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Review

Activated carbon seed technologies: Innovative solutions to assist in the restoration and revegetation of invaded drylands☆

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ABSTRACT

The demand for seed-based restoration and revegetation of degraded drylands has intensified with increased disturbance and climate change. Invasive plants often hinder the establishment of seeded species; thus, they are routinely controlled with herbicides. Herbicides used to control invasive plants may maintain soil activity and cause non-target damage to seeded species. Activated carbon (AC), which has a high adsorption of many herbicides, has been incorporated into seed pellets and coatings (seed technologies) to limit herbicide damage. Though various AC seed technologies have been examined in numerous laboratory and field studies, questions remain regarding their effectiveness and how to improve it, and what causes variation in results. We synthesized the literature on AC seed technologies for dryland restoration and revegetation to attempt to answer these questions. AC pellets compared to seed coatings were more thoroughly tested in the field and generally provide strong herbicide protection. However, greater amounts of AC in seed coatings appear to increase their effectiveness. Seed coatings show more potential for use than pellets because they are less logistically challenging to use compared to pellets, but need more field testing and refinement. Results often differ between laboratory and field studies, suggesting that field studies are critical in determining realized effects. However, seedling establishment failures from other barriers make it challenging to evaluate the effectiveness of AC seed technologies in the field. AC seed technologies are an innovative tool that with continued refinement, especially if other barriers to seedling establishment can be overcome, may improve the restoration and revegetation of degraded drylands.

1. Introduction

Degradation of drylands around the globe is reducing biodiversity and ecosystem goods and services (Milton et al., 1994; Millennium Ecosystem Assessment, 2005; Han et al., 2008). Degradation has accelerated because of increased anthropogenic disturbance and climate change (Foley et al., 2005; Huang et al., 2016). This has resulted in an intensified need for restoration and revegetation research and application (United Nations General Assembly, 2019; Lázora-González et al., 2023). Most restoration and revegetation of drylands are seed-based because it is less expensive and time consuming compared to other methods that are challenging to apply across large landscapes (Pérez et al., 2019; Shackelford et al., 2021). However, seed-based restoration and revegetation efforts in drylands often have low (<10%) success at establishing perennial vegetation (James et al., 2011; Shackelford et al., 2021), which may be attributed to highly diverse conditions in space and time that make it difficult to generalize restoration plans in many dryland ecosystems (e.g. Svejcar et al., 2017). Improvements in success with seed-based restoration and revegetation are clearly needed, and even small increases in success would likely have large on-the-ground impacts.

Seed enhancement technologies (SETs), developed to overcome

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abiotic and biotic barriers to seedling establishment, show great theoretical promise for increasing success and providing a diversified set of tools for the adaptive management of degraded dryland ecosystems (Madsen et al., 2016; Brown et al., 2021; Svejcar et al., 2022; Jarrar et al., 2023). SETs have been developed to reduce the impacts of barriers to seedling establishment such as crusting soils (Madsen et al., 2012), seed predation (Taylor et al., 2020), timing of germination (Madsen et al., 2018; Richardson et al., 2019; Larson et al., 2023), water stress (Pedrini et al., 2021), and herbicide toxicity (Madsen et al., 2014; Davies, 2018). Of these technologies, limiting herbicide damage to seed species has received a great deal of attention recently, likely because degraded drylands are frequently dominated by invasive plant species. An adaptive management approach to simultaneously controlling invasive plants and reestablishing desired species is critical to the restoration of many of these ecosystems (Dittel et al., 2023). One common practice in an adaptive management framework for controlling invasive species is the application of herbicides prior to establishing more desirable plant communities.

SETs designed to limit herbicide toxicity are needed in restoration and revegetation efforts because herbicides commonly used to control competitive invasive plants may otherwise limit seeded species establishment. Pre-emergent herbicides and some contact herbicides, such as glyphosate, that are frequently used to control invasive plants can remain active in the soil and negatively impact the emergence, growth, and establishment of seeded species (Davies et al., 2014; McManamen et al., 2018; Munro et al., 2023). SETs that contain activated carbon (AC), such as pellets and coatings, may reduce herbicide toxicity to seeded plants. AC has a high adsorption capacity for many herbicides and organic compounds because of its high surface area and abundant submicroscopic pores per unit volume (Bovey and Miller, 1969; Coffey and Warren, 1969). AC is often made by pyrolyzing carbonaceous source materials in a furnace at extreme temperatures, though it can also be made chemically. The ‘activated’ refers to the creation of many small pores that greatly increases the surface area. In crop systems, AC has been applied as a slurry in bands over seeded rows to protect crops from herbicide damage (Burr et al., 1972; Lee, 1973). However, weeds emerging from seeds within the AC band are often protected from herbicide control (Lee, 1973; Kratky, 1975), thus, competition from weeds may not be reduced to desired levels within AC bands. Limiting the protection from herbicide toxicity to the area in the immediate vicinity of the seed would improve the control of invasive plants and, thereby, increase the likelihood of successful establishment of seeded species. To accomplish this task, AC has been integrated into SETs to limit non-target herbicide damage to seeded species (Madsen et al., 2014; Svejcar et al., 2022).

Though numerous evaluations of different AC seed technologies have been performed, many questions remain about their effectiveness, what causes variation in results, and how they could be improved. To attempt to answer these questions, we synthesized the literature investigating the use of AC seed enhancement technologies to limit herbicide damage to seeded species in efforts to improve restoration and revegetation of degraded drylands. However, quantitative synthesis of the effects of AC technologies is limited because of variability in the physiochemical composition of AC technologies, site properties, and seeding methods. We also discuss the limitations of AC seed technologies and suggest important avenues for future research to improve their effectiveness and efficiency.

2.1. Pellets and coatings

Two common methods for incorporating AC into SETs are as a pellet or as a seed coating (Fig. 1). AC pellets have also been referred to as herbicide protection pods (HPPs) in the literature (e.g., Clenet et al., 2020; Baughman et al., 2021). AC pellets include multiple seeds within each pellet, while AC seed coatings are applied to individual seeds. AC pellets are often made by incorporating AC into a dough mixture containing seeds and other substrates and then extruding it through a die (Madsen et al., 2014, 2016; Davies et al., 2017; Baughman et al., 2021; Brown et al., 2023a). As the dough is pushed out of the die it is cut into the desired pellet lengths. AC seed pellets can also be made with molds (Brown et al., 2023b). Seed coatings containing AC can be applied using a rotary method (Madsen et al., 2014), a vortex method (Holfus et al., 2021), or commercially (Baughman et al., 2024; Duquette et al., 2024). The rotary method attaches AC to the seeds using a rotary coater and a binder (Madsen et al., 2014). The vortex method adds additional AC to seeds already coated with the rotary method by layering the coated seeds with AC and binders on vibrating plate and hand mixing them, drying, and repeating until desired application rate is achieved (Holfus et al., 2021). The vortex and commercial coatings can apply more AC to seeds than rotary methods (Holfus et al., 2021; Duquette et al., 2024).

Early seed coatings were not as effective as pellets because the thin coating of AC was not enough to provide full protection from herbicides, particularly at the higher rates often needed to successfully limit invasive plants (Madsen et al., 2014; Baughman et al., 2023). However, some more recent AC seed coatings performed as well as small AC pellets at limiting herbicide damage (Baughman et al., 2023). Seed coatings with more AC have also been demonstrated to be comparable to pellets in a laboratory study with the preemergent herbicide imazapic (Duquette et al., 2024). This suggests that advancements in AC seed coatings may make them a viable alternative to AC pellets for protecting seeded species from herbicide damage. This would be extremely valuable because coated seeds are smaller in size and are less logistically challenging to

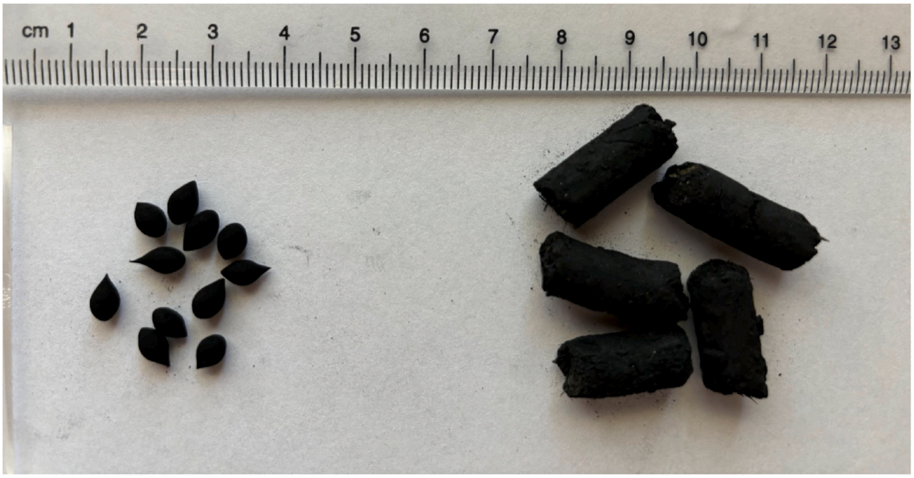

Fig. 1. Activated carbon seed coatings (left) and pellets (right) used to protect seeded species from herbicide toxicity.

use with standard revegetation equipment, such as seed drills, compared to pellets.

However, AC pellets have been more rigorously evaluated than AC seed coatings for restoration and revegetation of drylands (Table 1). To date, AC seed coatings have only been limitedly tested in the field (Terry et al., 2021; Baughman et al., 2023), while AC seed pellets have been tested, and proven effective at limiting herbicide damage to seeded species, multiple times in the field in Australia (e.g., Brown et al., 2023a; Munro et al., 2023) and the United States (e.g., Davies et al., 2017; Davies, 2018; Clenet et al., 2020) with several different herbicides. AC seed coatings are a promising option, but further testing is needed with other herbicides, with more species, and in the field before they can be recommended as a substitute for AC pellets.

1.2. *Laboratory versus field studies*

Laboratory and field studies have been used to investigate the ability of AC seed technologies to limit non-target herbicide damage in the restoration and revegetation of drylands. We found 17 manuscripts in the literature, eight were field-based studies, eight were laboratory-based studies, and one included both field and laboratory studies, investigating the use of AC seed technologies to limit herbicide damage to seeded dryland plant species (Table 1). Laboratory studies consistently show positive results of AC seed technologies for limiting herbicide damage to seeded species (e.g., Madsen et al., 2014; Clenet et al., 2019; Brown et al., 2019). In contrast, some species seeded in field studies failed to establish enough individuals (see section below on failures) to evaluate if AC seed technology protected seeded species from herbicide effects (Clenet et al., 2020; Baughman et al., 2023, 2024; Davies et al., 2023a). Similar to the literature on AC seed technologies, SETs, in general, have greater positive effects in laboratory compared to field studies (Berto et al., 2024).

Laboratory studies control the environment, often ensuring adequate soil moisture and optimal temperatures for seedling germination, emergence, and growth, limit competition, and exclude seed predators and herbivores. Providing sufficient conditions for survival greatly increases the probability of having enough seedlings emerge and survive to evaluate if AC seed technologies are providing herbicide protection. Some, though not complete, herbicide protection with AC seed technologies may be enough to allow survival under optimal conditions (i.e., in the laboratory), but in the field, incomplete herbicide protection may make seedlings more vulnerable to environmental stress and competition (Baughman et al., 2024). Herbicide impacts on plants can also differ between laboratory settings and field studies, suggesting that laboratory studies can reveal potential effects, but field trials are needed to identify realized effects (McManamen et al., 2018). Laboratory studies are useful for evaluating new AC seed technologies and providing proof-of-concept of new ideas, but field studies are undeniably needed to determine if technologies will have meaningful effects on restoration and revegetation efforts.

1.3. *Cost to seed species incorporated into pellets*

Negative impacts of AC seed enhancement technologies in the absence of herbicides on seedling emergence and growth have been observed in some laboratory studies (Clenet et al., 2019; Baughman et al., 2021; Brown et al., 2023b), but not necessarily always realized in field studies (Baughman et al., 2023). In fact, sagebrush, a small-seeded shrub species, had severely reduced emergence and stunted growth when incorporated in pellets in a laboratory study (Clenet et al., 2019), but was successful in a field experiment (Clenet et al., 2020). Pellets are likely difficult for small seeded species to emerge from as well as challenging for their radicle to grow through to reach the soil. This may be particularly noticeable in larger pellets (Baughman et al., 2021) and when seeds are near the center of pellets (Brown et al., 2023b).

In laboratory studies, favorable temperatures and soil moisture result in rapid germination of seeds incorporated into pellets. In these situations, the integrity of the pellets remains largely intact. In field studies, pellets may be planted, but water and temperature requirements for seed germination may not be met for several months. Freeze-thaw and wet-dry cycles may break down pellets in the field, making it much easier for seedlings to emerge and send the radicle out of the pellet material (Clenet et al., 2020). Hence, the cost of pellets to seeded species likely varies by environmental effects on the integrity of the pellet as well as the construction of the pellet. The cost, or lack of a cost, of being incorporated into pellets also likely depends on species. For example, some studies have reported that activated carbon pellets do not impede emergence (Brown et al., 2019) and can even improve emergence of some seeded species (Brown et al., 2023a), but other species have been noticeably negatively impacted by being incorporated within pellets (Clenet et al., 2019; Baughman et al., 2021; Brown et al., 2023b). There may be a cost to seeded species of being incorporated into seed pellets, but the effect likely varies by species, seeding environment, AC seed technology integrity, and interactions among these factors.

1.4. *Seeding method effects*

There appears to be a distinct difference in success depending on how AC seed technologies are implemented in the field. Similar to the results typically seen with bare seed, methods simulating drill seeding (Davies et al., 2017; Davies, 2018; Clenet et al., 2020) appear to be more successful at establishing species incorporated into AC seed technologies than broadcast seeding (Baughman et al., 2023; Davies et al., 2023a). Broadcast seeding is often not effective for establishing perennial grasses because of poor seed-to-soil contact (Svejcar et al., 2023a). To date, AC seed technologies have not been developed to overcome the limitations of broadcast seeding.

In addition, if preemergent herbicide is applied, broadcast-sown seeds may be the most susceptible to the herbicide compared to seeds drilled below the soil surface. Most preemergent herbicides bind strongly to soil particles, particularly in soils with higher clay and organic matter content (Duncan and Scifres, 1983). This strong binding

Table 1
List of studies conducted in the laboratory, field, or both investigating the ability of activated carbon seed technologies to provide herbicide protection for dryland restoration and revegetation. AC = activated carbon technology, P = seed pellet, C = seed coating, P/C = seed pelleting and seed coating, HP = herbicide protection.

Laboratory			Field			Laboratory and Field		
Manuscript	AC	Evidence of HP	Manuscript	AC	Evidence of HP	Manuscript	AC	Evidence of HP
Baughman et al. (2021)	P	Yes	Baughman et al. (2023)	P	Yes	Baughman et al. (2024)	P/C	Yes (lab) No (field)
Brown et al. (2019)	P	Yes	Brown et al. (2023a)	P	Yes			
Brown et al. (2023b)	P	Yes	Clenet et al. (2020)	P	Yes			
Clenet et al. (2019)	P	Yes	Davies et al. (2017)	P	Yes			
Duquette et al. (2024)	P/C	Yes	Davies (2018)	P	Yes			
Holfus et al. (2021)	C	Yes	Davies et al. (2023)	P	No			
Madsen et al. (2014)	C	Yes	Munro et al. (2023)	P	Yes			
Svejcar et al. (2024)	P	Yes	Terry et al. (2021)	C	Yes			

limits the herbicides downward movement and concentrates it in the upper soil layers. Therefore, seeds buried to a greater depth may experience less herbicide toxicity (Walker, 1973; Mester and Buhler, 1991). Consequently, drill seeding may complement AC seed technologies in their ability to mitigate herbicide toxicity.

Seeds incorporated in AC seed technologies have also been more successful when seeded in furrows compared to broadcast seeding (Terry et al., 2021; Baughman et al., 2023). Furrows simulate a drill row created by the disk on the drill seeder, but, dissimilar to drill seeding, seeds are not purposefully buried but may become buried as soil is redistributed over time. Furrows can improve seedling success by creating a micro-environment where soil moisture is more consistent and soil temperatures are moderated (Call and Roundy, 1991; Winkel et al., 1991; Witharama et al., 2007). In general, drill seeding or seeding in furrows will improve overall seedling establishment and considering the extra cost associated with using AC seed technologies should probably be the default methods. Drill seeding is probably the ideal method for species that can be buried, such as larger seeded perennial grasses, but furrowing may be better for species that can easily be buried too deep such as small-seeded plants. However, broadcast seeding is still an important restoration tool that can be used to establish desired species (Applestein et al., 2018; Svejcar et al., 2023a), especially in locations where equipment for drill seeding and furrowing cannot be used because of terrain, rockiness, logistics, or regulations.

1.5. *Composition of AC seed technologies*

Composition, including size, seed position, material sources, and combinations of different materials, also play a critical role in the functioning and efficacy of AC seed technologies. The size of AC technologies relative to the size of the seeds being incorporated may have a major impact on the ability of seeds to emerge (Baughman et al., 2021). Too large of a pellet may be difficult for some species to emerge from successfully (Baughman et al., 2021). Conversely, if not enough AC is used relative to the rate of herbicide being applied, then the level of protection provided by AC may be insufficient to benefit seed germination, emergence, and growth (Madsen et al., 2014). Finding a balance between the total AC used and the amount of material used relative to seed size is critical to the emergence of seeded species and the level of protection provided by the AC seed technology (Madsen et al., 2014; Baughman et al., 2021; Brown et al., 2023a, 2023b).

Seed position within a particular AC seed technology can impact both the ability of seeds to emerge and the level of protection provided from herbicide toxicity (Brown et al., 2023a, 2023b). AC pellet production entail seeds being thoroughly mixed in a dough and extruded via a mechanized device such that the position of seeds within pellets is random: seeds might be in the middle or edge of a pellet (Madsen et al., 2014; Baughman et al., 2021; Brown et al., 2023a). This position can influence outcomes in a couple of ways. For example, if small-seeded species are incorporated into AC seed technologies like pellets that have large proportional amounts of material relative to the seed size, seeds in the center of the pellet may not be able to emerge due to physical constraints (Clenet et al., 2019; Baughman et al., 2021). Wherein seeds positioned at the bottom of an AC pellet demonstrated higher emergence and survival, likely because of greater herbicide protection and fewer constraints to emergence (Brown et al., 2023a, 2023b). Clearly, seed position within AC seed technologies can influence the efficiency of the technology and the emergence and growth of seeded species. However, there are so many parameters and permutations for pellets and coating it is difficult to generalize.

The relative and total quantity of AC used likely plays a role in the ability of AC seed technologies to provide enough protection for seeds against the different types and rates of herbicides being applied. The relative proportion of AC to other materials in pellets (by weight and hereafter referred to as relative AC) to date has a wide range: 54% (Madsen et al., 2014), 35% (Davies et al., 2018), 33% (Clenet et al., 2019), 10% (Brown et al., 2019), and 5% (Brown et al., 2023a). Similarly, the relative AC in seed coatings varies among studies: 92% (Madsen et al., 2014), 67% (Terry et al., 2021), 33% (Holfus et al., 2021), and 10% (Brown et al., 2023a). The total quantity of AC has variable effects on emergence (Brown et al., 2019) and growth (Madsen et al., 2014) of species incorporated into AC seed technologies. For example, Madsen et al. (2014) found AC pellets with 54% relative AC and 44 mg total AC per seed were effective at protecting seeds from five rates of herbicide application, while AC coatings with 92% relative AC and 6 mg total AC were only effective at lower rates of herbicide application. However, the relative impact of the AC is also highly dependent on the additional materials being added. The relative and total quantity of AC in seed technologies plays a key role in both the emergence and survival of seedlings, but the specific responses to those technologies likely depend on soil and environmental conditions (Brown et al., 2023a).

1.6. *Failures*

Abiotic and biotic barriers can cause failures in establishing seeded species using AC seed technologies in the field as both singular and concomitant drivers of morality (Fig. 2). Low establishment of seeded species is typical for semiarid drylands due to the harsh environmental conditions (Hardegree et al., 2016; Svejcar et al., 2017; Shackelford et al., 2021; Svejcar et al., 2023a). Inadequate soil moisture is often to blame for seeded species failing to establish, but other environmental stressors such as freezing of newly emerged seedlings, heatwaves, insect outbreaks, and flooding can also cause seedling mortality (Boyd and Lemos, 2013; Svejcar et al. 2017, 2023b; Parker et al., 2024). Many failures to detect an advantage from using AC seed technologies are likely caused by environmental factors leading to the mortality of seeded seedlings and seed, not necessarily a lack of protection from herbicide toxicity. However, if herbicide protection is limited, such as with some seed coatings, some herbicide damage to seedling growth may make them more vulnerable to environmental stressors (Baughman et al., 2024).

Biotic barriers to seedling establishment may also make it difficult to determine if AC seed technologies are limiting herbicide toxicity to seeded species. Seed predators (Brown and Heske, 1990; Maron et al., 2012), seed pathogens (Chambers and MacMahon, 1994; Gornish et al., 2015), and seedling herbivory (Hulme, 1994; Davies et al., 2023b) in the field likely limited the emergence and survival of seeded species. For example, a fungicide seed coating increased the emergence of a native bunchgrass by more than 50% (Hoose et al., 2022), likely by limiting seed mortality from fungi. Similarly, competition can also decrease the survival of newly emerged seedlings (Maron, 1997). In a study in eastern Oregon (Davies et al., 2023a), high amounts of residual perennial vegetation were released from competition with invasive annual grasses with a preemergent herbicide application. Competition from these residual perennial plants, combined with below average precipitation, likely limited the establishment of perennial species seeded in AC pellets (Davies et al., 2023a).

Clearly, both abiotic and biotic barriers to seedling establishment exist in the field. Overcoming one barrier may not result in the successful establishment of seeded species if other barriers still exist. The high rates of failure with seed-based restoration and revegetation in drylands makes it challenging to determine the effectiveness of AC seed technologies as well as investigate methods to refine them, necessitating numerous field experiments across multiple sites and years to tease out the effectiveness of AC seed technologies.

1.7. *Challenges to using AC seed technologies*

AC seed technologies could become a very impactful tool that land managers have for the restoration and revegetation of invaded dryland ecosystems. While these technologies may become quite valuable, it is

Micro scale (10s of m):
- Diverse soil surface topography
- Interspace and canopy
- Variance in moisture and light exposure
- Diverse exposure to soil microbes and pathogens

Site scale (100s-1000s of ha):
- Different temperature and moisture conditions based on aspect and elevation
- Variation in granivore and herbivore populations
- Diverse soil types and characteristics

Ecosystem scale (1,000,000s of ha):
- Different temperature and moisture regimes
- Variance in light exposure driven by latitude
- Variability in plant community composition

Fig. 2. Understanding the abiotic and biotic drivers of success at different scales (micro site to ecosystem) is critical to the understanding of efficacy of product when testing and developing activated carbon seed technologies. Great Basin map (RAP fractional cover of herbaceous annuals) on right is from Smith et al., 2021.

critical to recognize the financial and logistical limitations to their widespread use.

Restoration and revegetation of invaded drylands are expensive because of the cost of controlling invasive plants and seeding desired species, at times to the point that it is unfeasible for some areas (Davies et al., 2021; Pedrini et al., 2022). Incorporating seeds into AC pellets or coating seeds with AC will incur additional cost (Madsen et al., 2016), though costs will vary substantially by technology, quantity, and commercial availability. Regardless, the added financial burden of amending seeds with AC seed technologies may be too high in land management plans for many land managers or at least limit the scale of its use.

Utilizing AC seed technologies also adds logistical challenges. First, getting seeds pelleted or coating with AC is an additional step, that may be quite time consuming, to seeding efforts that may already be constrained by a limited window of opportunity to seed. AC seed technologies also increase the bulk of seeding material, which increases the storage and shipping needs (Baughman et al., 2023). Standard rangeland seeding equipment is also not designed to deliver pellets, thus specialized or modified equipment will likely be needed to seed AC pellets. The additional materials associated with AC seed technologies can also make it difficult to seed species at the recommended rates without additional seeding passes. This can increase the time it takes to seed as well as the cost. The logistical challenges associated with increased bulk is substantially greater for pellets than seed coatings, but effective AC seed coatings are substantially larger than bare seeds (Baughman et al., 2023; Duquette et al., 2024) and, hence, also present a logistical barrier to implementation.

While AC seed technologies can likely become a valuable component of restoration and revegetation efforts in invaded drylands, its use will be constrained by financial and logistical barriers. Strategically applying AC seed technologies when and where it will be the most valuable will be necessary to achieve large landscape restoration and revegetation goals.

1.8. Research needs

The development of AC seed technologies for dryland restoration is still in its infancy with testing occurring in the western US and western Australia. Five types of herbicides have been applied in these studies (Table 2) and a total of ten grass, six shrub, three forb and two tree species have been tested to date (Table 3). While a great deal of information can be gleaned from the studies found in this review, there are still many research needs related to AC seed technologies. As more refined AC technologies are developed, they will need to be evaluated against the more standard strategy for restoring and revegetating invaded rangelands of waiting to seed until after herbicide toxicity has largely subsided.

Empirical testing of the material compositions of AC seed technologies is a key research need. Variations in AC physical and chemical properties can have a major impact on the adsorptive capacity of the resulting AC (Mahmudov and Huang, 2010). The AC used for seed technology development studies so far has been sourced from a wide variety of companies and likely have high variation in specific surface area and surface charge (e.g., Mahmudov and Huang, 2010). For example, Baughman et al. (2024) utilize AC derived from coal, while Madsen et al. (2014) utilize AC derived from wood. Variation in physical

Table 2
Herbicide types applied in activated carbon (AC) seed technology studies.

Mode	Herbicide chemical name	Herbicide product name	Herbicide Group	Citations
Pre-emergent	Imazapic	Panoramic 2SL	2/B	Madsen et al., (2014); Davies et al., (2017); Davies (2018); Clenet et al., (2020); Terry et al. 2021[Ŧ] (Baughman et al., 2021 doesn't list brand, just says imazapic)
	Imazapic	Plateau BASF	2/B	Holfus et al., (2021); Baughman et al., (2023); Duquette et al., (2024); Svejcar et al., (2024)
	Indaziflam	Esplanade 200 SC	29/O	Clenet et al., (2019); Davies et al., (2023); Svejcar et al., 2024*
	Simazine	Simazine 900 WG	5/C	Brown et al., (2019); Brown et al., (2023b)
Post-emergent	Glyphosate	RoundUp	9/M	Munro et al. (2023)
	Fluazifop-p	Fusilade Forte	1/A	Brown et al., (2023a); Munro et al., (2023)

Table 3
Dryland plant species utilized in activated carbon (AC) seed technology studies and whether or not evidence of herbicide protection (HP) was found. How many manuscripts reported finding or not finding evidence of HP for that species was reported in paratheses.

Species	Common name	Functional group	Seed mass (mg)	Evidence of HP	Manuscript(s)
Acacia pulchella	prickly moses	*shrub*	7.17[a]	Yes (1)	Munro et al. (2023)
Achillea millefolium	yarrow	*forb*	0.12[a]	Yes (1)	Svejcar et al. (2024)
Agropyron cristatum	crested wheatgrass	*grass*	4.03[a]	Yes (3)	Clenet et al., (2020); Davies et al., (2017); Svejcar et al., (2024)
Agropyron desertorum	desert wheatgrass	*grass*	2.66[b]	No (1)	Davies et al. (2023)
Agropyron fragile	Siberian wheatgrass	*grass*	2.12[a]	Yes (2) No (1)	Davies (2018); Davies et al., (2023); Svejcar et al., (2024)
Anigozanthus manglesii	red-and-green kangaroo paw	*forb*	0.96[a]	Yes (1)	Munro et al. (2023)
Artemisia tridentata ssp. *wyomingensis*	Wyoming big sagebrush	*shrub*	0.93[a]	Yes (2) No (3)	Baughman et al., (2021), 2023; Clenet et al., (2019), 2020; Davies (2018)
Banksia menziesii	firewood banksia	*tree*	77.4[a,c]	Yes (1)	Munro et al. (2023)
Bassia prostrata	forage kochia	*forb*	0.89[c]	No (1)	Davies (2018)
Coleogyne ramosissima Torr.	blackbrush	*shrub*	17.54[a]	Yes (1)	Svejcar et al. (2024)
Elymus elymoides [Raf.] Swezey	bottlebrush squirreltail	*grass*	8.00[a]	Yes (5)[e] No (2)[e]	Baughman et al., (2023), 2024; Clenet et al., (2020); Davies (2018); Duquette et al., (2024); Svejcar et al., (2024)
Eucalyptus todtiana	coastal black butt pricklybark	*tree*	6.30[d]	Yes (1)	Munro et al. (2023)
Gompholobium scabrum	painted lady	*shrub*	7.70[a]	No (1)	Munro et al. (2023)
Jacksonia furcellata	gray stinkwood	*shrub*	6.55[a]	Yes (2)	Brown et al., (2023a), 2023b
Leymus cinereus	basin wildrye	*grass*	2.85[b]	Yes (1)	Clenet et al. (2020)
Lolium rigidum	annual ryegrass	*grass*	2.90[c]	Yes (1)	Brown et al. (2019)
Poa ampla	Sherman bluegrass	*grass*	0.01[c]	No (1)	Davies et al. (2023)
Poa secunda	Sandberg bluegrass	*grass*	0.45[b]	Yes (3) No (1)	Baughman et al., (2021), 2023; Clenet et al., (2020); Davies (2018)
Pseudoroegneria spicata	bluebunch wheatgrass	*grass*	5.26[a]	Yes (9)[e] No (2)[e]	Baughman et al., (2023), 2024; Clenet et al., (2019), 2020; Davies (2018); Duquette et al., (2024); Holfus et al., (2021); Madsen et al., (2014); Svejcar et al., (2024); Terry et al., (2021)
Purshia tridentata	antelope bitterbrush	*shrub*	0.24[c]	No (1)	Clenet et al. (2020)
Thinopyrum intermedium	intermediate wheatgrass	*grass*	5.27[b]	No (1)	Davies et al. (2023)

[a] Data collected by authors.
[b] Larson et al. (2015).
[c] Seed information database, 2024.
[d] Hallet et al. (2011)
[e] Baughman et al. (2024) found evidence of HP in a laboratory experiment, but in a field experiment they did not find evidence HP.

and chemical properties of the carbons used could play a major role in the efficacy of AC seed technologies and is an understudied area of research. A record of source materials (e.g., wood, coal), pyrolysis temperature, pyrolysis time, and activation method in addition to total and relative quantity of carbon used is needed to provide consistent comparison across diverse climoedaphic gradients and with application of different types and rates of herbicides.

Though activated carbon is the key ingredient being incorporated in AC seed technologies, all technologies use some combination of additional materials to ensure that the AC stays bound around the seeds. Pellet technologies often utilize material such as bentonite clay, compost, and poly-absorbent materials to ensure AC pellet integrity (Madsen et al., 2014; Brown et al., 2019; Clenet et al., 2019). Similarly, seed coatings with AC often utilize a polyvinyl binder, or something similar, that acts as a glue to keep the AC around the seed (Holfus et al., 2021). However, the types of materials used, and the relative proportion of materials being used is not consistent among studies. Variation in the types of materials being applied may result in varying interactions within the AC seed technology, wherein certain chemical and physical properties of the materials may interact to create diverse conditions for seeded species under varying environmental conditions. Additional research is needed investigating the effects of different additional materials and relative proportion of these materials across environmental gradients on herbicide protection and seedling emergence, growth, and establishment.

The efficacy and impact of herbicides are highly dependent on the environmental context in which it is applied. As such, a larger scale evaluation of different herbicides applied in management contexts is needed to better understand the efficacy of AC seed technologies. The dryland species tested in the AC seed technology studies in this review represent a range of functional types and seed masses (Table 3). However, broader testing of species that are representative of the wide range used in drylands with different seed sizes and seed morphologies is needed.

Environmental conditions through time and space have highly variable effects on non-AC seed technologies (Davies et al., 2018) and the efficacy of AC seed technologies and herbicides likely vary across similarly diverse spatiotemporal scales. As such, understanding the impacts of AC seed technologies and herbicide applications in a wide range of environmental contexts (Fig. 2) and across varying life stages will be critical to determining efficacy of a product. Large scale, concerted efforts that systematically test distinct environmental contexts with consistent material compositions of AC seed technologies will be crucial in moving forward towards a product that is both effective and cost efficient for use in land management.

Herbicide toxicity is not the only barrier to seedling establishment in invaded drylands. Hence, it would be valuable to investigate incorporating other seed enhancement technologies designed to mediate other barriers (see Failures section) to seedling establishment into AC seed technologies. Integrating a bet hedging approach (Davies et al., 2018) with AC technologies may increase the likelihood of having some seeds germinating when conditions are favorable for seedling establishment. However, additional materials added to overcome other barriers could reduce the adsorption capacity of AC. Improved delivery of AC seed technologies during seeding efforts could also increase seedling establishment and reduce logistical challenges.

Further investigation into the potential and the causal mechanism for negative impacts from being incorporated into pellets, and potentially the thicker seed coatings with more AC currently being developed, on seeded species are needed. This knowledge could be potentially used to modify AC seed technologies to mediate negative impacts on seeded species. Different extrusion methods, shapes, sizes, and formulations may improve the emergence and growth from pellets (Clenet et al., 2019; Baughman et al., 2021; Brown et al., 2023b).

The high degree of variability in the physiochemical configuration of AC seed coatings and pellets, soil and environment characteristics, seeding methods, herbicides and their application, and interactions among these factors makes it challenging to synthesize the “effects” of AC technologies and explain causes of variation. Hence, it is vital to report the source material for AC, amount used, the method applied to create ‘activated’ carbon, other materials used in AC technologies, and method used to apply AC to improve comparisons among study results. Reporting seeding method, herbicide, and herbicide application details is also vital to improve potential for cross-comparisons. In field studies, it would also be critical to report soil and environmental characteristics, particularly precipitation and temperature, to allow for cross-comparisons among studies.

2. Conclusions

Restoration and revegetation of drylands degraded by invasive plants is a complex issue that requires innovative solutions. Many endeavors are currently failing where invasive species dominate and applications of herbicides are needed because of herbicide toxicity to desired species establishment or re-invasion by invasive plants. AC seed technologies show potential as a tool for improving restoration and revegetation of drylands when invasive plants need to be controlled with herbicides that may remain soil active after application. They have repeatedly been demonstrated to provide protection from herbicides, especially with higher amounts of AC, thereby allowing seeded species to establish while invasive plant competition is limited. However, strategies using AC seed technologies to overcome herbicide toxicity need to be compared to the traditional strategy of waiting to seed until herbicide toxicity has abated to determine if the addition cost of AC seed technologies is worth it. AC seed technologies also do not overcome other barriers to seedling establishment and represent an opportunity to be one tool in a toolbox of options for land managers to combat increasingly complex challenges to ecosystem restoration (Svejcar et al., 2023b). AC seed technologies are also costly and can be logistically challenging to use, especially pellets because of their larger size. AC pellets, compared to seed coatings, have been more thoroughly evaluated and proven effective in the field, but more recent seed coatings with increased quantities of AC show promise. Effective AC seed coatings would be invaluable because they would be less logistically challenging to use than pellets. AC pellets may at times negatively impact emergence and growth of some species in the absence of herbicides. The cost compared to the benefit of being incorporated into AC pellets in the presence of herbicides is minor. That being said, overall success could be improved if the cost of being incorporated into AC pellets could be minimized. Clearly there are numerous research avenues that need to be undertaken to improve AC seed technologies that may increase restoration and revegetation success as well as reduce the cost and logistical challenges associated with its use. With continued scientific advancements, AC seed technologies may assist in restoring and revegetating invaded drylands.

CRediT authorship contribution statement

Kirk W. Davies: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Danielle R. Clenet:** Writing – review & editing, Writing – original draft, Conceptualization. **Matthew D. Madsen:** Writing – review & editing, Conceptualization. **Vanessa S. Brown:** Writing – review & editing, Visualization, Conceptualization. **Alison L. Ritchie:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Lauren N. Svejcar:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization.

Declaration of competing interest

We have not conflict of interest to declare.

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Data availability

No data was used for the research described in the article.

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