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Knowledge of Cover Crop Seed Traits and Treatments to Enhance Weed Suppression: A Narrative Review

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Abstract: Cover crops, as either a living plant or mulch, can suppress weeds by reducing weed germination, emergence and growth, either through direct competition for resources, allelopathy, or by providing a physical barrier to emergence. Farmers implementing conservation agriculture, organic farming, or agroecological principles are increasingly adopting cover crops as part of their farming strategy. However, cover crop adoption remains limited by poor and/or unstable establishment in dry conditions, the weediness of cover crop volunteers as subsequent cash crops, and seed costs. This study is the first to review the scientific literature on seed traits of cover crops to identify the key biotic and abiotic factors influencing germination and early establishment (density, biomass, cover). Knowledge about seed traits would be helpful in choosing suitable cover crop species and/or mixtures adapted to specific environments. Such information is crucial to improve cover crops' establishment and growth and the provision of ecosystem services, while allowing farmers to save seeds and therefore money. We discuss how to improve cover crop establishment by seed priming and coating, and appropriate seed sowing patterns and depth. Here, three cover crop families, namely, *Poaceae*, *Brassicaceae*, and *Fabaceae*, were examined in terms of seed traits and response to environmental conditions. The review showed that seed traits related to germination are crucial as they affect the germination timing and establishment of the cover crop, and consequently soil coverage uniformity, factors that directly relate to their suppressive effect on weeds. *Poaceae* and *Brassicaceae* exhibit a higher germination percentage than *Fabaceae* under water deficit conditions. The seed dormancy of some *Fabaceae* species/cultivars limits their agricultural use as cover crops because the domestication of some wild ecotypes is not complete. Understanding the genetic and environmental regulation of seed dormancy is necessary. The appropriate selection of cover crop cultivars is crucial to improve cover crop establishment and provide multiple ecosystem services, including weed suppression, particularly in a climate change context.

Keywords: agroecology; seed dormancy; plant establishment; germination; climate change; *Poaceae*; *Brassicaceae*; *Fabaceae*

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1. Introduction

Weeds are a major constraint to crop production and should be managed through direct or indirect methods [1] to secure crop productivity and the high quality of the harvest [2]. Chemical weed control remains the most widely used weed control method due to its high efficacy/cost ratio. However, overreliance on herbicides in combination with monoculture has led to the evolution of weed herbicide resistance [3] and a loss of weed diversity [4], leading to the emergence of a few dominant weed species responsible for high yield losses [5]. In particular, the development of herbicide resistance holds a critical role in hindering further herbicide usage for weed control [6]. The intensive use of herbicide is now questioned for its effects on the environment and human health [7]. The intensive use of primary tillage and false seedbed during the fallow period, coupled with in-crop mechanical weeding, are questioned for their impact on soil health, economic profitability, and environmental impacts [8]. Therefore, ecological-based and nature-based options for weed management are required and appear to be promising for various type of farming systems [9].

Annual cover crops, living mulches, and companion crops can be used to improve weed management [10,11] and enhance soil health [12–14]. Cover crops are plant species cultivated between two main cash crops which can provide multiple ecosystem services, including suppressing weeds through competition [15–17], allelopathy [18], and a physical barrier [19,20], or indirectly by providing a habitat for seed predators [21–23]. Cover crop species with high biomass accumulation, early season emergence, and rapid growth are more efficient at outcompeting weeds through resource competition. Indeed, even if field demonstrations of their allelopathic properties remain scare [18], cover crops can exudate allelopathic substances, proportionally to their biomass production, that suppress weeds further [17]. However, identifying the mechanisms by which cover crops exert their negative effects on weeds in the field remains challenging [24], but crucial to improve their efficacy. Cover crops have proven to be an effective ecological-based weed management tool in various agricultural systems [25–28]. Cover cropping is one of the main pillars of weed management in no-till and conservation agricultural systems [29]. However, since tillage and herbicide represent major drivers on weed communities [30], most studies have failed to highlight a carrying over effect of cover crops in tillage-based systems [31]. Furthermore, the usage of cover should be optimized in tillage-based systems as a part of integrated weed management strategies used in order to reduce the reliance on herbicide use [32].

In order to increase the use of cover crops, knowledge is required to identify the factors hampering farmers' adoption. It is well documented that the level of weed control provided by cover crops greatly depends on rapid growth and soil coverage, which in turn are influenced by the relative weed/cover crop growth at early phenological stages, such as seed germination and seedling emergence [33]. This is of particular importance, especially when cover crops are exposed to stressful abiotic conditions caused by climate change. They must establish a high biomass and coverage faster than weeds through a faster growth at an earlier stage. In addition, climate change might interfere with the allelopathic potential of cover crops because the persistence of allelochemicals may change with soil humidity and temperature, and may not be as effective to inhibit weed seed germination [34,35].

Here, we review the scientific literature and critically address the factors that affect the germination of cover crops in response to environmental and agronomic factors, seed traits of main cover crop species, and methods to increase cover crop seed germination. Such knowledge is required to improve the establishment and management of cover crops and will eventually enhance their integration into cropping systems.

2. Factors Affecting Cover Crops' Seed Germination

There are several agronomic and environmental factors that impact the seed germination of cover crops. Knowing the germination responses of cover crop seeds to different conditions would be beneficial for the effective utilization of cover crops against weeds while providing desirable agroecosystem functions.

2.1. Abiotic Factors

Temperature and Soil Moisture

Temperature and soil water are two important abiotic factors impacting germination and the early growth of seedlings [36], among others such as soil pH, active limestone, and texture [37]. The lowest water potential at which a seed can germinate, known as base water potential. is partially correlated with the species indicator values [38]. Such data on base water potential could be helpful to predict seed germination under various soil moisture levels. However, cardinal temperatures are the best criteria to determine the optimum habitant for a specific cover crop. Seed traits, including age, the nutrient status of the seeds, and the quality of the seeds can affect their responses to temperature and soil water [39].

Accounting for temperature and water requirements for the seed germination of cover crop seeds can help in designing cover crop mixtures with similar sowing periods and responses to environmental conditions, hence reducing the risk of heterogeneous seed germination. Furthermore, both simulating the emergence of cover crops under various environmental conditions and predicting the exact date of cover crop emergence are feasible by having such data [40,41].

Tribouillois, et al. [42] determined the germination response of a variety of cover crop species to a wide range of temperature and water potentials, showing that suitable temperature was highest for the cover crop from *Brassicaceae*, followed by *Poaceae*, *Asteraceae*, and *Fabaceae*. Most of the tested species germinated well under the warm conditions of summer, while some *Fabaceae* species showed a sensitivity to high temperature. Generally, cover crop species studied by Tribouillois, Dürr, Demilly, Wagner and Justes [42] showed two contrasting types of final germination percentage (Figure 1). First, the germination of all *Fabaceae* species, all C3 *Poaceae*, some *Brassicaceae* (Brassica napus L., Sinapis alba L. and Eruca sativa Mill.), Phacelia tanacetifolia Benth. and *Helianthus annuus* L. was steady in the temperature range 24–35 °C and then decreased near 40 °C. Secondly, *Brassicaceae*, the two C4 *Poaceae*, *Guizotia abyssinica* (L.f.) Cass. and *Fagopyrum esculentum* Moench germination percentages were negligible at the extreme ends of the tested temperature range (Figure 1).

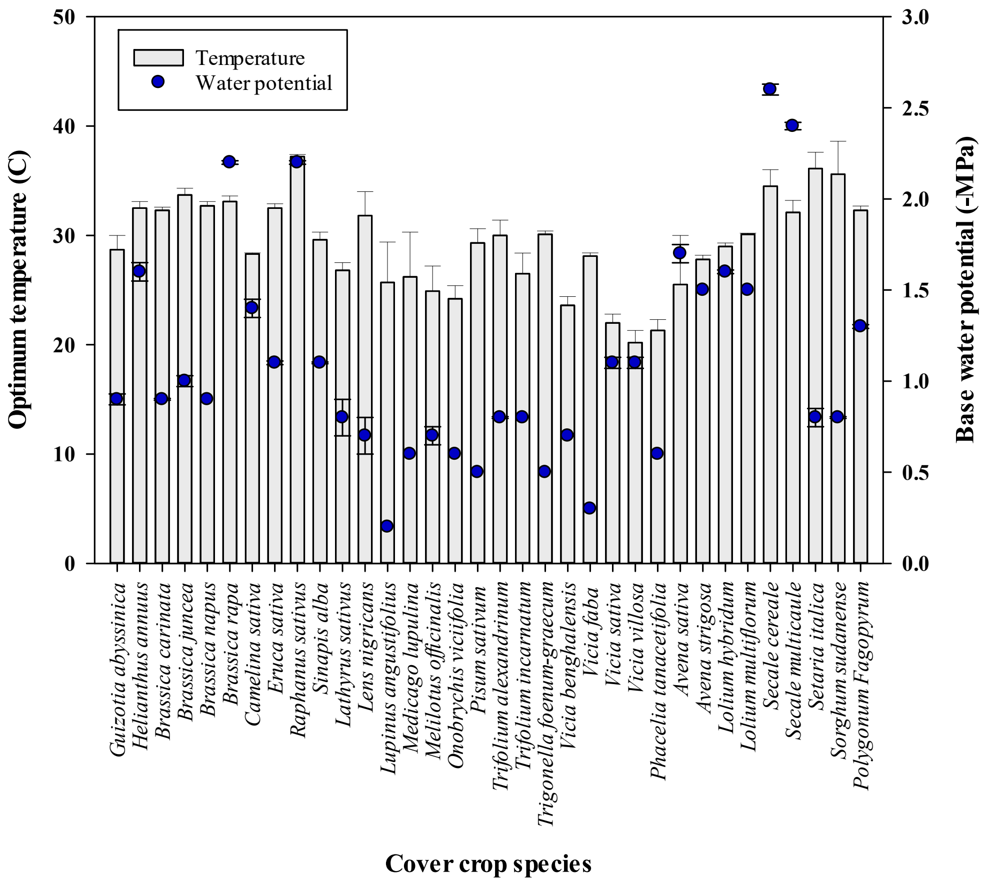

Figure 1. Influence of temperature and base water potential on the final germination percentage of a wide range of cover crop species [adapted from Tribouillois, Dürr, Demilly, Wagner and Justes [42]].

Tribouillois, Dürr, Demilly, Wagner and Justes [42] reported that by decreasing the water potential, the germination of some cover crop species such as *Lupinus angustifllius* L., *Vicia faba* L., *Trigonella foenum-graecum* L., and *Pisum sativum* L. decreased, but the slope of reduction varied greatly among species (Figure 1). The lowest base water potential was recorded for species of *Poaceae* (−1.6 MPa) (especially C3 species), followed by *Brassicaceae* (−1.4 MPa) and *Fabaceae* (−0.6 MPa) (Figure 1). In comparison to species from *Poaceae* and *Brassicaceae*, the seed germination of *Poaceae* was sensitive to water stress (Figure 1). Most *Fabaceae* species were sensitive to low water availability, which indicates that they are better suited to rainy climates. Regardless of botanical family, the tested cover crop species were grouped based on favorable temperature and water potential, which was very informative for choosing a cover crop for a given climate condition and growing season. [42] argued that the value of the base water potential of large-seeded plants is higher than that of small-seeded plants, as they require more water for consumption.

2.2. Seed Dormancy

It is well established that due to the poor termination of cover crop growth and seed dormancy characteristics, cover crops have a great potential for becoming weedy in subsequent crops. Seed dormancy is the failure of an intact viable seed to complete germination under favorable conditions [43]. Seed dormancy is a complex trait, in that both its development and breaking is regulated by a combination of environmental and genetic factors [43–45].

The domestication and breeding of major crop species has resulted in the removal of most dormancy mechanisms in their seeds inherited from their wild ancestors [46]. However, cover crop seeds have several dormancy mechanisms as they have not undergone vigorous domestications processes (genetic and morphological changes within the plant that makes it suitable for cultivation) [43,46,47]. Seed dormancy can limit the agricultural use of many cover crop species in different ways, especially for the *Fabaceae* family. Hence, information on the genetic and environmental factors affecting seed dormancy is required to prevent them becoming weedy in subsequent crops.

Previous studies have demonstrated that the combined effects of cover crop genotype and climate conditions during seed development on the maternal plants and then storing condition during postharvest determine the mechanism and level of seed dormancy [47–49]. It is well established that climate conditions surrounding the parental plants have the highest contribution to the germination ability of their resultant seeds [50]. In addition, seed rain during the growing season or after incomplete termination can contribute to the weediness of cover crops in farmlands [51,52].

Several seed-dormancy-breaking methods have been suggested to alleviate and overcome dormancy, which vary depending on the dormancy type (Table 1). Despite the interest in releasing cover crop seeds from their dormancy and enhancing their germination rate, these practices would increase seed costs [53].

Table 1. Seed dormancy mechanisms and methods to break the dormancy of cover crop species.

Cover Crop Species	Dominant Dormancy Pattern	Main Method of Breaking Dormancy	References
Fabaceae			
Vicia spp., *Trifolium* spp., *Lathyrus sativus*, *Pisum sativum*, *Melilotus officinalis*, *Lupinus* spp., *Faba* spp., and *Eruca sativa*	Physical (hard seed), physiological	Mechanical abrasion, after-ripening	[54–57]
Brassicaceae			
Brassica spp.	Induced secondary dormancy	Alternating temperatures and the presence of light	[58–60]
Raphanus sativus	Mechanical resistance and non-leachable chemical inhibitors associated with the pericarp	Dry storage	[61,62]

Table 1. *Cont.*

Cover Crop Species	Dominant Dormancy Pattern	Main Method of Breaking Dormancy	References
Poaceae			
Sorghum spp.	Seed covering structures (mechanical, permeable, and chemical barriers)	Removal of seed coat structures	[63]
Secale cereale	limited innate and induced dormancy		[64]
Lolium spp.	Non-deep physiological dormancy	Chilling at low temperatures and dry after-ripening	[65,66]
Avena spp.	High temperature dormancy	After-ripening in dry storage at temperatures higher than 20 °C	[66,67]
Setaria spp.	Presence of germination inhibitors in the seed coat	Seed coats removed	[68]
Aegilops spp., *Anisantha* spp., *Anisantha* spp., *Bromus* spp., *Hordeum* spp., and *Trachynia* spp.	Non-deep physiological dormancy	High temperatures through dry after-ripening	[68]

3. Seed Traits of Main Cover Crop Species

Worldwide, cover crop species cultivated in different agricultural ecosystem are commonly from the genera *Vicia* sp., *Trifolium* sp., *Secale* sp., *Lolium* sp., *Hordeum* sp., *Sorghum* sp., *Raphanus* sp., and *Sinapis* sp. The three main botanical families are *Poaceae*, *Fabaceae*, and *Brassicaceae* [34], and their seed germination requirements vary greatly among botanical families [69]. The following sections provide useful information, particularly from a seed germination perspective, to improve the selection of crop species in specific production situations.

3.1. Fabaceae

Cover crops of the *Fabaceae* botanical family are popular because of their ability to convert atmospheric nitrogen into plant-available forms. Rapid establishment, the high capability of biomass accumulation, improving soil organic matter, enhancing soil structure, reducing soil erosion risk, and suppressing weeds are some properties of legume cover crops [70–72].

Despite several agronomic benefits and desirable agroecosystem functions of cropping systems that incorporate *Fabaceae* plants as cover crops, seed dormancy limits their use. *Vicia* sp. and *Trifolium* sp. are the main cover crop species (Table 1). From a weed management point of view, these cover crop species are noxious and there are limited options for their control in main crops [73]. Seeds of legumes demonstrate both physiological and physical seed dormancy, and can therefore persist in the soil seed bank [54].

3.1.1. *Vicia* sp.

Vicia villosa Roth is considered to be the only species from the Vicia genus that can survive moderate to harsh winter conditions [74] Seeds produced by *V. villosa*, similar to other species of this genus, are dimorphic, comprising of both soft and hard seed coats. Hard seeds of *V. villosa* persist for more than two years and have a higher rate of dormancy-breaking during the first 6 months. Furthermore, it is estimated that >45% of vetch seeds recently shed from the maternal plant are able to germinate [54].

Similar to other members of the legume group, combinational dormancy (physiological and physical) occurs in seeds of *V. villosa*. Many hard seeds, after the removal of physiological dormancy, are capable of germinating over a wide range of environmental conditions (Table 1). The release of seeds of *V. villosa* from dormancy would be accelerate by the after-ripening environment in the summer. Hence, in summer, the dormancy of *V. villosa* seeds would be alleviated and the emergence of seedlings would take place in autumn. Afterwards, the best-established seedlings would survive the harsh winter [75].

According to this information, it could be concluded that mitigating the seed dormancy of hairy vetch and providing enough water for its successful germination are two main factors determining the acceptance of this crop as a fall-planted legume cover crop. Dormant seeds add to the soil seedbank in two different ways: contaminated seeds aimed at the cultivation of the cover crop, and those from unsuccessfully determined cover plants.

It has been reported that priming is not effective in releasing dormancy in hard (viable seeds that do not imbibe water and thus fail to germinate in an apparently favorable scenario) and physiologically dormant seeds, while negatively affect seedling growth, particularly under water deficit conditions (Rolston 1978).

Hard seeds and regrowth after termination with mechanical means usually results in the weediness of *V. villosa* in subsequent crops. As under reduced tillage conditions the common methods of cover crop vegetative growth termination are mowing or roller crimping, the regrowth of *V. villosa* is a challenge in conservation systems. In order to reduce the risk of regrowth, conducting mowing during full flowering (50 to 100%) and the early pod setting of plants is suggested [51]. Furthermore, the adoption of early flowering cultivars is more suited as they can be terminated earlier than warm season crops established in spring. Hence, in addition to a low percentage of dormant seeds and their ability to survive a hard winter, early flowering is a major specific trait.

In addition, different genotypes of *V. villosa* exhibit pod dehiscence [47], resulting in the shattering of seeds prior to the harvest operation yield and adding dormant seeds to the soil seedbank. The percentage of indehiscent pods is partly related to the environmental conditions surrounding the growing mother plants [76]. Despite the negative effects of evolution dormancy in the seeds of *V. villosa* and their pod dehiscence, these traits would make the utility of cover crops in agroecosystems cost effective [77]. This is mainly due to the improvement of self-regeneration no-till cropping systems [54].

The faba bean (*V. faba*, broad bean, horse bean), another important member of the legume group, is cultivated as a winter annual. It tolerates cold temperatures, as opposed to field peas, since the cold does not terminate *V. faba* growth. Furthermore, *V. faba* fixes more N_2 than other cool-season legumes, like winter pea (*P. sativum*) and lupin (*Lupinus albus* L.) [78]. Peas are sensitive to the cold, limiting their cultivation during winter in temperate regions. Legume seeds are generally not hard and tolerate bad soil [79].

Factors contributing to the weediness of legume cover crops, and *V. villosa* in particular, are the development of combinational dormancy mechanisms in seeds, the capacity for regrowth after mechanical termination, and pod dehiscence. When compared to other members of *Fabaceae*, *V. villosa* is less domesticated. To minimize the weediness threat of *V. villosa* in subsequent cash crops, breeding to reduce pod dehiscence, proper cultivar selection, the avoidance of any environmental stress to growing plants, and the choice of suitable termination times and methods could be useful recommendations.

3.1.2. *Trifolium* sp.

Several species of the genus *Trifolium* are commonly adopted for cover cropping, due to their rapid growth and allelopathic activity (containing phenols and isoflavonoids) on weeds [80,81].

Seeds of different clover species can germinate in low temperatures and grow well in shady, cool, and moist conditions, which is common under the closed canopy of cash crops. Hence, clovers are the best option to use for interseeding [82]. Nevertheless, small seed sizes, low seedling vigor, the development of seed dormancy, and poor establishment are some weaknesses of clovers are hindering their extensive application as cover crops [83].

Similar to most *Fabaceae* species, the seeds of clover exhibit a variable ratio of hard seeds. The proportion of hard seeds depends on soil and environmental factors such as temperature, relative humidity, soil texture, fertility, and photoperiod [84]. Accordingly, varieties of the same species show variation in the seed hardiness percentage. Hence, clover species may persist in soil seed banks and become weeds in the next crop [85]. Research suggests that the growth characteristics of *Trifolium* sp. Abilities vary greatly among species, suiting each species for their intended uses.

3.2. Poaceae

There are numerous annual and perennial grass species that can be used as cover crops. Globally, cereals commonly used as cover crops are *Secale cereale* L., *Avena sativa* L., *Lolium perenne* L., and *Sorghum bicolor* (L.) Moench. [86]. Grasses present special traits suitable for weed suppression proposes within crops, mainly superficial root systems, allowing them to control weeds without competing for water with the main crop [87]. The best results from cultivating grasses have been achieved when they are established in optimum time, which in turn is dependent on the seed germination process [68].

Winter annual grasses germinate during fall, coinciding with cool and moist conditions. This cycle is regulated by the presence of non-deep physiological dormancy commonly overcome by high temperatures of summer during dry-after-ripening [88]. Furthermore, the optimum temperature for germinating the seeds of these plants is about 16 °C, preventing the germination of non-dormant and freshly shed seeds in summer (Table 1).

Jiménez-Alfaro et al. [68] evaluated seed germination in response to various temperature regimes by collecting seeds from six winter annual grass species growing in Spanish olive gardens to determine their suitability to be used as ground cover in Mediterranean agroecosystems.

Their results showed that, contrary to previously published works, dormancy showed a low effect on preventing summer germination. However, this low level of dormancy was helpful in inhibiting seed germination immediately after dispersal and under hot and dry conditions during the summer.

In general, low temperatures and adequate moisture, which are common characteristic of the fall season of temperate regions, provide suitable conditions for the seed germination of these winter annual grasses [68].

S. cereale is the most common winter grass cover crop. In this crop, the amount of nitrogen scavenged, the main benefit of adopting this species as cover crop, is greatly dependent on biomass production, growing season length, and the burial depth of the seed in the soil [89].

S. cereale is one of the most recently domesticated cereals, so it poses a great danger to spreading as an important weed [90]. This species is very challenging in cereal crops like wheat and barley, as there is no chemical option for its control. In addition, seeds of its wild relatives exhibit varying level of dormancy, which enable *S. cereale* to maintain its presence in the subsequent crops in the rotation [11].

3.3. Brassicaceae

Cover crops belonging to the *Brassicaceae* family (mustards or Cruciferae) contain various allelochemicals, mainly glucosinolates. Derivates of this compound, including organic cyanides, oxazolidinethione, and isothiocyanates, can suppress weeds [91]. By the incorporation of residues of mustards into soils, its allelochemicals act as a biofumigant against the germination and growth of weeds [92].

To maximize the efficacy of *Brassicaceae* species in enhancing agroecosystem productivity and hindering its weediness in subsequent cash crops, the optimum timing of termination is necessary. Under poor termination, the high growth rate and pod-shattering characteristics of some *Brassicaceae* cover crops make surviving plants problematic weeds. Additionally, seeds added to the soil seed bank remain dormant for many years and become a challenge for the next crops [93] (Table 1).

Mustard seeds are very small, hindering them from emerging from deep layers and coarse-texture soil layers [94]. Therefore, preparing a soft and fine seedbed is essential for successful establishment. This is a very important issue that should be considered about Brassicacea, as the main mechanism by which they suppress weeds is through rapid soil coverage [95].

From this review, it could be argued that a suitable establishment time and the optimum density of cover crops are the most important challenges for achieving the desired ecosystem services and the highest degree of weed suppression from all three main cover crop groups, namely, *Fabaceae*, *Poaceae*, and *Brassicaceae*, and others regardless of their seed and seedling emergence traits. Climate variables, oil properties, management practices, and species characteristics together contribute to influence these challenges [96].

Tribouillois et al. [96] investigated the emergence dynamics of cover crop species, mainly from three botanical families (*Fabaceae*, *Poaceae*, *Brassicaceae*), under different field conditions to estimate the emergence duration and time in response to different sowing conditions with a static model. The results indicated a drastically high variation in emergence duration and percentage depending on the situations of each cover crop species. Furthermore, they concluded that the emergence of cover crops is strongly related to water availability.

In addition, they showed that crucifer cover crop species, such as *Brassica rapa* and *S. alba*, by having a short emergence duration, are capable of being cultivated in late summer. This is because their germination and emergence processes take place within a few days, enabling them to benefit from rare rainfall or the moisture of the seedbed. In opposition, the sowing of legumes with delayed emergence is sensitive to water deficit, probably because of the seeds' slower water consumption. The rapid emergence of *Brassicaceae* may explain their ability to suppress weeds effectively.

4. Solutions for Enhancing Cover Crop Seed Germinability

4.1. Agronomic Practices

Sowing Time and Planting Geometry

Cover crops can be undersown between rows of cash crops, providing a living mulch of companion cover crops that can inhibit the seed germination of photoblastic seeds and the suppression of seedling growth [97]. Undersown cover crops for weed suppression are used for low, taprooted competitive crops like sugar beet, cotton, and canola, which are sown in wide row spaces [98].

The main types of cover crop sowing methods are drilling and broadcasting (aerial spreading or interseeding) seeds. Drilling seeds by burying the seeds into the soil will result in a better cover crop establishment when compared with the broadcasting method [99]. In small-seeded species, required seeding rates are higher for broadcasting seeds as cover crops establish poorly [100].

Broadcasting cover crop seeds into living cash crops (like corn and sugar beet), particularly at crop maturity, can allow for better cover crop establishment as seeds benefit from warm and moist conditions created by leaves [101]. Broadcasting cover crops into cash crops at crop maturity has several advantages, mainly more biomass production, although the seeding rate is higher (at least 25 to 50%) than that of the drilling sowing method [102,103]. Furthermore, interseeding would result in the poor establishment of cover crops as seeds left on the soil surface are exposed to biotic and abiotic stresses, such as water deficit, low-light conditions, and seed predators [89,104]. Mirsky et al. [105] suggested a soil depth range of 3 to 5 cm to obtain the highest seed germination percentage.

On the other hand, in no-till conditions, broadcasting cover crop seeds into the crop residue reaming from harvesting either winter or summer crops provides a protective means for the seed germination and seedling emergence of cover crops against adverse factors such as wind speed, soil evaporation, and chilling temperature [106,107]. A linear relationship between cover crop stand counts and seeding rate has been reported, with an exception of species from *Poaceae*. In cover crops of *Poaceae*, limited available water will further restrict their seeding rate in the broadcast interseeded method [108].

The rapid emergence of cover crops sown in a tillage system would result in more weed management as cover crops emerge more rapidly, due to better access to soil moisture [109,110]. Poor soil–seed contact in no-till usually limits seed germination, as locating seeds on the straw deprives seeds from water for germination. On the other hand, deep tilling by burying weed seeds worsens the weed problem [97]. Hence, providing suitable seed contact with the soil by optimizing the seeding depth (2–3 cm) is crucial for the successful germination and seedling growth of cover crops.

4.2. Seed Pre-Treatment

4.2.1. Seed Priming

Seed priming is the process of accelerating water absorption by seeds and the onset of the metabolism phases of germination, before radical protrusion and then drying and stabilizing at the original moisture level [111]. Seed priming by initiating physiological and biochemical contents of treated seeds enhances aspects of the seed germination and seedling emergence of a wide range of crop species (Table 2).

Table 2. Seed mass and seed germination responses of a wide range of cover crop species to seed treatment (priming and coating).

Cover Crop Species	1000-Seed Weight (mg) §	Seed Treatment	
		Priming	Coating
Guizotia abyssinica	3.3	+ [112]	Unknown
Helianthus annuus	48.0	+ [113]	+ [114]
Brassica carinata	5.0	Unknown	Unknown
Brassica juncea	3.0	+ [115]	Unknown
Brassica napus	2.7	+ [116,117]	+ [118]
Brassica rapa	3.7	+ [119,120]	+ [121]
Camelina sativa	1.3	+ [122,123]	Unknown
Eruca sativa	1.3	+ [124]	Unknown
Raphanus sativus	13.0	+ [125]	Unknown
Sinapis alba	8.0	Unknown	Unknown
Lathyrus sativus	176.0	+ [126]	Unknown
Lens nigricans	21.5	Unknown	Unknown
Lupinus angustifolius	179.4	Unknown	Unknown
Medicago lupulina	1.5	Unknown	+ [127]
Melilotus officinalis	2.5	Unknown	Unknown
Onobrychis viciifolia	23.0	+ [128]	+ [127]
Pisum sativum	168.8	+ [129,130]	+ [131]
Trifoliumalexandrinum	3.0	+ [132]	Unknown
Trifolium incarnatum	4.7	Unknown	Unknown
Trifolium hybridum	0.83	Unknown	
Trifolium resupinatum	1.48	Unknown	Unknown
Trifolium pratense	2.04	+ [133]	+ [134]
Trifolium subterraneum	6.28	+ [135]	Unknown
Trifolium repense	075	+ [136]	+ [127]
Trigonella foenum graecum	16.0	+ [137]	Unknown
Vicia faba	359.6	+ [138]	Unknown
Vicia sativa	53.8	+ [139]	Unknown
Vicia villosa	26.7	+ [140,141]	Unknown
Phacelia tanacetifolia	1.8	+ [142]	Unknown
Avena sativa	39.4	+ [143]	+ [144]
Lolium hybridum	3.4	Unknown	Unknown
Lolium multiflorum	2.7	+ [145]	+ [146]
Secale cereale	32.3	+ [147]	Unknown
Secale multicaule	18.8	Unknown	Unknown
Setaria italica	2.2	+ [148]	Unknown
Sorghum sudanense	13.8	+ [149]	Unknown
Fagopyrum esculentum	25.0	Unknown	Unknown

§ 1000-Seed weight [42,150].

Seed priming improves the seed germination and seedling establishment of cover crops in the early growing season. In addition, it causes the rapid growth of cover crops through increasing the water uptake and nutrients, securing higher as well as more uniform cover crop stands [132,151]. Seed germination and seedling emergence responses to seed priming vary among species (Table 2). Cover crop species with a small seed size and hard seed coating [152,153] are more likely to benefit more. In addition, both priming media and duration impact seed germination and seedling emergence [154].

In semi-arid areas, a lack of moisture in early autumn inhibits seed germination and the seedling growth of cover crops. Hence, accelerating the germination of cover crops by priming not only makes their seedlings more tolerant to water stress, but also enhances their competitiveness against weeds. For example, Yusefi-Tanha et al. [141] reported that the priming of hairy vetch seeds with potassium nitrate and distilled water prompted guaiacol peroxidase and catalase activity in seedlings and subsequently enhanced the ability of the seedling to resist oxygen free radicals resulting from the peroxidation of different compounds. Furthermore, they demonstrated that the performance of different priming methods in enhancing the germination of hairy vetch varied depending on ambient temperature.

Under low temperature conditions, the hydropriming (soaking seeds in water) of hairy vetch had a higher positive impact on seed germination in comparison with either halopriming or hydropriming. In contrast, under a higher temperature (15 °C) the efficacy of priming was not significantly different from non-primed conditions, showing the advantage of priming only under adverse conditions. Yusefi-Tanha et al. [141] concluded that both halopriming and hydropriming were more efficient in improving seedling establishment and the early growth of hairy vetch at lower temperatures by enhancing physiological parameters and the germination process.

In another study, the effect of seed priming duration on the germination of some cover crop species' seed size and germination traits, including cereal rye (*S. cereale*), perennial ryegrass (*L. perenne*), hairy vetch (*V. villosa*), and oriental mustard (*Brassica juncea* L.), was investigated [115]. They determined the effectiveness of priming for the seedling emergence of perennial ryegrass and hairy vetch under compaction for evaluating the seedling vigor.

Similar to the above-mentioned study, Snapp et al. [115] demonstrated that seed priming accelerates germination for hairy vetch, mustard, and perennial ryegrass. Perennial ryegrass, with the smallest seed size among the evaluated species, was the only species in which seed germination was improved substantially by priming under non-stress conditions. They showed that the seedling emergence of hairy vetch and perennial ryegrass in compacted soil was improved by seed priming (Table 2), by 39% and 42%, respectively, compared with unprimed seeds [115]. This is a valuable result, as cover crops can be cultivated in compacted soil, as in the early years of conservation agriculture.

Hydro-priming and osmo-priming (soaking seed in chemicals that reduce the osmotic potential of seed) are regularly applied to improve seed performance in various cultivated crops [155]. Increased seed germination by priming seeds with potassium nitrate (KNO_3) can be achieved using one or more mechanisms, including the softening of the impermeable seed coat, the release of ethylene within embryonic tissues, and the washing out of seed germination-inhibitor compounds from seeds [156,157]. For example, [140] pointed out that hydro-priming is suitable for older seeds of pod vetch [*V. villosa* and *Vicia dasycarpa* Ten.], while they also found osmo-priming (with KNO_3) to be a better pre-treatment for freshly harvested seeds.

4.2.2. Seed Coating

Covering seeds with external materials to improve their handling and protection and, to a considerably lesser extent, germination enhancement, seedling vigor, and stand establishment is called seed coating [158]. Seed coating with biostimulants consisting of microbial inoculants, beneficial bacteria and fungi, nitrogen-containing compounds, biopolymers, and plant extracts is more environmentally friendly and effective compared to less sustainable conventional pesticides and fertilizers [159–161]. Amongst other seed coating techniques, seed pelleting, film coating, and seed encrusting are the most commonly used. Seed germination and the seedling vigor of coated seeds are not only influenced by chemical properties of applied compounds, but also, to a higher extent, by physical properties and the thickness of the coating. Hence, an optimum coating thickness also should be determined for a given cover crop species in order for the seed coating to be effective.

Qiu et al. [134] investigated the seed germination and seedling growth of red clover (*Trifolium pratense* L.) and perennial ryegrass (*L. perenne*) seed responses to coating with different combinations of soy flour, diatomaceous earth, micronized vermicompost, and concentrated vermicompost extract. Results indicated that the germination percentage, uniformity, speed, and seedling growth of coated seeds of red clover were higher when compared with the non-treated-seeds control.

In opposition to red clover, seed coating with various biostimulants reduced the seed germination for perennial ryegrass, while the growth in seedlings produced by coated seeds was significantly enhanced. The results of this study emphasize the importance of species-specific responses to coating treatments when adopting seed coating for improving the germination and subsequent establishment of the desired cover crops.

5. Conclusions

The delivery of most ecosystem services is related to cover crop biomass productivity and results from successful establishment and early growth, which in turn are affected greatly by cover crop seed traits. Here, we showed for the first time that seed traits of cover crops are the major drivers of cover crop weed suppression. Furthermore, information on the response of cover crop seed germination to biotic and abiotic factors, as well as methods for improving germination and seedling emergence, is crucial. Farmers facing climate change are looking for species/varieties with appropriate seed traits which, coupled with innovative farming strategies, could allow them to obtain a fair return on investment. The information presented in this review on the seed traits and treatments of cover crops would be helpful for a diversity of stakeholders (e.g., farmers, extension services, researchers, seed companies) wanting to use cover crops more effectively.

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