrigation in water-limited environments. Periodically mow or roll the living mulch to control growth. Optimize spatial arrangement to maximize benefits while minimizing competition between the main crop and living mulch. These strategies can significantly enhance the effectiveness of legume-based weed management in agricultural systems. Farmers and researchers can work towards more sustainable and effective weed management practices in agriculture by implementing these strategies and continuing to research the long-term impacts of living mulch systems.

Future Directions: Advancing Research and Adoption of Pulse-Based Weed Management

The future of pulse-based live mulches holds great promise, with ongoing research and advancements in several key areas (75). One area of focus is cultivar selection, where efforts are being made to develop pulse varieties specifically suited for use as living mulches, featuring traits such as low growth habit, drought tolerance and allelopathic properties. Management optimization is another crucial aspect involving refining techniques for establishing and maintaining pulse-based living mulches, including optimal seeding rates, planting times and termination methods (101). Economic viability is examined through cost-benefit analyses to demonstrate the long-term financial advantages of incorporating pulse-based living mulches into farming systems.

The integration of precision agriculture, leveraging advanced technologies like remote sensing and precision planting, is being explored to optimize the placement and management of these mulches. Furthermore, research is underway to study the potential of pulse-based living mulches to enhance crop resilience in the face of climate change and extreme weather events. The role of pulse-based living mulches in improving nutrient use efficiency and reducing the need for synthetic fertilizers is also a key area of investigation, as is their potential contribution to integrated pest and disease management strategies (102).

There is a push for policy support, advocating for policies and incentives that encourage the adoption of pulse-based living mulch systems as part of sustainable agricultural practices. As research in these areas progresses, a more comprehensive understanding of the potential of pulse-based living mulches in sustainable agriculture can be expected. This will be crucial in addressing modern farming systems' complex challenges, including weed management, soil conservation and environmental protection.

Conclusion

Conventional farming heavily relies on synthetic herbicides and mechanical practices for weed control. However, this approach raises concerns about health risks, environmental pollution, costs, and herbicide-resistant weeds. These challenges have sparked interest in alternative, non-chemical methods for weed management. Pulse crops as living mulches present considerable benefits regarding weed suppression, soil health improvement and environmental sustainability. Their strategic deployment is poised to revolutionize future weed management practices, underscoring the imperative for ongoing research and innovation. Field research, particularly those involving farmers and extension personnel, is essential for raising awareness of the benefits of legumes in weed control, soil sustainability and cost-effectiveness. Continued investment in this area of research can lead to the development of more resilient, efficient and environmentally friendly farming practices, offering significant advantages for producers and ecosystems. As we advance, it becomes increasingly clear that the strategic use of pulse crops can play a pivotal role in shaping future weed management practices.

Authors' contributions

DR contributed towards conceptualization, literature review and editing; KGS designed the framework for comparative analysis and editing; MG provided expertise on biological weed management strategies, proofreading and editing the manuscript; JE collected and compiled the data and visual representations; KA focussed on environmental and sustainability analysis; PV handled citation management, review of literature, formatting and manuscript preparation. All authors read and approved the final manuscript.

Compliance with ethical standards

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