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Review

Non-Chemical Weed Management in Vegetables by Using Cover Crops: A Review

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Abstract: Vegetables are a substantial part of our lives and possess great commercial and nutritional value. Weeds not only decrease vegetable yield but also reduce their quality. Non-chemical weed control is important both for the organic production of vegetables and achieving ecologically sustainable weed management. Estimates have shown that the yield of vegetables may be decreased by 45%–95% in the case of weed–vegetable competition. Non-chemical weed control in vegetables is desired for several reasons. For example, there are greater chances of contamination of vegetables by herbicide residue compared to cereals or pulse crops. Non-chemical weed control in vegetables is also needed due to environmental pollution, the evolution of herbicide resistance in weeds and a strong desire for organic vegetable cultivation. Although there are several ways to control weeds without the use of herbicides, cover crops are an attractive choice because these have a number of additional benefits (such as soil and water conservation) along with the provision of satisfactory and sustainable weed control. Several cover crops are available that may provide excellent weed control in vegetable production systems. Cover crops such as rye, vetch, or Brassicaceae plants can suppress weeds in rotations, including vegetables crops such as tomato, cabbage, or pumpkin. Growers should also consider the negative effects of using cover crops for weed control, such as the negative allelopathic effects of some cover crop residues on the main vegetable crop.

Keywords: cover crops; weeds; vegetables; non-chemical weed control; allelopathy; physical weed control

1. Introduction

Several production problems diminish the quality and yield of vegetables. Salinity, drought stress and climate changes are a few abiotic factors that decrease the yield of vegetables while the major biotic factors that reduce the yield include disease pathogens, insect pests, viruses, and weeds [1]. The yield losses caused by unchecked weeds in vegetable production systems may be between 45 to 95% depending on the production environment [2]. Despite the common use of herbicides in the USA, the loss in value of certain vegetables due to weeds ranged between 8% to 13% [3]. Weeds not only reduce the yield of vegetables but also decrease their quality and market value [4].

Chemical weed control has been a great option in conventional vegetable production systems because it provides effective and sustainable weed control. However, overuse of herbicides causes environmental concerns because herbicides have negative effects on non-target organisms (beneficial species), may pollute the food and groundwater with their residue, and cause toxicity in mammalians [5,6]. There has been a greater interest in non-chemical weed control after people became more aware of the damage caused by the misuse of herbicides [7].

Weeds in either organic or conventional vegetable production systems can be controlled through hand hoeing or mechanical cultivation. Inter-row cultivation has a proven usefulness for controlling weeds in vegetable production systems but the high cost of fuel may constrain this practice. Moreover, the practice of inter-row cultivation may accelerate soil erosion [8–10]. Programmed weed-controlling robots have potential for the automation of weed management operations. However, because the technology is expensive, it still needs some time to be adopted by the vegetable growers. The root system of vegetables may be damaged by the hand-hoeing, and this practice is labor-intensive and costly [7,11,12].

Organic and conventional vegetable productions need effective weed control strategies. The use of cover crops for allelopathic and physical weed control is among the effective strategies [13–16]. Cover crops can be considered as effective tools to suppress weeds in vegetable fields [14,17]. Cover crops can act as an alternative to tillage for controlling weeds and reducing yield losses caused by weeds [18]. Cover crops are not grown as a cash crop but rather are grown for several of their ecological benefits. Some of the synonyms used for cover crops are living mulch, catch crop, smother crop and green manure. These can be grown during fallow periods, along with the main cash crop or during a part of the growing season of a cash crop. The ecological benefits of cover crops are not limited to improvements in soil fertility, soil conservation or pest suppression. Cover crops modify the microclimate of the companion crop by intercepting sun radiation, provide a habitat for beneficial biological agents, such as insects that prey on weeds or other detrimental insects, modify the energy of raindrops and play a role in the uniform distribution of precipitation in the soil. Besides those features, cover crops may decrease erosion, conserve soil moisture, increase soil fertility and improve its structure. Negatively, sometimes cover crops may also facilitate/promote some pests and, if not removed prior to the critical period for weed control of the companion crop, can themselves act as weeds and reduce crop yield [19].

Previous research shows that cover crops can be grown for weed control in various agricultural systems [20–22]. Many cover crops have been investigated in different parts of the world and have shown good results. For example, cover crops such as fodder radish (*Raphanus sativus* L.), vetch (*Vicia* spp.), rye (*Secale cereale* L.) or their appropriate combinations can provide effective weed control in no-till organic crop production systems [23]. *S. cereale* with allelopathic potential decreased the barnyard grass (*Echinochloa crus-galli* (L.) P. Beauv.) leaf count and dry biomass [24]. A number of review articles are available that address various aspects of cover crops. Nevertheless, to the best of our knowledge, no review article addresses the use of cover crops for achieving non-chemical weed control in vegetable crops. Hence, in this review paper, we have reviewed the literature to explain the yield losses caused by weeds in the vegetables, the need for non-chemical weed control in vegetables, the use of cover crops for weed control in vegetables and the disadvantages of the cover crops.

2. Yield Losses Caused by Weeds in Vegetable Crops

Weeds are a significant issue in the production of vegetables. Several factors affect the degree of vegetable yield reduction and damage to quality caused by weeds. The most important of these are the competitiveness of the vegetable plants with the infesting weeds, the relative densities of weeds and vegetable plants, weed emergence time, and the competition duration [25–27]. Vegetables planted either as seeds or seedlings are weak competitors because of their shallow root system and sluggish growth, especially during the early stages. Hence, the vegetables are highly sensitive to weed competition and need to be kept weed-free during that early growth stage. The yield losses caused by weeds in various vegetables have been reported in previous studies. For example, weed cover in pea (*Pisum sativum* L.) was 73% if it was grown without any cover crop, i.e., without any weed control practice [28]. Decrease in yield of lettuce (*Lactuca sativa* L.) because of weed competition has been reported in previous studies [29]. In a study from England, a density of 65 weeds m^{-2}, including a mixture of broadleaf and narrow leaved weeds, could completely destroy the lettuce crop [29]. Similarly, a study from California showed that lettuce–weed competition for the whole growing season decreased the yield by 50% [30]. In Florida, a season-long lettuce–weed competition reduced the yield of lettuce by 56% [31]. Besides the yield reduction, the quality of lettuce is also reduced due to weed competition [32]. Similarly, weed competition in soybean (*Glycine max* (L.) Merr.) during the first (v1) and third foliates (v3) stages (according to BBCH) was critical in damaging the crop plant development [33].

Similarly, in pepper (*Capsicum annuum* L.), weeds such as purple nutsedge (*Cyperus rotundus* L.) could decrease the fruit yield by up to 44% [34]. In another study, the fruit number of the bell pepper (*C. annum*) was decreased by 94% if its growth was interfered with by the weed Palmer amaranth (*Amaranthus palmeri* (S.) Wats.) [16]. Moreover, a weed-free period of 12.2 weeks was needed by chili pepper (*C. annum*) to avoid a yield decrease of more than 5% [35]. Yield of the tomato (*Solanum lycopersicum* L.) was decreased by 48%–71% when the vegetable plants were growing in competition with weeds such as large crabgrass (*Digitaria sanguinalis* (L.) Scop.), tall morning glory (*Ipomoea purpurea* (L.) Roth), common cocklebur (*Xanthium strumarium* L.), and jimsonweed (*Datura stramonium* L.) [36].

3. Need for Non-Chemical Weed Control in the Vegetable Crops

Non-chemical weed control is desired for several reasons. The development of modern vegetable production systems is likely to be slowed if weed management options are limited [37]. The availability of non-chemical weed control methods along with weed control with herbicides will increase the likelihood of achieving sustainable weed control in vegetable production systems. Furthermore, there is a strong demand for organic foods, particularly for vegetables globally, and this organic vegetable production is not possible without non-chemical weed control [38].

Herbicide-resistant weeds in vegetable production systems also stress the need for non-chemical weed control [39]. Similarly, the misuse of herbicides causes environmental pollution, and non-chemical weed control should be available as an additional choice for sustainable weed control [7,40].

4. Types of Cover Crops

Cover crops could be classified into four groups based on their taxonomy. Table 1 gives a comprehensive list of cover crops that have been used for controlling weeds in vegetables and other crops, and for achieving other ecological benefits. According to this classification, there are grasses, legumes, Brassicaceae plants, and others. Important examples of grass cover crops are ryegrass (*Lolium multiflorum* Lam.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum* spp.). *R. sativus* and mustards (*Sinapis* spp.) are important in the Brassicaceae plants. Similarly, beans (*Phaseolus* spp.), vetches (*Vicia* spp.) and peas (*Pisum* spp.) are important pulses that are grown as cover crops (Table 1). Growers may select a few of these cover crop species, considering their specific farm situations. For example, they may avoid using legumes and prefer cereal cover crops if the soil is rich in nitrogen or has nitrogen residue from the previous crop. On the other hand, legume cover crops may be preferred if the soil has less nitrogen [41].

Table 1. A list of important cover crops used for weed control and other ecological advantages.

Cover Crop Type	Name of Cover Crop	Reference
Cereals	Bristle oat (*Avena strigosa*)	[42]
	Winter rye (*Secale cereale*)	[43]
	Oat (*Avena sativa*)	[43]
	Sudangrass (*Sorghum* × *sudanense*)	[44]
	Wheat (*Triticum aestivum*)	[44]
Legumes	Pea (*Pisum sativum*)	[45]
	Cowpea (*Vigna unguiculata*)	[44]
	Subterranean clover (*Trifolium subterraneum*)	[45]
	Crimson clover (*Trifolium incarnatum*)	[45]
	Egyptian clover (*Trifolium alexandrinum*)	[45]

Table 1. *Cont.*

Cover Crop Type	Name of Cover Crop	Reference
Legumes	Red clover (*Trifolium pratense*)	[45]
	Sunn hemp (*Crotalaria juncea*)	[45]
	Velvet bean (*Mucuna pruriens*)	[45]
	Soybean (*Glycine max*)	[45]
	Faba bean (*Vicia faba*)	[45]
	Hairy vetch (*Vicia villosa*)	[43]
	Common vetch (*Vicia sativa*)	[46]
Brassicaceae plant	Forage radish (*Raphanus sativus*)	[42]
	Rapeseed, canola (*Brassica napus*)	[45]
	White mustard (*Sinapis alba*)	[45]
Non-legumes	Buckwheat (*Fagopyrum esculentum*)	[42]
	Flax (*Linum usitatissimum*)	[42]
	Niger (*Guizotia abyssinica*)	[42]

5. How Cover Crops Suppress the Weeds?

Suppression of weeds through cover crops is dependent on several factors and a selective weed control is offered by some cover crops [13,42–46]. Therefore, cereal, legume and brassicaceae cover crops are widely used in various cropping systems.

Weed suppression through cover crops is achieved by more than a single action. Importantly, both competition and allelopathy have been assumed as mechanisms of weed suppression by cover crops [46,47]. One important mechanism of action of a cover crop is its physical effect on weeds. Most of the studies on the effects of cover crops on weeds essentially consider the quantity of accumulated cover crop biomass [48]. A cover crop with high biomass production is likely to produce a good physical effect on weeds, and hence result in effective weed suppression. Early-season total biomass accumulation by cover crops reduces the risk of weed emergence (Figures 1 and 2) [49,50]. The grass cover crops *L. multiflorum*, *A. sativa*, and *S. cereale* had a higher biomass than the other cover crops and suppressed the weeds effectively (Figures 3 and 4).

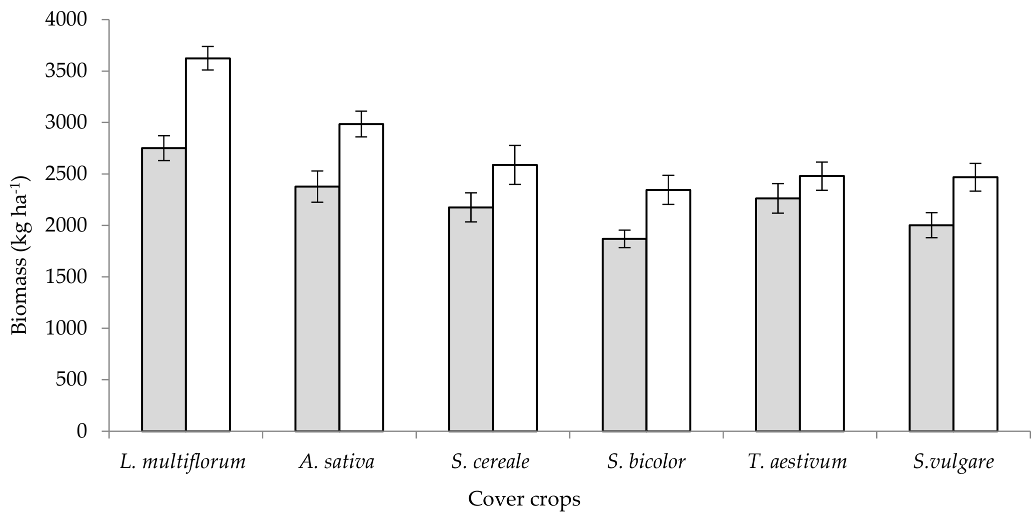

Figure 1. Biomass production (kg ha^{-1}) of cereal cover crops in different vegetable production systems prior to termination in 2005 (gray bars) and 2006 (white bars). Vertical lines represent standard errors of the means ($p < 0.05$) [49,50].

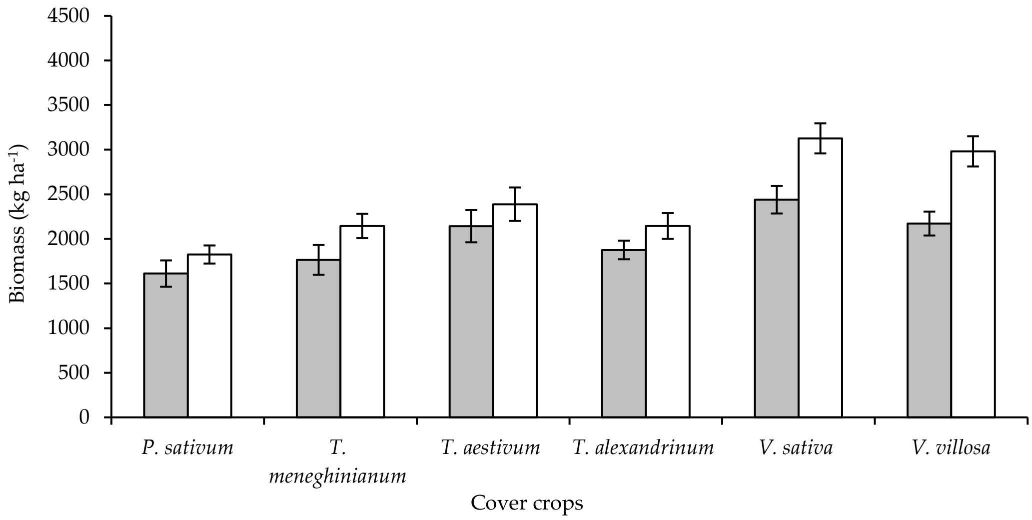

Figure 2. Biomass production (kg ha^{-1}) of cover crops in different vegetable production systems prior to termination in 2005 (gray bars) and 2006 (white bars). Vertical lines represent standard errors of the means ($p < 0.05$) [49,50].

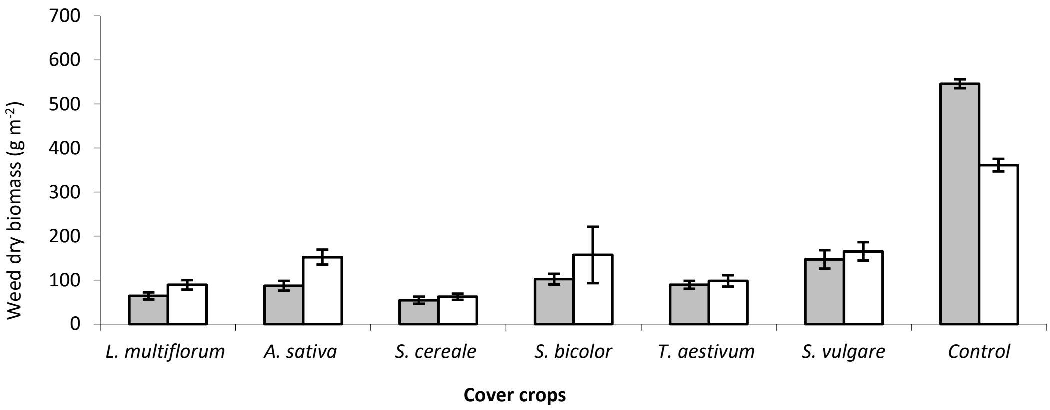

Figure 3. Effects of various cereal cover crops in different vegetable production systems on the dry biomass production (g m^{-2}) of weed species at the time of cover crop termination in 2005 (gray bars) and 2006 (white bars). Vertical lines represent standard errors of the means ($p < 0.05$) [49,50].

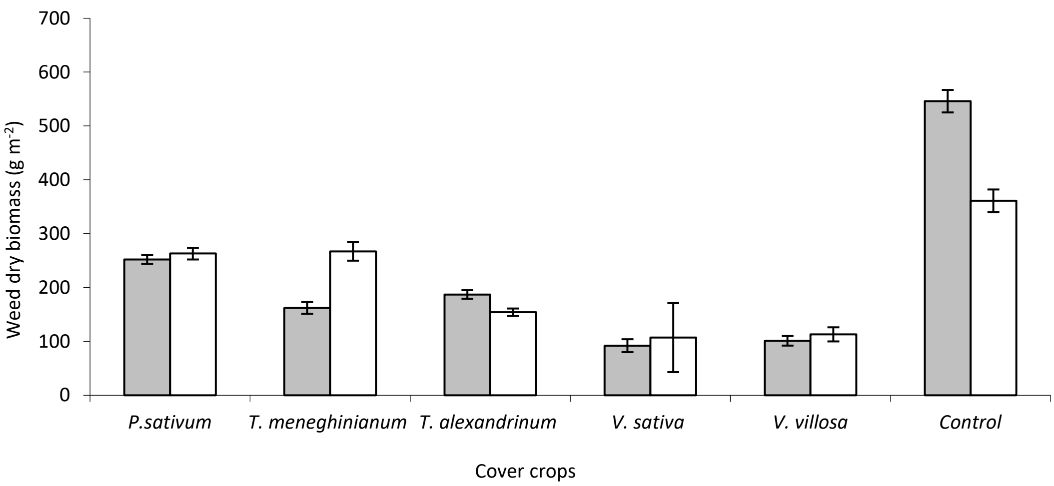

Figure 4. Effects of various legume cover crops in different vegetable production systems on the dry biomass production (g m^{-2}) of weed species at the time of cover crop termination in 2005 (gray bars) and 2006 (white bars). Vertical lines represent standard errors of the means ($p < 0.05$) [49,50].

The biomasses of *L. multiflorum*, *A. sativa*, and *V. sativa* species were recorded as having the highest values (Figure 1). On the other hand, the biomasses accumulated by *P. sativum*, *S. bicolor*, and ball clover (*Trifolium meneghinianum* Clementi) species were recorded as the lowest values, respectively. Cover crops had a stronger impact on the biomass of weeds than on their density. Even if weeds were found in a high number after a cover crop, there was a greater decrease in their biomass [51]. Sometimes, a mixture of cover crops may perform better than a single crop, but this may not always be the case. A comparison of *S. cereale*, hairy vetch (*Vicia villosa* Roth), and a *S. cereale*–*V. villosa* combination showed that *S. cereale* was the best weed suppressor cover crop and the mixture of *S. cereale*–vetch was similar to the *S. cereale* cover crop [51].

A statistical relationship (correlation) has also been consistently described for the quantity of cover crop biomass and the extent of weed suppression (Figures 3 and 4). A cover crop biomass of 8 t ha^{-1} or higher may be enough to achieve a satisfactory and sustainable weed suppression [48]. For instance, forage radish is an important cover crop and its weed-suppressing mechanism has been reported previously [52]. Rapid canopy development and other weed-competitive traits of forage radish were found to be a cause of weed suppression and allelopathy was found to have no role [52]. Generally, early soil coverage and a high seeding rate of cover crops can increase pressure on weeds. Growing a cover crop with a higher seeding density means producing more biomass of cover crop; this will ultimately suppress more weeds [53]. *S. cereale* cover crop seeding rates did not affect the weed emergence, but a high cover crop dry biomass produced a high seeding rate that decreased the weed biomass [54].

Weed dry biomasses because of the application of cover crops, including *P. sativum*, *T. meneghinianum*, and *T. alexandrinum* species, were recorded as having the highest values after the value of control plots (Figures 3 and 4). On the other hand, the dry biomass of *L. multiflorum*, *S. cereale* and *T. aestivum* species were recorded as having the lowest values, respectively.

The density of weeds in sudangrass (*Sorghum vulgare*), *S. bicolor*, and *T. aestivum* were recorded as having the highest values after the value of control plots (Figure 5). On the other hand, the weed density of *L. multiflorum*, *A. sativa*, and *S. cereale* were recorded as having the lowest values, respectively.

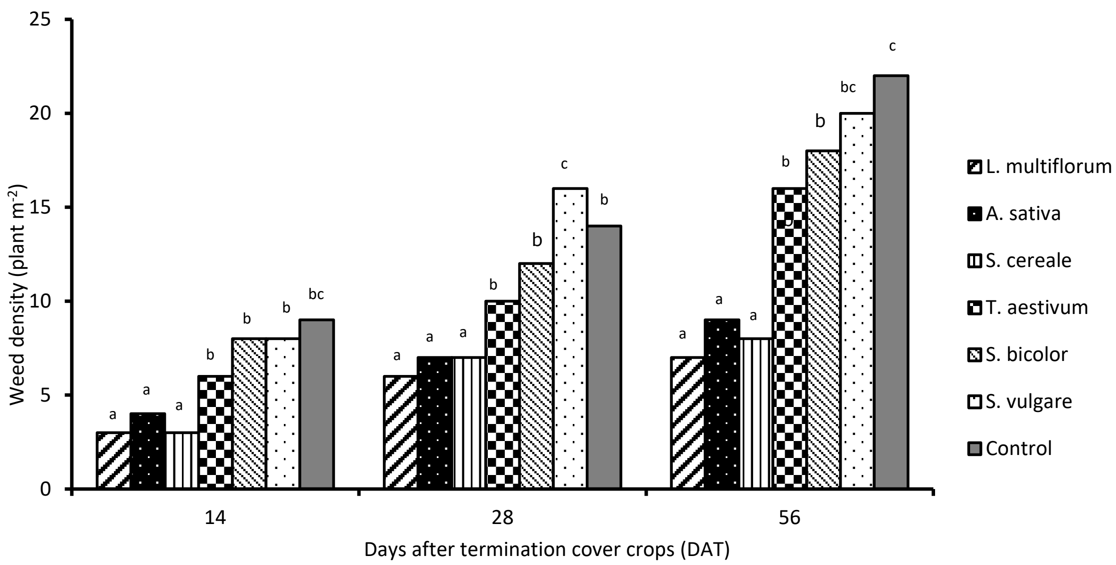

Figure 5. Effects of various cereal cover crops in different vegetable production systems on weed density after different time of cover crop termination. Vertical lines represent standard errors of the means ($p < 0.05$) [49,50].

Several other mechanisms exist that help the cover crops to suppress weeds in vegetable crops. For instance, competition for space between living cover crops and weeds reduces the space for weeds. Shading is the other mechanism through which cover crops are likely to suppress weeds in vegetable crops. Further, the cover crops alter the light quality that is likely to influence the development of weeds [55]. For example, far-red light reflection causes developmental changes in weeds that reduces their biomass and seed production [56]. Some cover crops induce the germination of weed seeds, and hence cause a depletion of the weed seed bank; e.g., a mixture of *S. cereale*, buckwheat (*Fagopyrum esculentum* Moench), and yellow mustard (*Brassica juncea* (L.) Czern.) grown as a cover crop helped to completely deplete *Setaria* spp. in the weed seed bank, and caused an 80%–85% decrease in the germinable seed bank of velvetleaf (*Abutilon theophrasti* Medik.) and common lambsquarters (*Chenopodium album* L.) [57]. The long-term practicing of cover cropping results in a reduction in the weed seed bank in the soil [58]. Earlier emergence of a cover crop may enable it to cause a high suppression of weeds [59]. The weed dry biomass in organically grown vegetables was inversely proportional to the seeding rates of legumes (e.g., *V. faba, P. sativum*) and cereal (*A. sativa*) [60].

The allelopathic potential of cover crops is the other important method through which cover crops suppress weeds (Table 2). *S. cereale* is among the most effective and important cover crops and its allelopathic potential has been reported consistently in the literature [61–63]. *S. cereale* varies in the concentration of allelochemicals and, hence, the effect on weeds. The cultivars varied in their content of benzoxazinoides, while weeds had a variable uptake of allelochemicals that caused some weeds to be more sensitive to cover crops. For example, in greenhouse and field experiments, redroot pigweed (*Amaranthus retroflexus* L.) and common purslane (*Portulaca oleraceae* L.) showed a greater response to *S. cereale* cover mulches than *C. album* [64]. Allelochemicals such as DIBOA, BOA, DIBOA-glucoside, and AZOB have been reported from *S. cereale* plants, and the persistence of these allelochemicals in the soil had a correlation with the accomplished level of weed control [47,65,66].

Plants from the Brassicaceae family are an important cover crop group for weed suppression. Glucosinolates are important allelochemicals that are present in brassica species and may have a role in the weed control activity [67]. Brassica cover crops exude these glucosinolates to the soil environment, where they are converted to their active form, i.e., isothiocyanates. For instance, six allelochemicals (isothiocyanates) were identified in field mustard (*Brassica rapa* L.); these were 2-phenylethyl-ITC, n-butyl, 3-butenyl, benzyl, allyl, and 4-pentanyl [68]. Previous studies have described the allelopathic effects of cover crops on weeds. Weeds such as *C. album* and wild foxtail millet (*Setaria media* (L.) Vill.) were suppressed by 60% by cover crops such as white mustard (*Sinapis alba*), *R. sativus*, *V. sativa* and the mixture of these cover crops suppressed the weeds by 66% [69]. In many instances, it may be difficult to quantify the exact mechanism of weed suppression by cover crops. In such cases, both competition and allelopathy, or any of these, may be involved. For example, the cover crops decrease the emergence of weed seedlings, expansion of the weed canopy and biomass production by weeds, and this was achieved either through physical effect or allelopathy [70].

There is particular significance in using cover crops for weed control in no-till systems. In conventional vegetable production systems, the weeds are controlled by using tillage as a tool along with other weed control methods, such as herbicide applications. However, no-till vegetable production has been popular in recent years due to associated benefits such as environmental and resource conservation, and cost-effectiveness. Growing vegetables in the no-till system limits the weed control options as it restricts the use of tillage, which is a practice primarily carried out for seedbed preparation and weed control. Cover crops are an excellent option to control weeds in no-till vegetable systems. Cover crops also conserve the soil and water and promote a healthy environment for sustainable vegetable production.

Another important question that arises in the use of cover crops is the persistence of allelopathic substances in soil and according activity levels. Soil factors can modify the allelopathic activity of cover crops in the soil; the most important of these factors are the ion-exchange capacity of the soil, the concentration of organic matter in it and the biotic content [79]. For example, phenolic acid concentrations may reach a maximum after 10–15 days of cover crop incorporations and may remain effective until 20–25 days [80]. This cover crop residue inhibits the germination of weed seeds and decreases the weed density, but their effects are active for a short time and the weeds often reemerge [81] (Table 3).

Table 2. Allelochemicals reported in various cover crops.

Cover Crop	Allelochemicals	Reference
Rye (*Secale cereale*)	MBOA, BOA, HMBOA, DIBOA	[71]
Barley (*Hordeum vulgare*)	Gramine, hordenine, p-hydroxybenzoic acid, vanillic acid, p-coumaric acid, syringic acid, ferulic acid	[72,73]
Sorghum (*Sorghum bicolor*)	Sorgoleone, m-coumaric acid, caffeic acid, chlorogenic acid	[74]
Wheat (*Triticum aestivum*)	DIMBOA, 2,4-Dihydroxy-1,4-benzoxazine-3-one (DIBOA)	[75]
	DIMBOA, syringic acid, vanillic acid, p-hydroxybenzoic acid, cis-ferulic acid, trans-ferulic acid, trans-p-coumaric acid, cis-p-coumaric acid	[76]
Field mustard (*Brassica rapa*)	2-Phenylethyl-isothiocyanate	[67]
Rapeseed (*Brassica napus*)	Glucosinolates, 2-Phenylethyl-isothiocyanate, benzyl isothiocyanate, allyl isothiocyanate, 3-butenyl isothiocyanate,	[77,78]
Field mustard (*Brassica campestris*)	Benzyl isothiocyanate, allyl isothiocyanate, 3-butenyl isothiocyanate	[78]

Table 3. Cover crops with an allelopathic potential and the weeds suppressed by cover crops.

Cover Crop	Weeds Suppressed	References
Wheat (*Triticum aestivum*)	*Ipomoea lacunose*, *Eleusine indica*, *Amaranthus palmeri*	[82]
Rye (*Secale cereale*)	*Eleusine indica*, *Amaranthus palmeri*, *Ipomoea lacunosa*	[82]
Rye (*Secale cereale*)	*Chenopodium album*, *Abutilon theophrasti*	[83]
Annual ryegrass (*Lolium multiflorum*), rye (*Secale cereale*), bristle oat (*Avena strigosa*), common vetch (*Vicia sativa*), radish	*Brachiaria plantaginea*, *Bidens pilosa*, *Euphorbia heterophylla*	[23]
Hairy vetch (*Vicia villosa*), oat (*Avena sativa*)	*Digitaria sanguinalis*, *Eleusine indica*, *Amaranthus retroflexus*, *Datura stramonium*	[84]
Sorghum sudangrass (*Sorghum bicolor* × *Sorghum sudanense*)	Broad leaved weeds	[85]
Bristle oat (*Avena strigosa*), hairy vetch (*Vicia villosa*)	*Amaranthus palmeri*, *Portulaca oleracea*, *Helianthus annuus*	[86]
Rye (*Secale cereale*), hairy vetch (*Vicia villosa*), barley (*H. vulgare*) × triticale, Austrian winter pea (*Pisum sativum*)	*Chenopodium album*, *Amaranthus hybridus*, *Thlaspi arvense*, *Taraxacum officinale*, *Stellaria media*, *Elymus repens*, *Panicum crus-galli*, *Setaria glauca*	[87]
White mustard (*Sinapis alba*)	*Amaranthus blitoides*, *Chenopodium album*	[88]
Hairy vetch (*Vicia villosa*), subterranean clover (*Trifolium subterraneum*), oat (*Avena sativa*)/hairy vetch (*Vicia villosa*)	*Amaranthus retroflexus*, *Chenopodium album*	[89,90]

6. Disadvantages of Using Cover Crops for Weed Control in Vegetable Production Systems

Although cover crops can repress weeds and have additional ecosystem benefits, some negative aspects of using cover crops in vegetable production systems have also been noted. For example, some of the cover crops may promote some insect pests or disease pathogens [91]. Moreover, as vegetables have a different morphology and growth habit to other arable crops, there are chances that cover crops, along with weeds, may also compete with vegetable crops. Hence, a careful management plan is required when cover crops are to be used for weed control in vegetables [92].

Cover crops may not always provide effective control of weeds in vegetables, i.e., negative or no effects of cover crops in vegetables have also been noted. For example, forage soybean was used as a cover crop in collard (*Brassica oleracea* L.) vegetables; the cover crop was ineffective in controlling weeds [93]. Moreover, cover crops may occasionally have a positive effect on germination or seedling growth of weeds [94]. Additionally, some shortfalls of cover crops as a weed control technique are also on record. For example, cover crops may not be effective in controlling intra-row weeds; this is because neither their allelopathic effects nor shading effect reaches the intra-rows. This may also be the reason that cover crops usually damage only the weeds and not the crops [95,96]. Through the use of cover crops in vegetables, annual weeds are easily controlled, but perennials generally receive a lower impact while sedges are difficult to control [97]. Other research work also showed that cover crops may have weak effectiveness against perennial weeds such as nutsedges (*Cyperus* spp.) [47,58]

Another important aspect is that high biomass production (in order to gain greater weed suppression) may disturb the seeding operation, crop establishment and other crop management operations [98]. Similarly, allelochemicals from cover crops can pose a negative effect on the main vegetables along with their effects on weeds [64]. A well-established practice is to grow cover crops and then desiccate these through some means (e.g., herbicide application, mechanical incorporation). The residue cover crop suppresses the weeds in the next season crop; however, there is a likeliness that this cover crop residue will also negatively affect the germination and seedling growth of the main crop. For example, the germination, seedling emergence or establishment of spinach (*Spinacia oleracea* L.) and lettuce were negatively affected by the allelopathic activity of two important cover crops, *S. cereale* and winter oilseed rape (*Brassica napus* L.) [94]

7. Cover Crops for Weed Control in Vegetable Crops

Cover crops are now commonly used in organic vegetable production systems in some parts of the world [97]. For example, growing legumes and grass cover crops in the mixture (e.g., growing *S. cereale* in mixture with soybean, using both as cover crops) is likely to decrease the seed production by weeds, and hence a reduced weed seed bank is expected with this kind of cover crop application [98].

Cover crop mulches in vegetable production systems of the United States could provide fields free of weeds: important cover crops were oilseed radish (*Raphanus sativus* L.), *S. alba* and *B. juncea* [99]. Similarly, legume cover crops velvetbean (*Mucuna deeringiana* (Bort) Merr.), jumbiebean (*Leucaena leucocephala* (Lam.) de Wit), jackbean (*Canavalia ensiformis* (L.) DC.)] are traditionally used in Mexico for controlling weeds in field crops and achieving other ecological benefits of cover crops, such as improved soil fertility [100].

A number of mulches—*V. villosa*, Egyptian clover (*T. alexandrinum* L.), *A. sativa*, *T. meneghinianum*, wheat (*Triticum aestivum* L.), *S. cereale*, *V. sativa*, *L. multiflorum*—were tested for their weed control efficacy in tomato [49]. The cover crops were killed before transplanting tomato seedlings. Out of the tested mulches, two mulches, i.e., *L. multiflorum* and *S. cereale* decreased the weed biomass by more than 75%. Two of the other of mulches (*V. sativa* and *V. villosa*) were also effective for weed control in tomato [49]. Similarly, *V. villosa* as a cover crop in tomato produced a biomass of 7.49 t ha^{-1}, and the mulch from this cover crop decreased the biomass of some weed species (*A. retroflexus*, *D. sanguinalis*, *P. oleracea*) by 40%, and their density by >70% in tomato [89,90]. In another study, *S. cereale* was grown as a cover crop and desiccated to stay as mulch one week before planting tomato. However, in this study, additional weed control measures were required to achieve satisfactory weed control [101]. In another study, cover crops such as *T. incarnatum* and *V. villosa* effectively controlled the weeds in tomato production but did not improve the tomato yield [102].

Among several cover species, the most effective for weed control in cabbage (*Brassica oleracea* var. capitata) were *S. bicolor*, sudangrass (*Sorghum sudanense* (P) Stapf.), and *V. villosa*, which caused the highest decrease in weed biomass and density [50]. Cover crops were effective in suppressing weeds such as *A. retroflexus*, European heliotrope (*Heliotropium europaeum* L.), *P. oleraceae*, field pennycress (*Thlaspi arvense* L.), annual sow thistle (*Sonchus arvensis* L.), black nightshade (*Solanum nigrum* L.), shepherd's-purse (*Capsella bursa-pastoris* (L.) Medik), *C. album*, sun spurge (*Euphorbia helioscopia* L.), wild mustard (*Sinapis arvensis* L.), etc., for almost two months. Weed control by *V. villosa* doubled the kale (*Brassica oleracea* L. var. acephala DC) yield compared to untreated control [50]. In cucumber production, the physical pressure and allelopathic effects of (*S. bicolor* × *S. sudanense*.) and *S. cereale* helped to cause a more than 80% decrease in weed densities [14]. *V. villosa* was also effective in controlling weeds but it yielded similar to control treatment. Nevertheless, *S. cereale* and *S. bicolor* × *S. sudanense* significantly increased the cucumber yield over control [14].

Lettuce is extensively used as a salad as well as in the making of rolls, wraps, sandwiches and several other recipes. As lettuce is mostly consumed as fresh leaves, non-chemical pest control is more important for this vegetable crop. Along with other non-chemical methods, cover crops have also been investigated for weed control in lettuce fields [17]. For example, the cover crop of cowpea (*V. unguiculata* (L.) Walp.) (grown in summer and then either kept as mulch or incorporated in the soil during fall) had very few weed species and higher lettuce yields compared to the other cover crop, *S. vulgare*, or the fallow treatment [17]. In pepper production, the cover crop species with the highest competitiveness against weeds were oat (*Avena sativa* L.), *L. multiflorum*, common vetch (*Vicia sativa* L.) and *V. villosa* [103]. By the end of the first and second months of cover crop incorporation, the *V. villosa* had the highest weed suppression (70% or higher) and the plots with the same cover crop had the highest pepper yield [103]. Similarly, cowpea as a cover crop was also effective in weed control in pepper production, along with an increase in the growth and biomass production of pepper plants [104].

Ladino clover (*Trifolium repens* L.) as a cover crop residue was effective to suppress weeds in squash (*Cucurbita maxima* Duch.) at four weeks after planting; however, the effectiveness of the cover crop to affect weeds was diminished by the end of the second month of planting [105]. In another study, *S. cereale* and *H. vulgare* as cover crops in sugarbeet (*Beta vulgaris* L.) suppressed weeds such as *D. sanguinalis*, hooked bristlegrass [*Setaria verticillata* (L.) P.Beauv.], and *E. crus-galli*. This weed suppression was likely due to the allelopathic potential of *H. vulgare* and *S. cereale* [106]. *V. villosa*, *S. cereal*, or a mixture of these two cover crops was evaluated for their weed control ability in sweet corn. Either alone or in a mixture, the two cover crops suppressed the weeds and increased the yield of sweet corn [107]. Similarly, in another study, cover crops such as *S. cereale*, *V. villosa*, and wheat suppressed the early season weeds by nearly 50% in sweet corn. However, the cover crops were not effective in controlling sedge weeds. Wheat and *S. cereale* as a cover crop or a mixture of these with *V. villosa* had a negative effect on the yield of sweet corn [108].

Generally, it is assumed that weed control through cover crops in vegetables can be improved by using a mixture of cover crops belonging to different functional groups [109]. However, this may not always be true. For example, thirteen mixtures of cover crops were evaluated for their weed suppression in vegetables [110]. Mixtures of any cover crops poorly suppressed weeds if the mixture was a poor weed competitor or had poor mechanical desiccation. Importantly, individual cover crops that performed well with good establishment and weed competition also perform well when grown in mixtures. Cover crops that performed well both as individual crops and in a mixture were *H. vulgare*, *S. cereale*, *V. villosa*, and *T. incarnatum*, and these were subsequently used for weed control in tomato [110]. In another study, the use of cover crops in no-till planted vegetables could highly decrease the emergence of hairy nightshade (*Solanum sarrachoides* Sendtn.) and Powell's amaranth (*Amaranthus powellii* S.Watson) [111].

In contrast to conventional studies that determine the effect of cover crops on weed control in vegetables, some innovative techniques have also been investigated. For example, *S. cereale* cover crop inoculated with the plant beneficial fungus *Trichoderma virens* could control weeds in transplanted vegetables [112]. However, the number of such studies is very limited.

8. Integration of Cover Crops with Vegetable Crops

There is a good opportunity to grow cover crops during the fallow period. The cover crops grown during the fallow period restrict the growth of weeds and seed establishment, hence providing weed-free fields for the upcoming vegetable crop season. For example, *S. cereale*, *R. sativus* and *B. napus* were strong inhibitors of weeds during the fallow period [113]. Cover crops are sown one to two months (or a few weeks) prior to the sowing of the main crop and then desiccated or killed. In some instances, cover crops and vegetables can grow together for a period of a few weeks. Along with the use of glyphosate, the use of mechanical killing of cover crops has also been proposed. Desiccation of cover crops may be easy when it is performed during flowering, or immediately before or after this period. Easy mechanical manipulation of cover crops such as *H. vulgare*, big flower vetch (*Vicia grandiflora* Scop.), *S. cereale*, *T. subterraneum*, crimson clover (*Trifolium incarnatum* L.), and *V. villosa* was achieved when crops were at bloom or post-bloom stage [114]. Cover crops were planted at the end of March and harvested in two months (end of May), and the main crops were planted within a week. Undercutter was a better terminator than field disks in reducing the biomass of grass weeds and increasing soybean and maize yields [115]. Cover crop management should be done with regard to the action mechanism of cover crops against weeds. For instance, if a cover crop has a high allelopathic activity, it may be mixed into the soil after its killing. However, if the cover crop suppresses weeds through its shading or a physical effect, then it may be left scattered on the soil after desiccation [116].

9. Conclusions

Non-chemical weed control is desired and it is important in vegetable crops for several reasons. With rising concerns regarding herbicide evolution in weeds and herbicide residue issues in the edible parts of vegetables, it is necessary to attempt weed control in vegetables through techniques such as cover crops. The discussion in this review shows that several cover crops suppress weeds in vegetable crops through their physical or allelopathic effects. Nevertheless, widespread implementation of cover crops across the world is lacking. Technological gaps and lack of site-specific experimentation may be reasons behind this. Local-scale experimentation and bridging the technological gaps can aid in a widespread utility of cover crops for sustainable weed control in vegetable production.

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