

Review

The Potential of Three Summer Legume Cover Crops to Suppress Weeds and Provide Ecosystem Services—A Review

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Abstract: Recently, there has been growing interest in the use of summer cover crops that can be grown during summer fallow periods of crop rotation. This study evaluates the potential of sunn hemp (*Crotalaria juncea* L.), velvetbean [*Mucuna pruriens* (L.) DC.] and cowpea [*Vigna unguiculata* (L.) Walp.] as three annual legumes summer cover crops. The main objective of this review was to conduct global research comparing these summer cover crops to investigate the benefits, challenges, and trade-offs among ecosystem services when implementing these summer cover crops. In European agriculture, there are three main windows in crop rotation when these summer legumes can be grown: Around mid-spring after winter fallow, early summer after harvest of a winter crop, and mid-to late summer after harvest of an early-season crop. All three legumes can suppress weeds while they are actively growing. After termination, their mulch can create unfavorable conditions for weed emergence. Sunn hemp and velvetbean cover crops can cause a reduction in weed biomass of more than 50%. In addition to their ability to suppress weeds, sunn hemp, velvetbean, and cowpea provide a variety of ecosystem services, such as improving soil health, quality, and fertility, controlling pests, and sequestering carbon. The review highlights their promising role in weed suppression and their contribution to sustainable agricultural practices. However, further research is needed to evaluate their performance in weed management and their environmental impact in field trials under different soil-climatic conditions, as cover cropping is an effective practice but highly context-specific.

Keywords: cover crops; weed control; ecosystem services; *Crotalaria juncea* L.; *Mucuna pruriens* (L.) DC.; *Vigna unguiculata* (L.) Walp.



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1. Introduction

The overuse of synthetic herbicides in agriculture has been associated with undesirable effects on the environment and human health and can also affect soil functions and properties due to their long residence time in the soil [1]. In addition, over-reliance on chemical weed control and extensive use of a few herbicide modes of action have led to the spread of herbicide-resistant weed ecotypes [2]. Therefore, the development of integrated weed management (IWM) systems that incorporate non-chemical agronomic practices is considered essential to address these issues [3]. In the European Union (EU), this is also crucial to achieve one of the EU's Green Deal targets of reducing pesticide use in agriculture by 50% by 2030 [4].

The use of cover crops is one of the agronomic practices considered valuable for weed management. Cover crops are any plant species planted in or after a main crop, grown between fallow periods in the rotation, and then terminated before the next crop

is planted [5]. During the active growth phase, cover crops suppress weed growth by competing for resources or releasing allelopathic root exudates into the soil [6]. Termination is usually done around flowering either mechanically with flail-mowers, roller-crimpers, or by using non-selective herbicides such as glyphosate [7]. After termination, cover crop residues are left on the soil surface to create unfavorable conditions for weed seed emergence by preventing light penetration into the soil or by releasing allelochemicals from dead plant tissue that inhibit weed seed germination [8]. Another option is to incorporate cover crop residues into the soil [9].

In addition to their ability to suppress weeds, cover crops can improve yields of subsequent crops and provide multiple ecosystem services by improving soil structure, reducing soil disturbance and erosion, and optimizing water and nutrient use on agricultural lands [10]. Species that produce large amounts of biomass are very useful for sequestering carbon and increasing soil organic carbon content. This is because cover crops replace bare soil during the fallow period in the crop rotation, and thus enhance carbon assimilation [11]. In addition, the roots and shoots of cover crops feed bacteria, fungi, earthworms, and other soil microorganisms whose activity increases soil carbon content over time [11]. Cover crop species with a deep taproot are also beneficial for nutrient scavenging [12]. There are also cover crops that are useful for suppressing soil nematodes, diseases, and insect pests [13–15].

As for the window of crop rotation in which a cover crop is grown, the most common practice is to plant a cover crop that grows in the winter. Winter cereals as cereal rye (*Secale cereale* L.), oat (*Avena sativa* L.), and barley (*Hordeum vulgare* L.), grasses (*Lolium* spp., *Festuca* spp.), legumes as hairy vetch (*Vicia villosa* Roth), clovers (*Trifolium* spp.), and Austrian winter pea (*Pisum sativum* L.), species from the botanical family of Brassicaceae and multispecies mixtures of the above functional groups are the most widespread [16]. Winter cover crops take advantage of winter precipitation and accumulate large amounts of biomass by mid-spring, when they are terminated before the next cash crop is sown in the spring [5]. In contrast, cover crops that grow in summer, i.e., summer cover crops, are relatively unexplored compared to winter cover crops. However, it is worthwhile to summarize information on their potential to suppress weeds and provide valuable ecosystem services during summer fallow. Summer cover crops can produce large amounts of biomass in a short time, reduce agricultural inputs, improve soil physical properties, and successfully suppress weeds [17]. More specifically, identifying low-input annual legumes that can be grown as summer cover crops would be beneficial for biodiversity, soil fertility, and the agroecological transition to sustainable agriculture [18].

The present study focused on three annual legume summer cover crops: sunn hemp (*Crotalaria juncea* L.), velvetbean [*Mucuna pruriens* (L.) DC.], and cowpea [*Vigna unguiculata* (L.) Walp.]. The main objective of this review was to summarize information on the ability of each species to suppress weeds and the ecosystem services these summer legumes provide in agriculture. The success of cover crops, especially in suppressing weeds, depends on various factors. These factors include the timing of planting, cover crop densities and biomass, the timing of cover crop termination, the cash crop following in the rotation, and multiple climatic variables. Cover crops are a vital component of integrated weed management. Additionally, further practical research is needed, particularly regarding timing and effective termination in subtropical conditions.

2. Overview of Selected Species

The three species evaluated as summer cover crops are legumes that belong to the botanical family Fabaceae, the third largest plant group, which includes about 800 genera and nearly 20,000 species [19]. We focused on legumes because the species of this family improve soil fertility and increase soil organic matter as they have the ability to fix atmospheric nitrogen due to root colonization by rhizobacteria of the genus *Rhizobium* [20]. The soil-climatic requirements of the legumes that have been included in this insight review make them suitable as cover crops during the summer period (Table 1).

Table 1. Main soil-climatic requirements of selected summer cover crops.

Summer Legume Cover Crop	Main Soil Requirements	Optimal Temperature ¹ (°C)	Minimum Rainfall (mm)
Sunn hemp	Well-drained (pH 5–8)	10–30	≥400
Velvetbean	Well-drained (pH 5–8)	19–27	≥400
Cowpea	Well-drained (pH 5–8)	13–28	≥400

¹ Average monthly temperature including day-night temperature variations.

Sunn hemp is a fast-growing, warm-season annual legume with an erect growth that can grow up to 2.5–3.0 m tall. The optimal temperature for its growth is between 10 and 30 °C, with a minimum rainfall requirement of 400 mm [21]. Sunn hemp can produce significant biomass within a short timeframe, ranging from 1 to 6 tonnes per acre, with nitrogen fixation varying from 10 to 17 kg N per acre [22,23]. Velvetbean is an annual, twining, climbing shrub with long tendrils that can grow over 15 m long [24]. It thrives at annual growth temperatures between 19 and 27 °C and requires a minimum annual rainfall of 400 mm, while cowpea growth is optimized at temperatures between 13 and 28 °C with an annual rainfall of about 300 mm or even less [25]. Cowpea is an annual tropical and subtropical legume that grows erect, tendrillous, semi-tendrillous, or bushy [26]. The average biomass production for cowpea and velvetbean is 3 and 2.7 tonnes per acre, respectively, with nitrogen fixation potentially reaching 18 and 8 kg N per acre for cowpea and velvetbean, respectively [27–29]. All three species are low-input cover crops, which means their need for fertilization and irrigation is limited while they can also adapt to marginal lands [30]. Sunn hemp and velvetbean adapt well to infertile soils; there is no need for fertilizer when growing cowpea [25]. The soil should be well-drained; this is the only requirement because none of these species tolerates waterlogging; soil pH is not a limiting factor as they can grow in a range between 5 and 8 [31–33]. All three species have rapid growth rates during the summer months of the growing season because they are resistant to drought and high temperatures [31–33].

In European agriculture, and especially in southern Europe, where these summer legume cover crops are best adapted due to the Mediterranean climate that is characterized by prolonged droughts and high temperatures, there are three main windows in the crop rotation where these summer legume cover crops can be established (Figure 1).

**Figure 1.** Windows for establishment of summer legume cover crops in the crop rotation.

The first time window is about mid-spring after winter fallow, while the second is about early summer after the harvest of a winter crop such as bread wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* Desf.), or barley. In these cases, these summer legumes have plenty of time to produce large quantities of biomass and cleanup areas infested with noxious summer weeds that emerge from early spring through fall [34]. The final window in the rotation could be around mid- to late-summer after harvest of an early-sown maize hybrid (*Zea mays* L.) or an early-sown sunflower hybrid (*Helianthus annuus* L.) or after harvest of maize for silage production. At this time, summer legume cover crops can suppress late-emerging weed species such as Palmer amaranth (*Amaranthus palmeri* S.Watson) and prevent their seed production; the special mention of Palmer amaranth is due to its recent invasiveness in the Mediterranean region [35].

From a wide variety of legumes that can be grown as summer cover crops in semi-arid environments, these particular species were included in this work because there is evidence

of their ability to both suppress weeds and provide multiple ecosystem services, as shown in detail in the following sections.

3. Weed Suppression

A crop's competitive ability against weeds is often associated with characteristics such as rapid initial growth, a dense canopy, and high biomass production, while several cultural practices such as a false seedbed, increased sowing density, narrow rows, etc., can further enhance weed suppression [10]. Indeed, there is evidence that actively growing sunn hemp is a suitable cover crop for weed suppression. Morris et al. [36] reported that a cover crop of sunn hemp established at a seeding rate of 45 kg seed ha⁻¹ reduced grass weed and sedge biomass by 80% in field trials where the dominant grass weeds were barnyardgrass [*Echinochloa crus-galli* (L.) P.Beauv.], prickly sida (*Sida spinosa* L.), broadleaf signalgrass (*Urochloa platyphylla* Nash R.D. Webster), alexandergrass (*U. plantaginea* Link R.D. Webster), and fall panicum (*Panicum dichotoflorum* Michx.), and the dominant sedge was yellow nutsedge (*Cyperus esculentus* L.). In another study by Mosjidis and Wehtje [37], it was observed that even at low to medium densities of 20–50 plants m⁻² (with seeding rates of 4.5 to 17.9 kg seed ha⁻¹), weed biomass decreased by more than 50% in fields infested with redroot pigweed (*Amaranthus retroflexus* L.), sicklepod [*Senna obtusifolia* (L.) Irwin and Barnaby], large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and tinkgrass [*Eragrostis cilianensis* (All.) E. Mosher]. Maximum weed biomass reduction reached 96% at a seeding rate of 45 kg seed ha⁻¹. The authors attributed the ability of sunn hemp to suppress weeds to its rapid growth rates. Bundit et al. [38] reported remarkable suppression of grass weeds, broadleaf weeds, and sedges, resulting in a 95% reduction in total weed biomass when a seeding rate of 67 kg seed ha⁻¹ was selected. Bhaskar et al. [39] selected seeding rates of 65 and 90 kg seed ha⁻¹ that reduced weed biomass by 73 and 92%, respectively, in their two-year field trials, in which common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleracea* L.), hairy galinsoga (*Galinsoga quadriradiata* Ruiz & Pav., 1798), Powell's amaranth (*Amaranthus powellii* S.Watson), and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.] were the dominant weeds. Weed suppression was almost complete (98–99% reduction in weed biomass) in fields infested with Palmer amaranth and common sunflower (*Helianthus annuus* L.) at a Sunn hemp seeding rate of 45 kg seed ha⁻¹ [40]. Similar results have been reported for weed suppression by velvetbean and cowpea under field conditions (Table 2).

Table 2. Weed suppression of the selected summer cover crops in field trials.

Summer Legume Cover Crop	Seeding Rate/ Population Density	Weed Suppression (%)	Case Study
Sunn hemp	45 kg seed ha ⁻¹	80	Morris et al. [36]
Sunn hemp	31.4 kg seed ha ⁻¹	96	Mosjidis and Wehtje [37]
Sunn hemp	67 kg seed ha ⁻¹	95	Bundit et al. [38]
Sunn hemp	65–90 kg seed ha ⁻¹	73–92	Bhaskar et al. [39]
Sunn hemp	45 kg seed ha ⁻¹	98–99	Soti and Racelis [40]
Velvetbean	50,000 plants ha ⁻¹	≥60	Collins et al. [41]
Velvetbean	53,000 plants ha ⁻¹	≥70	Chikoye and Ekeleme [42]
Velvetbean	75,000 plants ha ⁻¹	60	Kanatas et al. [43]
Cowpea	28 kg seed ha ⁻¹	98–99	Soti and Racelis [40]
Cowpea	172,000 plants ha ⁻¹	54–81	Wang et al., 2004 [44]
Cowpea	80,645 plants ha ⁻¹	81–86	Woghiren et al. [45]
Cowpea	10 seeds m ⁻¹ of row	≥90	Harrison et al. [46]

Collins et al. [41] reported that velvetbean had greater weed suppression ability compared to sunn hemp. These authors found that velvetbean reduced smooth pigweed (*Amaranthus hybridus* L.) biomass by at least 60% at a density of 50 plants m⁻², even when weeds were present at high densities in their experimental field (15 plants m⁻²). Chikoye and Ekeleme [42] recorded a significant reduction in shoot biomass of a perennial summer grass, specifically cogongrass [*Imperata cylindrica* (L.) P.Beauv.], when using velvetbean.

Other studies reported that velvetbean was able to reduce the density of noxious perennial weeds such as johnsongrass [*Sorghum halepense* (L.) Pers.], silverleaf nightshade (*Solanum elaeagnifolium* Cav.), and field bindweed (*Convolvulus arvensis* L.) under Mediterranean soil-climatic conditions [43]. In the above study, velvetbean achieved optimal suppression of perennial weeds when its establishment was enhanced by two inter-row hoeing operations. Although a 60% reduction in weed density is not an indicator of excellent weed suppression, it should be kept in mind that control of perennial weeds is almost impossible when non-chemical cultural practices are used without subsequent application of herbicides with systemic activity [47]. Therefore, even the medium efficacy of velvetbean in this experimental field was encouraging.

At this point, it should be clarified that although several studies mention velvetbean as a cover crop at first glance, the legume has actually been used as an intercrop in maize fields, achieving remarkable weed suppression [48–50]. Consequently, the studies by Collins et al. [41], Chikoye and Ekeleme [42], and Kanatas et al. [47] are rare field experiments in which velvetbean was actually tested as a summer cover crop for weed control. Generally, the terms “cover crop” and “intercrop” are confused in the literature. Cover crops are planted to cover the soil during fallow periods in the rotation, while intercrops are companion crops that coexist with the main crop in the same field during a specific time window [51]. Therefore, further research is needed to evaluate the potential of velvetbean to reduce weed pressure in field trials. In this regard, the legume should be tested as a cover crop during fallow periods in crop rotation rather than in relay-intercropping systems [52]. The use of velvetbean as a summer cover crop is a very attractive non-chemical option for weed control, as noted by Collins et al. [41], who observed the formation of a very dense velvetbean canopy only 6 weeks after sowing that smothers weed growth by intercepting light to ungerminated weed seeds and weed seedlings in the understory.

As with velvetbean, cowpea can limit weed infestations during its active growing season. Soti and Racelis [40] observed that cowpea reduced the biomass of noxious weeds, namely Palmer amaranth and common sunflower, by almost 100% when sown at 28 kg seed ha⁻¹. There are several genotypes of cowpea, but taller genotypes with a wider canopy have an advantage in competing with weeds. Wang et al. [44] reported that cowpea plants with an upright growth habit caused a 54 and 81% reduction in common sunflower and common purslane biomass, respectively. They attributed these results to the shading ability of tall cowpea genotypes to weeds. According to Woghiren et al. [45], this cover crop achieves optimal weed suppression at high densities ($\geq 80,000$ plants ha⁻¹). Specifically, these researchers found that cowpea can suppress weed growth in such populations by reducing dry weight per unit area by more than 80% in fields infested with summer annual weeds such as *Amaranthus* spp., *Ageratum* spp., *Setaria* spp., *Brachiaria* spp., etc. Harrison et al. [46] found that this summer legume suppressed weed biomass by at least 90% in an average of 11 cowpea genotypes and two experimental growing seasons where the experimental area was infested with grass, broadleaf weeds, and yellow nutsedge.

Apart from their ability to outcompete weeds during their active growth phase, the allelopathic properties of the residues of these summer legume cover crops after termination create unfavorable conditions for weed seed germination, thus reducing weed emergence [53]. For example, sunn hemp leaves contain the phytotoxic non-protein amino acid hydroxynorleucine, which may be partially responsible for weed suppression when sunn hemp mulch is left on the soil surface [54]. Residues of sunn hemp have been reported to inhibit seedling germination and growth by 96–100% in several weed species, including smooth pigweed, Italian ryegrass (*Lolium multiflorum* L.), and sicklepod [55]. Velvetbean is also allelopathic to summer weeds [27]. The phenomenon of allelopathy in velvetbean is attributed to the presence of L-3-[3,4-dihydroxyphenylalanine (L-DOPA)] released from both the leaves and roots of the plant, and it is estimated that velvetbean can contribute 200 to 300 kg ha⁻¹ of L-DOPA to the soil annually [56]. The phytotoxicity of ground dried residues of velvetbean on germination, plant height, and dry weight of goosegrass [*Eleusine indica* (L.) Gaertn.] and smooth amaranth resulted in a reduction in

their dry weights to 85% and 79% of the control, respectively [53]. Methanol and ethyl acetate extracts of cowpea contained allelopathic compounds, demonstrating their potential for weed management applications. More specifically, increasing concentrations of cowpea methanol extract significantly reduced germination percentages of common chickweed (*Stellaria media*) and wild carrot (*Daucus carota*), with wild carrot germination reaching zero at an 8 g/L concentration, while common chickweed germination percentages decreased by 75%. Similarly, cowpea ethyl acetate extract concentrations led to significant reductions in common chickweed and wild carrot germination percentages, with maximum reductions of 32% and 84% observed at the 8 g/L concentration, respectively [57]. Another promising alternative for weed control is the use of mulch on the soil surface of cowpea. In a study by Hutchinson and McGiffen [58], cowpea mulches resulted in 80% lower weed density. Weed biomass in cowpea-mulched plots was also reduced by 67–90% in a field where the predominant species were purple nutsedge (*Cyperus rotundus* L.), common purslane, redroot pigweed, and common lambsquarters.

4. Ecosystem Services

There is much evidence of the ecosystem services that are associated with growing these legumes as summer cover crops (Figure 2).

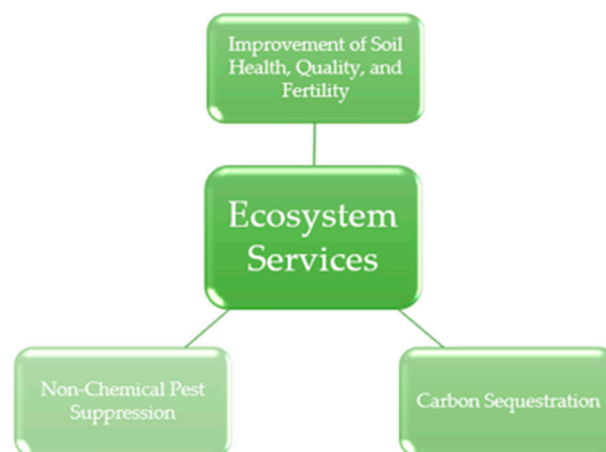


Figure 2. Ecosystem services provided by summer cover crops.

For instance, growing sunn hemp as a cover crop resulted in an accumulation of 190 to 319 kg N ha^{−1} in a subsequent crop of processing tomatoes (*Solanum lycopersicum* L.), leading to a significant increase in yield for two consecutive years [59]. When sunn hemp is used as a mulch or green manure, it is most beneficial in the early to mid-flowering stage because most of the macronutrients are contained in the leaves and flower heads [60]. This cover crop can also prevent soil erosion and increase soil organic matter and cation exchange capacity, which improves moisture retention properties and reduces soil compaction [61]. Soil organic carbon concentration was 1.25 times greater with sunn hemp on average than in untreated plots in the research by Blanco-Canqui et al. [62]. Plants can also contribute to the scavenging of residual nitrogen in deeper soil layers due to their extensive root systems, which could improve nitrogen use efficiency in organic systems and increase concentrations of mineralizable nitrogen [63]. Regarding soil health restoration from herbicide residues and other synthetic compounds, sunn hemp cultivation has been effective in scavenging herbicide concentrations in groundwater during summer fallow [64]. Furthermore, a number of different plant-parasitic nematodes are suppressed by sunn hemp, and resistance to several species of root-knot nematodes has also been demonstrated [15]. In addition to root-knot nematodes, sunn hemp is a poor host and releases allelopathic chemicals that are toxic to nematode species with agricultural impact [65]. Furthermore, sunn hemp produces a large amount of biomass that can have a significant impact on soil organisms once the

cover crop is terminated and incorporated into the soil, while stimulating the growth and reproduction of beneficial nematode-trapping fungi and soil mites [66].

In agriculture, velvetbean is used as a cover crop, affecting the forms of organic C and N in the soil, their availability, and the accumulation of organic carbon in the soil [67]. In 2023, Braos et al. [68] conducted a study examining several cover crop species to evaluate their effects on total soil carbon content. Of all cover crops studied, the highest values corresponded to velvetbean suggesting that this cover crop is a promising candidate for carbon sequestration (18.8 g kg^{-1}). In another research, velvetbean accumulated a considerable amount of nitrogen, with 43–57% derived from the atmosphere through biological nitrogen fixation [69]. This accumulated nitrogen was released during decomposition, with 7.5 to 19% being taken up by the following crop, resulting in a 25 to 68% increase in maize yields [69]. In addition, velvetbean releases nitrogen gradually, which promotes synchronization between nitrogen release and nitrogen uptake by the following crop [70]. Another benefit of a velvetbean cover crop relies on species' effects on insect and nematode populations. Decomposition of velvetbean leaves in potting soil results in a significant decrease in nematode populations of *Meloidogyne* spp. and *Nacobbus aberrans* in the roots of tomato due to the strong nematotoxic effect of velvetbean [48]. In addition, the leaf leaching of velvetbean showed a toxic effect that led to a reduction in the population of *Spodoptera* spp. larvae [48]. In another research, Samiksha et al. [71] examined the seeds of velvet bean, which contain a peptidase inhibitor that impedes the population growth of the *Zeugodacus cucurbitae* (Melon fruit fly) by increasing larval mortality, reducing pupal weight, and inhibiting adult emergence, with additional antibacterial properties. This provides new insights into the potential utilization of peptidase inhibitors derived from velvet bean or other leguminous plants as biological pesticides, or alternatively, transferring the gene to susceptible plants to mitigate damage [71]. Also, according to Vargas-Ayala et al. [72], velvetbean can also increase the abundance and diversity of beneficial soil microbial communities.

Cowpea is another summer cover crop with environmental benefits such as enrichment of the soil with organic matter, improvement of soil physical properties, prevention of nutrient leaching, and contamination of surface and groundwater [73]. Especially in organic production systems, legume cover crops such as cowpea are an economically important source of nitrogen [74]. In cowpea, typically 90% of plants' nitrogen is found in the crowns, while the remaining 10% is found in the roots and stubble [75]. Residual nitrogen from cowpea planted as a cover crop in two rows 50 cm apart and centered on the beds at a seeding rate of 60 kg ha^{-1} before transplanting broccoli (*Brassica oleracea* var. *italica*) reduced nitrogen fertilizer inputs in the main crop by at least 50% [27]. In another field trial [76], a cowpea cover crop with a seeding rate of 60 kg ha^{-1} was reported to increase crop growth and yield in a rotation of lettuce (*Lactuca sativa* L.) and sugar melon (*Cucumis melo* L.). Moreover, there are nematode-resistant cowpea cultivars that can suppress nematode populations in the soil, such as *M. incognita* and *M. javanica*, as shown in a study by Roberts et al. [77]. These authors reported that the use of nematode-resistant cowpea as a cover crop resulted in the suppression of populations of *Meloidogyne* spp., leading to the highest tomato yields. Cowpea is also useful for carbon sequestration, as shown in the recent study by Simmons et al. [78], which was conducted at 204 sites in Mediterranean climates. The authors reported an increase in soil organic carbon (1.4 t ha^{-1}) in cowpea plots compared to fallow plots. The potential of all three species to sequester CO_2 from the atmosphere and store it in the soil in the form of organic carbon is important in mitigating the negative effects of climate change on the environment. This is particularly important for the EU, where carbon neutrality by 2050 is one of the key targets of the EU's Green Deal [79]. In addition, these legumes are capable of restoring polluted soils through the process of phytoremediation [80–82].

5. Conclusions

Sunn hemp, velvetbean, and cowpea are legume cover crops that can be grown during summer fallow periods of crop rotation and suppress weeds either through resource

competition or allelopathy. In addition, these legumes are able to provide multiple ecosystem services, such as improving soil health, quality, and fertility, controlling pests, and sequestering carbon. However, to fully understand their potential, further research is needed to evaluate their performance in weed management and their environmental impact through rigorous field trials across diverse soil and climatic conditions. Identifying research gaps, potential risks, and opportunities is crucial to optimizing the use of these species as summer cover crops. This will help highlight their full potential in enhancing soil health, improving biodiversity, sequestering carbon, and advancing the development of sustainable and resilient agricultural systems.

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