Modern Seed Technology: Seed Coating Delivery Systems for Enhancing Seed and Crop Performance

Irfan Afzal 1, Talha Javed 1, Masoume Amirkhani 2 and Alan G. Taylor 2,*

1 Seed Physiology Lab, Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan; iafzal@uaf.edu.pk (I.A.); talhajaved54321@gmail.com (T.J.)
2 Cornell AgriTech, School of Integrative Plant Science, Horticulture Section, Cornell University, Geneva, New York, NY 14850, USA; ma862@cornell.edu
* Correspondence: agt1@cornell.edu

Received: 9 October 2020; Accepted: 3 November 2020; Published: 5 November 2020

Abstract: The objective of modern seed-coating technology is to uniformly apply a wide range of active components (ingredients) onto crop seeds at desired dosages so as to facilitate sowing and enhance crop performance. There are three major types of seed treating/coating equipment: dry powder applicator, rotary pan, and pelleting pan with the provisions to apply dry powders, liquids, or a combination of both. Additional terms for coatings produced from these types of equipment include dry coating, seed dressing, film coating, encrustments, and seed pelleting. The seed weight increases for these different coating methods ranges from <0.05% to >5000% (>100,000-fold range). Modern coating technology provides a delivery system for many other materials including biostimulants, nutrients, and plant protectants. This review summarizes seed coating technologies and their potential benefits to enhance seed performance, improve crop establishment, and provide early season pest management for sustainable agricultural systems.

Keywords: seed enhancement; seed treatment; seed dressing; seed coating; film coat; pellet; organic agriculture

1. Introduction

High seed quality is always demanded by farmers and may result in up to a 30% increase in crop yields [1,2]. Sowing high-quality seeds is essential, but their use does not guarantee successful stand establishment. The difference in time between sowing and stand establishment is a crucial period. Seeds may be exposed to a wide range of biotic and abiotic stresses resulting in decreased stand performance [3]. However, judicious use of chemical, biochemical, and biological seed treatments can protect and enhance establishment, growth and potential productivity [4]. In this review, seed treatments refer to materials that are active components, while seed dressings are the minimal coating that results after the application of seed treatments onto seeds. Seed treatments are most effective when they are objective oriented and crop specific to ensure optimal stand establishment and enhance yields under changing climatic conditions [5].

Seed treatments may be applied commercially by the seed industry or in some cases “on farm” for crop protection and enhanced seedling growth [2,6]. There is also a growing trend for the development and use of organically approved treatments for sustainable agriculture. Collectively, innovative seed coating technologies are needed as delivery systems for the application of active ingredients at effective dosages to crop seeds [7,8].

A brief history of seed treatments for plant protection illustrates the practical need for better delivery systems and improved ability to sow seeds [9]. Copper sulphate was found to be an effective seed treatment for bunt on cereals in the 1800s when applied as a soak. However, treating large
quantities of seed required subsequent drying that made the process cumbersome and time consuming. The soaking process was replaced by the “heap” or “barn floor” method where a small amount of liquid was sprinkled over the seed and then mixed [9]. The soaking (also known as steeping) method is still in use for sugar beet seed using the method described by Halmer (2000) [10].

In 1866, a technique was developed to improve sowing of cotton seed using a paste of wheat flour to form a pellet [11]. During the mid-20th century, many coating technologies for improved agricultural productivity were developed and reviewed by Jeffs (1986) [9]. Seed coating technology continued to advance through the 1970s to 1990s and reviewed by Taylor and Harman (1990), Scott (1989) and Hill (1999) [7,12,13]. More recent reviews focus on seed enhancements and seed coating equipment in the 21st century by Taylor (2003), Pedrini et al. (2017), Halmer (2000), and Pedrini et al., (2020) [6,8,10,14].

Seed enhancements may be defined as post-harvest treatments that improve germination or seedling growth or facilitate the delivery of seeds and other materials required at time of sowing [15]. Seed coating is used for the application of biostimulants, plant nutrients, (including inoculants) and other products that will ameliorate biotic and abiotic stresses encountered after sowing [11,16].

The global market for seed coating materials (colorants, polymers, fillers and other additives) in 2019 was US $1.8 billion and is forecasted to reach $3.0 billion by 2025 [17]. The major group of active ingredients are chemical seed treatments estimated between $3 to $5 billion in 2020, and accounts for at least 2/3 of the total seed treatment market [18]. The biological seed treatment market includes a wide range of biologicals including biofertilizers, biopesticides and biostimulants [19]. The biological seed treatment market is estimated between $1 to $1.5 billion in 2020, and bioinoculants are the dominant group with about 70% of total [18].

The focus of this review is the use of selected seed coating components, including liquids and solid particulates, with designated seed coating equipment and technology for uniform delivery of treatments over seeds uniformly. Applications of selected seed treatment and coatings are presented as biostimulants, nutrients, and in management of abiotic and biotic stress. Seed coating technologies described may be applied to a wide range of crop seeds: grains, oilseed, vegetable, ornamentals, and other seed species [20].

There is considerable research and development by industry in the broader field of seed treatments, and much of this technology is proprietary. Many biological seeds treatments are being developed and marketed for pest management and as biostimulants. However, it is beyond the scope of this publication to critically review the merits and efficacy of these biologicals, though they are used commercially. Therefore, this review focuses on published papers and most are from refereed journals. This paper contains 112 references with 97 published papers or book chapters, 6 patents, 6 websites and 3 personal communications cited. Moreover, to provide relevancy to the seed coating industry, eight companies were acknowledged to provide valuable input in preparation of this review.

2. Seed Treatment Active Components and Other Coating Materials

A wide range of materials is used in seed treatments and coatings. These materials were categorized by their composition and origin as synthetic chemicals (SYN), natural products or derivatives from natural products (NP), biological agents (BIO) and minerals mined from the earth (MIN) (Table 1). Among these categories, particular materials may be used for organic use and labelling, and the US Organic Materials Review Institute (OMRI) [21] approved materials were noted as organic (OR). Seed treatment and coatings are further characterized by function, as active components, liquids or solid particulates.
2.1. Active Components

The purpose of active ingredients is aimed at protecting and enhancing seed and seedling performance in terms of germination, growth and development. The mode of action of the active ingredient dictates its role for protection and/or enhancement [16]. Active ingredients discussed in this paper include biostimulants, plant nutrients, protectants from abiotic and biotic stress, and inoculants (Table 1). Seed protectants are the most widely used group of ingredients for controlling pathogens and pests at the time of sowing. Fungicides, insecticides, nematicides, and bactericides are grouped as protectants [22]. Selected fungal and/or bacterial microorganisms are used commercially for plant protection, and as inoculants for nitrogen fixation [22,23]. Abiotic stresses due to saline soil conditions or drought stress may occur after sowing and selected biological and synthetic seed treatments may be applied in the seed coating to alleviate these stresses. Elicitors are being investigated as active components for pest management [24–26], and drought stress [27]. There is increased interest and demand for biostimulant- and nutrient-based seed treatments [8].

2.2. Liquids

Active components must be applied to seeds so that they adhere onto seeds throughout storage until planted. In addition, seeds treated with pesticides must easily be recognized as treated. Colorants are commonly used to indicate that seeds are treated and constitute about 60% of coating ingredient components, and in the case of seed pelleting are applied at the end of coating process [8]. Colorants also provide a visual of assessment of application uniformity, and cosmetic appearance. Water is the universal carrier of liquids that are atomized onto seeds during the coating process, and atomization is best achieved with low viscosity liquids. The proportion of water in the applied liquid is adjusted to maintain low solution viscosity. Adjuvants are used [20] as most chemical seed treatment active ingredients have limited water solubility, so surfactants are needed to produce aqueous seed treatment formulations. Surfactants may serve as an active component, and a seed coating technology with surfactants was documented to enhance germination and stand establishment when sown in water repellent soils [28].

Seed coating binders act as adhesives to adhere treatments to seeds. The binder provides the coating integrity during and after drying. They prevent cracking and dusting off during handling and sowing [2]. Commonly used binders (Table 1) for maintaining physical integrity of seeds are: polyvinyl alcohol [29], polyvinyl acetate [30], methyl cellulose [31], and carboxymethyl cellulose [32]. For organic seed coatings plant starches (maltodextrins) [33] and gum Arabic [34] are commonly used.
Most binders are commonly referred to as polymers [35]. In preparing binders in water, solution viscosity must be low for complete atomization of the liquid onto seeds, based on the fourth author’s experience preferably <100 centipoise (cP), or <0.1 pascal-second (Pa-s).

2.3. Solid Particulates

Solid particulates are the bulking materials used in seed coating technologies and form the physical coating after drying [7,30]. Solid particulates may also be binders. Solid particulate binders are applied as fine powders and become hydrolyzed as water is applied during the coating process. Fillers are also fine powders and can be mixed with the solid particulate binders to produce a seed-coating blend. Successful seed pelleting depends upon the optimization and selection of the most appropriate filler materials that do not interfere with germination [32].

Filler materials are generally inexpensive, non-toxic, easily available, and produce a uniform coating surface texture that should not impede radicle emergence [6]. Several filler materials are used for seed pelleting including diatomaceous earth [36], limestone, gypsum [32], bentonite [34], vermiculite [37], talc [38], zeolite [32], silica sand [39] and barium sulphate [40] (Table 1). These fillers are generally mineral materials that are mined from the earth with minimal modification except for grinding to obtain a fine powder size used in seed coating. Particle size should pass through a 200-mesh sieve (<75 µm) for uniform distribution over the seed surface based on the fourth author’s experience.

3. Seed Coating Equipment and Methods

The seed treatment and coating materials described in Section 2 provides an extensive list of potential ingredients. The next step in the seed coating process is when selected ingredients are applied with appropriate equipment to produce the final coated product. The selection of seed coating equipment and coating method is determined primarily by the dosage of actives, liquids and solid components applied per unit of seed. There are three major types of seed coating equipment used today: dry coating, rotary pan and pelleting pan (Figure 1). This coating equipment used singly or in some cases in tandem is paired with five coating methods: dry powder, seed dressing, film coating, encrusting and pelleting [6,8,10]. The overall goal of all coating equipment and methods is to achieve good application uniformity and adherence. Processes should not cause mechanical injury to seeds during coating [35].

![Figure 1](image-url)  
**Figure 1.** The three major types of seed coating equipment: dry powder applicator, rotary coater and drum coater used to produce five seed coatings: dry coating, seed dressing, film coat, entrustment and seed pellet.
3.1. Dry Powder Coating

Dry powder application is a seed coating method used for mixing seeds with a dry powder. The older term for this application method is “planter box” treatment [6]. Dry powders, also known as dusts, [20] are used for fungal or bacterial treatments followed by drying (hydration/dehydration) and seeds can have a shorter shelf-life after application [6]. This technology can be conducted on-farm for the application of labeled treatments for the control of pests [9].

Dry powder application equipment and technology has evolved to allow for more precise loading of material onto seeds. As can be seen in Figure 1 [41,42] a rotating stainless-steel brush sifts a powder material through a metering screen (Figure 1). The equipment is calibrated on a weight basis to deliver powder to a given weight of seed. The seed is not shown in the illustration, but would be moving underneath the dry powder applicator via most delivery systems (auger, conveyor, seed tender, etc.) [https://www.ctapplicators.com] [43]. This equipment is used for stand-alone dry powder application, or for the application of finishing powders after seed dressing or film coating (described in Sections 3.2 and 3.3). Another dry powder feeder equipment uses a computer-controlled auger with hopper vibrator to deliver coating powders, finishing powders or dry powder actives to seed by volumetric or weight basis [44]. Dry powder carriers may act as lubricants to improve seed flowability by reducing seed-to-seed friction in the planter [6]. The most common dry powders are talc and graphite [45], and recent research revealed that soy-based protein is an environmentally friendly and cost-effective seed lubricant that improves flow and singulation during planting without creating dust [46]. Thus, the use of soy-based protein has the potential to reduce the risk of negative impact on pollinators and people.

The dosage of dry coating powders applied to seeds is limited by their adherence onto seeds, and ranges from 0.06 to 1.0% of seed weight (Figure 2). This loading rate is inversely proportional to seed size, and the amount of powder retained increases as seed size decreases due to the increase in seed surface area of smaller seeds [45].

![Figure 2. Percent weight increase after dry coating, seed dressing, film coat, entrustment and seed pellet technologies. The grey shaded bar for seed dressing and film coat is addition of a finishing powder during the coating process. The percent weight increase shown on a log scale to aid comparison between technologies.](image-url)
3.2. Seed Dressing

Seed dressing is the most widely used method for low dosages of active components onto seeds [33]. Although there are many types of equipment used for coating [9], the most commonly used device is the rotary coater (Figure 1). Liquids are applied onto a spinning disc and atomized onto seeds that are spinning inside a metal cylinder, then the freshly treated seeds are discharged. A wide range of active materials especially chemical plant protectants can be applied with this method.

The dosage of liquid seed treatment formulations typically ranges from <0.05 to 1.0% by weight (Figure 2). For higher loading rates of chemical seed treatment, in particular insecticides, finishing powders or fluency powders are added immediately after the liquid application to absorb excess liquid [45]. The dry finishing powders can be added into the rotary coater during operation or applied immediately downstream with the dry seed coating equipment (Figure 1).

3.3. Film Coating

Film coating originally developed for the pharmaceutical and confectionary industries was adapted as a seed coating method [6]. Film coating consists of producing a continuous thin layer over the seed surface. The rotary coater is the primary seed coating equipment used for film coating (Figure 1). Film coating polymers (liquid components) are formulated to dissolve/dispense active ingredient prior to application on seeds. Film coating resulted in 90% application recovery [7], with little modification of shape and size during this process [7,8]. Film coating has gained in use and is the most adaptable among all seed applied technologies. The performance of film-coated seed is evaluated on the basis of germination and dust control. Film coating improves flow-ability of seed during treating/processing and sowing operations. This value-added treatment is preferred over conventional methods due to excellent delivery of protectants on value seeds and have a cosmetic appearance [6].

The weight increases for film-coated seed, ranges from 2 to 5% of seed weight (Figure 2) [16]. Seed weight build-up greater than 5% requires other seed coating equipment with drying capability during coating, primarily a ventilated pan and fluidized bed seed coating facilitate concurrent treating and drying [10]. However, both side-ventilated or perforated pan and fluidized bed are used much less in commercial practice than the rotary pan technology. As described for seed treatment (Section 3.2), dry finishing powders can be added into the rotary coater, or with the dry seed coating equipment to increase loading from 5–8% (Figure 2).

The choice of film forming polymers is important for success in field sowing [5,13] and in the protection of the environment. Corn seeds coated with a proprietary film-forming polymer, PolySeed CF (Rigrantec, Porto Alegre, RS, Brazil), improved precision seed placement compared to graphite treated or non-coated seeds with significant reduction in dust formation and leaching of applied insecticides [47]. Further, the film coating polymer had good seed treatment adhesion resulting in less dust-off into the environment [47].

3.4. Encrusting

Encrusting is a seed coating method with the addition of liquids and solid particulates that results in a coated seed that is completely covered, but the original seed shape is retained [16]. Encrusted seeds can be referred to as mini-pellets [6] or sometimes as coated seeds. The primary coating methods to produce encrusted seed are the rotary coater or coating pan (Figure 1). The addition of large amounts of water during encrusting requires that the freshly coated seed be dried to back to its original seed moisture content prior to packaging and storing. The weight increase after encrusting can range from 8 to 500% (Figure 2).

Encrusted seeds have been shown to improve seedling emergence. Significantly higher germination of fescue seeds was measured when seeds were encrusted before storage compared to encrusting after storage or non-treated seeds [48]. The seed coating thickness or percent build-up may impact germination rate, and encrusted seed requires more time to germinate as compared to film-coated
3.5. Pelleting and Agglomeration

Seed pelleting is a continuation of the encrusting coating process resulting in even greater build-up so that the original size or shape of the coated crop seed is not visible [8,16]. The materials and techniques used for this purpose are proprietary [8], but common mineral materials cited in the literature and in patents are presented (Table 1). The binders may be liquid or formulated as dry powders (Table 1). Dry powder binders are mixed with filler materials to produce a coating blend [51], only requiring water applied during the coating process as the liquid. The percent weight increase after pelleting and drying ranges from 500 to >5000 percent (Figure 1). It is common that the percent weight increase is expressed as a ratio of seed weight to dried pellet weight, so a 500% weight increase is a 1:5 build-up of seed to coating.

The selection of liquids paired with fillers (Table 1) is essential to ensure that the pelleted seed will germinate unimpeded by the pellet matrix [16]. The pelleting seed industry has conducted tremendous research and development on optimizing commercial pelleting products for growers. The demand of pelleted seed continues to grow among growers so seeds can be planted with precision. Precise seed spacing achieved with pelleted seed reduces the need for thinning operations. Pelleted seeds are commonly used for growing transplants. Pelleting is frequently performed on high-value, small-seeded horticultural crops (e.g., onion, lettuce, carrot, tobacco, and tomato [6,32,34,36].

Material properties for successful pelleting include particle size distribution, porosity, water absorbing and holding capacity and lack of toxicity [32]. For tobacco seed pelleting, a combination of bentonite and talc [38] or pumice [52] was highly recommended. Similarly, diatomaceous earth and a combination of gypsum and calcium carbonate were found to be effective in broccoli [53] and lettuce [32], respectively. Calcium peroxide was added as a seed coating component [12] after sowing in a water-saturated soil with limited oxygen availability, the calcium peroxide releases oxygen gas to the germinating seed. Calcium peroxide applied in a seed pellet improved emergence and crop establishment of rice under submerged conditions [54].

Pelleting requires the most time and expertise compared to other coating technologies due to extensive application of active components, liquids, and solid particulates (Table 2). The pellet should not cause any restriction to germination when sown in the field. Pellet integrity is dependent on the selection of material (fillers and binders) and appropriate technology [7].

Table 2. Comparison of amount of coating components and time needed for the dry coating, seed dressing, film coat, entrustment and seed pellet technologies. The (+) for seed dressing and film coating is the addition solid particulates as finishing powders. Relative comparisons are noted with number ‘+’.

| Coating Technology | Active Components | Liquids | Solid Particulates | Time Needed to Treat/Coat |
|--------------------|-------------------|---------|-------------------|--------------------------|
| Dry powder         | +                 | 0       | +                 | +                        |
| Seed dressing      | +                 | +       | 0 (+)             | +                        |
| Film coating       | ++                | +       | 0 (+)             | +                        |
| Encrusting         | +++               | +++     | +++               | +++                      |
| Pelleting          | ++++              | +++     | +++               | +++                      |

The objective of all the described coating methods thus far is for each seed to be singulated during the coating process to avoid doubles or agglomerates (two or more seeds in one coated propagule). However, it may be needed in certain cases to have more than one seed in a pellet. Seed agglomeration is an alternative coating technology in which multiple seeds are pooled into a single delivery unit [36]. The purpose of this technology is to sow multiple seeds of the same seed lot, different varieties of the same crop or multiple seed species. Seed agglomerates may be produced with
a pan coater or rotary coater (Figure 2). Other agglomeration technologies use extrusion equipment [14] and molding technology [48]. Moreover, producing “seed balls” is a pelleting technique that utilizes materials, seeds and supporting additives in small amounts such as mineral fertilizer [55]. Both seed agglomeration technologies are used for improving handling and sowing of small-seeded species for arid land restoration [56,57].

3.6. Comparison of Seed Treatment and Coating Technologies

Five seed treatment and coating technologies were discussed in Sections 3.1–3.5, and now each technology can be compared to provide relative differences. The range of weight increase after treatment/coating is shown for the five methods and is expressed on a log scale to better visualize percent weight increase or build-up (Figure 2). The coating technologies cover from <0.05% to >5000% weight increase (>100,000-fold range) that accommodates all crop seed specific treatment and coating needs and applications. Additional comparisons of the five coating methods are illustrated with respect to weight increase after coating, and the relative amounts of active components, liquids and solid particulates applied, and the time required to treat or coat a batch of seeds (Table 2). All coating technologies can apply active components, but the potential amount per unit seed is limited by coating technology. No water or liquids are applied with the dry powder method, while with the other coating methods the amount of water/liquids increase is proportional to the percent weight increase (Figure 2). Solid particulates may be added with seed dressing and film coating as the amount of water increases resulting in “stickiness” during seed treating and inadvertent agglomeration. The solid particulates are termed drying powders [20], finishing powders or fluency agents that help absorb excess moisture applied during coating. As stated previously, these drying powders can also serve as seed lubricants to reduce friction as seed flows through the seed treater or planter [20]. There is a clear distinction in choice of seed coating technology with respect to the amount of water applied. Seed dressing and film coating as described do not require further drying after treatment, while encrusting and pelleting require post-coating drying to remove excess water and to dry seeds to their original seed moisture content. Finally, each seed dressing/coating method requires time, and longer processing times are needed as the amount of coating materials increases.

Many factors affect the final coated seed properties including the rotator and atomizing disc rpm, the solid particulate particle size, porosity, water holding capacity, and the binder adhesion properties [49]. The success of coating process and uniform distribution of active components requires time for mixing in the coating equipment [35] and for accurate adherence of binder and powder to seeds [34].

There are two types of seed treatment/coating equipment systems: batch treater and continuous flow treaters [20]. A batch treater matches a known amount of seed with seed treatment and coating material at one time, while the continuous flow treats a known amount of seed with seed treatment and coating material at a given flow rate [35]. Dry powder applicator or rotary coater may be either a batch or continuous flow based in equipment design, while most drum coater technology used for small-seeded vegetable crop seeds is performed on a batch basis. Each seed coating method (Figure 1) requires precise metering to deliver the target dosage onto seeds. Seed treatment equipment is needed to proportion an accurate amount of material to the seed. Computer technology is often used to monitor seed flow and seed treatment application, known as proportion control [35]. There are two stages of seed treatment application to achieve uniformity of application from seed to seed: primary and secondary application [35]. Primary application is the direct application of liquids onto seeds, for example the atomizer (atomizing disk) in the rotary coater disperses liquids directly onto seeds (Figure 1). Secondary application is the seed-to-seed transfer of the applied material during mixing while in the seed coating equipment [35]. Dosage can be expressed on a weight basis, for example g/100 kg seed or quantity per seed, for example mg ai/seed (ai—active ingredient) [35].
4. Efficacy of Seed Treatments and Coatings

4.1. Biostimulants

There has been considerable effort over many decades on applying chemicals to seeds to improve germination and seedling growth. The term “biostimulants” was adopted in the 21st century and provides a better definition and grouping of materials that serve to enhance plant performance. Biostimulants may be defined as natural compounds that trigger physiological and molecular processes modulating crop yield and quality. There are several categories of plant biostimulants and these materials are natural products or biologicals. A review of biostimulants applied as seed coatings is summarized by category (Table 3): beneficial bacteria and fungi [58–60], plant and animal-derived proteins, protein hydrolysates and amino acids [50,51,53,61], carbohydrate derivatives [62,63], seaweed [64] and herbal extracts [65]. There are no seed applied references for other biostimulant categories including vitamins, humic and fulvic acids. All these compounds may enhance plant metabolism when applied in small quantity, but their mode of action is only partially understood [66,67].

Table 3. Review of biostimulants applied as seed treatments on seed germination, seedling growth and other measured parameters.

| Active Components (Source *) | Crop       | Application Mode/Type of Experiment | Main Findings                                                                 | Reference |
|------------------------------|------------|------------------------------------|-------------------------------------------------------------------------------|-----------|
| *Paraburkholderia phytofirmans PsJN Strain: BIO* | Wheat      | Seed coating—10 g seeds required 40 µL of the coating product Agicote Rouge T17 and PsJN inoculum (10^8 CFU mL⁻¹) | Increased straw yield (55–100%), grain yield (43–100%) and thousand kernels weight (19–58%) compared with the inoculated control in all 3 seasons | [58]      |
| *Arbuscular Mycorrhizal Fungi Inoculum: BIO*     | Cowpea     | Seed coating—Rhizopagus irregularis | No effect on seed yield, but 66% increase on shoot dry weight compared to the control | [59]      |
| Plant growth promoting bacteria: BIO             | Cowpea     | Seed coating—Pseudomonas libanensis | Plant biomass and seed yield significantly enhanced 101% and 52% compared to the control | [59]      |
| *Arbuscular Mycorrhizal Fungi: BIO*              | Chickpea   | Seed coating—a mixture of equal proportions of five R. irregularis isolates | Increased pod (160%), seed numbers (148%), and grain yield (140%) in field compared to the control | [60]      |
| Soy flour: NP                                   | Broccoli   | Seed coating—Application of plant-based protein to the seeds | All treatments with >30% soy flour in the coating had greater fresh and dry weight, leaf area compared with the control | [53]      |
| Soy flour: NP Vermicompost: NP, (OR)            | Broccoli   | Seed coating—Co-application of vermicompost and plant-based protein to the seeds | Seedling growth improved, increased shoot length (up to 114%), Shoot dry weight (42%) and root dry weight (51.5%) compared to the non-treated control seeds | [51]      |
| Soy flour: NP Vermicompost: NP, (OR)            | Red clover-Ryegrass | Seed coating—Co-application of vermicompost and plant-based protein to the seeds | All treatments showed a 40 to 60% increase in seedling dry weight and the seedling vigor indexes were 15% to 27% higher than control for red clover and 40% for ryegrass | [50]      |
Table 3. Cont.

| Active Components (Source *) | Crop       | Application Mode/Type of Experiment | Main Findings                                                                 | Reference |
|------------------------------|------------|------------------------------------|-------------------------------------------------------------------------------|-----------|
| Amino acid mixtures: NP      | Cucumber   | Seed coating—Application of 5 different amino acid mixtures to seeds | Total leaf area and dry weight were 35–50% and 26–30% higher for all amino acid mixtures (containing proline, hydroxyproline or their combination, amino acid mixture without proline and/or hydroxyproline) in comparison with no amino acid in coating | [61]      |
| Chitosan nanoparticles: NP   | Chilli     | Seed coating—20 and 100 ppm chitosan using top-spray fluidized bed coating equipment | Chitosan treatments enhanced germination (6–7%) and decreased seed fungal infection (12–28%) compared with the intact control seeds | [62]      |
| Chitosan: NP                 | Artichoke  | Seed coating—10 mL of 3% or 4% (w/v) chitosans solution applied to 100 g seeds | 4% (w/v) Chitosan B enhanced seedling growth (20%) compared with non-treated seeds | [63]      |
| Seaweeds: NP, (OR)           | Radish     | Seed coating—Algal homogenate 50 mg/g seeds | Seedlings’ length was 23% higher than in the control and seedling dry weight was 26% higher than in the control | [64]      |

* Source of material: Natural products or derivatives—NP, Biologicals—BIO, substances may be Organically approved—OR.

The application of biostimulant components has not been widely integrated as seed treatments in agriculture. Biostimulants applied as seed treatments and coatings are more cost effective and provide great potential to enhance stand establishment compared to foliar and soil application methods [51,59]. The global market for biostimulants applied as seed treatments in 2015 and 2019 was USD 112 million and USD 181 million, respectively and is forecasted to reach USD 338 million by 2025 [68].

The studies summarized in Table 3, reports on the beneficial effects of biostimulants applied as seed treatments and coatings on germination enhancement and growth stimulation on several crop species. For example, Amirkhani et al. [51,53] reported that seed coating with plant-derived protein enhanced germination indices and seedling uniformity, as well as the vigor index of broccoli, compared to non-coated seeds under optimum conditions. Moreover, the co-application of plant-derived protein and a nutrient-rich micronized vermicompost as a dry seed-coating binder and biostimulant significantly enhanced plant biometric parameters in germination and greenhouse studies [51,53]. In another study, Qiu et al. [50] reported enhancement in the percent germination and germination rate in red clover, and root enhancement in ryegrass, in response to biostimulant seed coating. The above studies suggest that biostimulant seed treatment practices enhanced uptake of soil-media nitrogen. The application of nitrogen in the seed coating accounted for less than 5% of the total nitrogen taken up by the roots. Therefore, the biostimulant was not merely a nitrogen fertilizer, but acted as a biostimulant to enhance nutrient uptake [51,53].

4.2. Nutrient Coating

Adequate nutrient availability is very important starting at the early stages of plant growth. Seed coating with appropriate amounts of macro- and preferentially micro-nutrients can reduce nutrient losses by placement on the seed, and also reduce competition from weeds. However, germination and seedling growth can also be hindered by macronutrient coatings due to phytotoxicity. To prevent
such toxicity, direct contact of nutrients should be avoided with seeds by including the initial layer or boundary layer followed by the nutrient coating.

Several investigations conducted on plant nutrients applied as seed coatings were summarized by Scott (1989), Farooq (2012) and Masuthi (2009) [12,69,70]. Successful coating of phosphorus on oats improved early plant growth [71]. In rice seeds, boron (2 g/kg seed) was applied as seed coating and significantly increased grain yield and boron contents over a control [72]. Losses of nutrients by seed coating reduced the cost of production as compared to soil applications [69]. Conventional broadcasting of fertilizers exhibited higher cost and losses, while coating with an equivalent rate of nutrients significantly produced higher yield of cereal crops [69,73]. Slow release nutrient (N-P-K) coating on maize seeds resulted in improved emergence and yield attributes as compared to conventional compound fertilizer application in the field [74].

The effects of applied nutrients to a wide range of field and vegetable crop seeds with pre-defined quantity of nutrients are summarized, and plant improvements in germination, emergence, plant growth and yield were cited (Table 4). All fertilizers were synthetic chemicals, but several are available as organically approved. Zinc oxide [75,76] and zinc sulphate [70,77–80] are the most promising micronutrients used in seed coating of cereal crops and pulses. Wiatrak [81,82] evaluated the effect of polymer coating with manganese, copper and zinc on wheat and soybean crops and found a cost-effective technique for the enhancement of plant growth and ultimate yield of both crops [81,82]. In another study, coating with a range of micronutrients (Zn, B, K, Mo, Fe, Mg, Mn) increased productivity of cotton, chickpea, groundnut and pigeon pea with minimum expenditure and higher returns [83].

Table 4. Review of plant nutrients applied as seed treatments on seed germination, seedling growth, yield and other measured parameters.

| Active Components (Source *) | Crop                          | Application mode/Type of Experiment | Main Findings                                                                 | Reference |
|-----------------------------|-------------------------------|------------------------------------|------------------------------------------------------------------------------|-----------|
| Boric acid (H₃BO₃)          | Rice                          | Application of H₃BO₃ at 1, 1.5, 2, 2.5 and 3 g B/kg by seed coating | 2 g B/kg significantly decreased panicle sterility, increased 1000-kernal weight (7%), grain yield (20%) and B contents (24%) over control | [72]      |
| Calcium oxide (CaO)         | Tomato                        | Application of CaO, bentonite and talc combination by pelleting | Increased final emergence (23%) and seedling growth over control. Better storability of pelleted seeds after 5 months | [34]      |
| Monopotassium phosphate (KH₂PO₄) | Pearl millet                  | Application of KH₂PO₄ at a rate of 400 g P ha⁻¹ by seed priming and seed coating | Seed coating increased vegetative biomass over 400% at early stages and panicle yield (50%) compared to control. The time to flowering (10–14 days) reduced by seed coating | [84]      |
| Micronutrients              | Wheat                         | Application of mixture of manganese, copper and zinc micronutrients by polymer coating | Seed coating with 395 mL 100 kg seeds⁻¹ improved dry matter yield (23%), N uptake (25%), P uptake (23%) and grain yield (2%) over control | [81]      |
| Micronutrients              | Soybean                       | Application of mixture of manganese, copper and zinc micronutrients by polymer coating | Compared to control, increased grain yield (14%) and plant Normalized Difference Vegetation Index (10.5%) with polymer seed coating at 395 mL 100 kg seeds⁻¹ | [82]      |
| Micronutrients              | Cotton/Pigeon pea/Chickpea/ Groundnut | Seed polymer coating with various micronutrients | Increased yield to the extent of 17% in cotton, 20% in pigeon pea, 16% in chickpea and 14% in groundnut over control | [83]      |
### Table 4. Cont.

| Active Components (Source *) | Crop | Application mode/Type of Experiment | Main Findings | Reference |
|--------------------------------|-------|-------------------------------------|---------------|-----------|
| **Zinc oxide (ZnO)** SYN       | Maize Soybean Pigeon pea | Application of ZnO at 25 and 50 mg Zn/g seeds by seed coating | Significant increased germination (93–100%) compared to control (80%). Improved growth and hormonal activity | [75] |
| **Zinc oxide (ZnO)** SYN       | Rice  | Application of ZnO coated urea at 2.0% (w/w) by seed coating | Significant increase in yield (28%) and micronutrients (40%) over control | [76] |
| **Zinc sulfate and Boric acid (ZnSO₄ + H₃BO₃)** SYN (OR) | Soybean | Seed coating with the dose 0.8 kg of H₃BO₃ + 0.8 kg of ZnSO₄/kg seeds. | Significantly improved growth and reduced shoot dry matter production | [77] |
| **Zinc sulfate and Zinc chloride (ZnSO₄ + ZnCl₂)** SYN (OR), ZnCl₂ SYN | Wheat  | Application of ZnSO₄ + ZnCl₂ at 1.25 g Zn/kg by seed coating | Improved chlorophyll a and b contents. Enhanced grain yield and Zn contents | [78] |
| **Zinc sulfate (ZnSO₄) SYN (OR), Borax SYN (OR), Arappu leaf powder (OR)** | Cowpea | Application of ZnSO₄, Borax and arappu leaf powder at 250 mg, 100 mg and 250 g/kg seed respectively by seed pelleting | Increased grain yield by 32% over control. Seed pelleting with arappu leaf powder alone and in combination with ZnSO₄ improved yield parameters | [70] |
| **Zinc sulfate and Boric acid (ZnSO₄ + H₃BO₃)** SYN (OR) | Stylosanthes | Application of ZnSO₄ with 90 g and H₃BO₃ with 120 g per kg seed | Significantly improved growth, development and modulation | [79] |

* Source of material: Synthetic Chemicals—SYN, Natural products or derivatives—NP, Biologicals—BIO, Mineral—MIN, substances may or may not be Organically approved—OR.

### 4.3. Abiotic Stress

Abiotic stresses may occur in the field and have a deleterious effect on germination and stand establishment. Abiotic stresses may be caused by drought stress or salinity stress. Both chemical and biological seed treatments and coatings have the potential to ameliorate deleterious effects of transient abiotic stress [4,85]. Superabsorbent polymers (SAPs) are hydrophilic polymers that can absorb over one hundred times their weight in water and have a long history of use in agriculture [86]. Seed coating technologies were developed to incorporate SAPs with filler materials to produce encrusted or pelleted seeds [87,88]. Hydro-absorbers and SAP improved germination potential by early and rapid completion of imbibition and active metabolism phases by improving water availability around the sown seed [49]. SAP supplies sufficient moisture and ensures oxygen availability to germinating seed under normal and stressful conditions [89]. SAP seed coatings were shown to increase germination and stand establishment at substantially lower application rates than soil-applied SAPs [90–92].

Salinity stress reduces soil water availability and results in an excess of sodium ions in the soil. Biological seed treatments may partially ameliorate the deleterious influence of salinity on plant growth. A commercial seed treatment formulation of *Trichoderma harzianum* was applied onto squash (*Cucurbita pepo*) seeds and studied in pot experiments in the greenhouse [93]. Pots were irrigated with 50 and 100 mM NaCl solutions and plant weight and leaf mineral content analyzed. The biological seed treatment increased plant growth at both salinity levels compared to the non-treated control. Moreover, the biological increased the leaf potassium to sodium ratio suggesting that one mechanism of a beneficial biological was altered mineral uptake. In another study, seed treatment with *T. harzianum* alleviated biotic, abiotic, and physiological stresses in germinating seeds and seedlings [94]. A recent
review on beneficial microbes applied as seed coatings stated several plant beneficial microbes (PBM)s enhanced drought or salinity tolerance [22].

4.4. Plant Protectants and Inoculants

Management of biotic stresses in agriculture is synonymous with plant protectants applied as seed treatments and coatings. These seed treatments may be fungicides, insecticides, bactericides, and nematicides [20]. In agriculture, control of these pests should be considered if damage exceeds an economic threshold [35]. Plant protectants are applied in anticipation that economic damage will occur from soil-borne or air-borne pathogens and/or pests. Therefore, seed treatments provide insurance from potential biotic stresses either singularly or in combination, as in the case with soil-borne pathogens and insect pests. A wide range of active components may serve as plant protectants including: synthetic chemicals, natural products, and biologicals (Table 1). Some of these plant protectants may be organically approved for use in crop protection. Based on the seed-treatment active component and its formulation, dosage and other attributes, these actives may be applied with specific paring of equipment. Methods include: dry powder applicator, rotary coater or drum coater to apply dry coating, seed dressing, film coat, and encrustment or pellet (Figure 1).

The literature on seed treatments as plant protectants is beyond the scope of this review. However, selected papers are highlighted on seed treatments and coatings as seed enhancements. Herbicide safeners are seed treatments that negate the potential herbicidal effect of selective herbicide chemistries on crop plants. Thus, herbicide safeners are tools for specialty crops and other plant species that lack chemical weed control options. The herbicide safener, flufeninom was effective on field soil treated with the herbicide, metolachlor on switchgrass (Panicum virgatum) [95]. Biologicals also known as plant beneficial microbes (PBM)s [22] may provide inconsistent pest management under a wide range of field conditions encountered at time of sowing. Synthetic chemical seed treatments provide more reliable pest control for conventional agriculture but are prohibited for organic crop production. Biopesticides that are derived from natural products or microbes and are organically approved have potential for pest management comparable to synthetic chemical seed treatments. Spinosad, a biopesticide for foliar application, was investigated as an onion seed treatment at Cornell University [96]. Spinosad seed treatment was comparable in efficacy to chemical seed treatments in the control of onion maggot (Delia antiqua). An organic formulation of spinosad was also effective for control of onion maggot and seed-corn maggot (Delia platura) when used in combination with other seed treatments [97]. Collectively, seed-coating technology as described in this paper provides a delivery platform for many other active components for improved pest management that are environmentally friendly for sustained systems. In addition, new generation biochemical, bio-pesticides reduces the reliance on synthetic agrochemical seed treatments [97,98]. Greater efficacy of fungicides has been achieved with good treatment adhesion resulting in less dusting [98].

The use of plant extracts as seed treatments can improve seed quality and reduce infestation of microbial pathogens [99]. Such plant extracts have antibiotic and antimicrobial properties that help in alleviation of biotic and abiotic stresses during seed emergence in the soil [100]. Natural occurring plant extracts are readily available, less expensive, and have promising effects on germination, plant growth, and yield as compared to traditional chemical fungicide treatments [99,101].

Seed pelleting was effective in sowing sesame seed. Pelleting significantly enhanced plant height, lateral branches and number of capsules per plant as compared to non-pelleted seeds [102]. Damping-off disease incidence was significantly reduced by pelleting of sesame seeds with the plant growth promoting microbe (strain E681) [29]. Pelleting does not normally affect shelf-life. An investigation on the storage of pelleted seeds revealed that quality of tobacco seed after pelleting was maintained up to 720 days when properly stored in aluminum cans [103].

Microbial seed coating is a method of coating seeds with plant beneficial microorganisms such as plant growth promoting bacteria (PGPB), rhizobia, and fungi to increase crop growth and yield through improvement in nutrition and protection against diseases and pathogens [22,23]. Coating
seeds with beneficial microbes is an efficient delivery system for application of beneficial microbes and is a promising tool for inoculation of different crop seeds with a reduced use of inoculum as compared to traditional seed treatments [7,12,37]. A typical inoculant formulation is based on the selection of the microorganism, a suitable carrier, and related additives [22,104]. Combination of carbon source materials with rhizobia not only aids in the survival of bacterial strains as a food source but also provides protection from the external environment [105]. In addition to seed coating as a carrier for food bases, pH can be adjusted for optimum growth of beneficial microbes [7]. Lime pelleting was shown to be helpful for rhizobia survival by neutralizing fertilizer acidity close to the seed [4]. Application of compatible rhizosphere microbes to chickpea seeds was effective to alleviate biotic stress through enhanced stand establishment, growth, and molecular attributes. Peat and biochar were effective for providing protection to the rhizobia by tightly absorbing it and preventing direct exposure to the external environment [106]. After seed coating with bacterial strains, rapid desiccation should be avoided, by selection of appropriate filler materials. Microbial survival on coated seeds may be attenuated, and generally old chemistry seed treatment fungicides including captain, thiram and carboxin are not recommended with Rhizobium inoculants [107]. Therefore, compatibility of new seed treatments should be tested to ensure efficacy of the biological.

4.5. Other Coatings

Different marker substances including visible dyes, fluorescent tracers and magnetic powders were incorporated into coatings to trace the seed in the supply chain and protect the true seeds from fake seeds in the market [8,52]. Color-coding is the most widely used marker system in coating processes for identification of a specific variety or seed treatment [23]. Colored seed is an indication of a seed coat treatment with appropriate fungicide or pesticide and is used to reduce the risk of livestock or human consumption [8]. Natural colorants can be used for storage of soybean seeds without loss of vigor [108]. Additionally, researchers have also evaluated the efficacy of fluorescein, rhodamine, and magnetic powder as anti-counterfeiting labels in tobacco seeds in order to enhance seed security in the supply chain [52]. Riboflavin is a natural fluorescent compound and was used for marking cucumber seeds for authentication [109]. Riboflavin was not phytotoxic after application nor after seed storage compared to non-treated seeds, and riboflavin fluorescence was not diminished after 10 months’ storage [109].

5. Conclusions and Future Prospects

Seed coating technologies have many virtues including protecting seeds from pests and diseases at the time of sowing and improving flowability for precision seeding [15]. Improved stand establishment and seedling vigor under biotic and abiotic stresses can be achieved by using appropriate seed coating equipment, methods, and materials. The growing demand for coated seeds is documented with many small and large companies in the market. Despite the extensive information on natural or synthetic active components, coating methods and polymers, the seed industry in many developing countries is not adopting this technology. Farmers in these countries are not utilizing seed treatments due to lack of resources as compared to 100% adoption in developed countries [4]. Usually, economical treatments are preferred if cost is not exceeding USD 20 per planted hectare [7]. Therefore, the success of seed coating technology depends upon the selection of inexpensive and readily available coating agents with low cost. Collectively, cost effective, simple materials and methods are needed for use in third world countries.

There is limited information available on the shelf life of treated and coated seeds. Specifically, it would be helpful to know if seed treatment phytotoxicity increases with the loss of seed vigor in storage [110,111]. Is there a reduction in seed treatment efficacy after seed storage, particularly for seeds treated with biologicals [7]? Investigations are needed on how to better integrate seed coating technologies with weed management exploiting herbicide safeners [95], or herbicide seed treatments [112]. Additional research and development are needed for new biochemical, bio-pesticide
plant protectants [96,97] that can be used for organic or conventional crop production for sustainable agricultural systems. Lastly, the knowledge of seed treatment and coating technologies should be directed for reliable and consistent stand establishment under changing climatic conditions. To accomplish these goals will require the development of new active components, with complimentary coating equipment, and coating technologies. This can best be achieved by continued efforts from multidisciplinary teams of seed scientists, agronomists, chemists, pest management specialists and engineers. These achievements may be accomplished through a partnership of academia with industry for the development of cost-effective materials and methods for wide-scale adoption in developed and third-world countries.

**Author Contributions:** I.A. Conceptualization, writing and original draft preparation, T.J. Writing and original draft preparation. M.A. Writing, preparation of both figures and three tables, A.G.T. Conceptualization and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This material is based upon work that is supported by the United States Hatch Funds under Multi-state Project W-4168 under accession number 1007938 to the fourth author, and Pakistan Science Foundation under a research project PSF/NSLP-489 to the first author.

**Acknowledgments:** The authors thank Hilary Mayton for critically reviewing this manuscript, and helpful suggestions were provided by Simone Pedrini for developing the illustration in Figure 1. We thank valuable input from seed treatment and coating industries, and seed companies: ABM, Aginnovations, BASF, Beck’s Hybrids, CTApplicators, Germains, Incotec and Syngenta.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Ellis, R.H. Seed and seedling vigor in relation to crop growth and yield. *J. Plant Growth Regul.* 2004, 11, 249–255. [CrossRef]
2. Afzal, I.; Rehman, H.U.; Naveed, M.; Basra, S.M.A. Recent advances in seed enhancements. In *New Challenges in Seed Biology- Basic and Translational Research Driving Seed Technology*; InTechOpen: London, UK, 2016; pp. 47–74.
3. Zinsmeister, J.; Leprince, O.; Buitink, J. Molecular and environmental factors regulating seed longevity. *Biochem. J.* 2020, 477, 305–323. [CrossRef] [PubMed]
4. Sharma, K.K.; Singh, U.S.; Sharma, P.; Kumar, A.; Sharma, L. Seed treatments for sustainable agriculture—A review. *J. Appl. Nat. Sci.* 2015, 7, 521–539. [CrossRef]
5. Halmer, P. Seed technology and seed enhancement. *Acta Hort.* 2008, 771, 17–26. [CrossRef]
6. Taylor, A.G. Seed treatments. In *Encyclopedia of Applied Plant Sciences*; Thomas, B.D.J., Murphy, B.G., Eds.; Elsevier Academic Press: Cambridge, UK, 2003; pp. 1291–1298.
7. Taylor, A.G.; Harman, G.E. Concepts and technologies of selected seed treatments. *Annu. Rev. Phytopathol.* 1990, 28, 321–339. [CrossRef]
8. Pedrini, S.; Merritt, D.J.; Stevens, J.; Dixon, K. Seed coating: Science or marketing spin? *Trends Plant Sci.* 2017, 22, 106–116. [CrossRef] [PubMed]
9. Jeffs, K.A. *Seed Treatment*, 2nd ed.; The British Crop Protection Council (BCPC) Publication: Surrey, UK, 1986; p. 332.
10. Halmer, P. Commercial seed treatment technology. In *Seed Technology and Its Biological Basis*; Black, M., Bewley, J.D., Eds.; Sheffield Academic Press: Sheffield, UK, 2000; pp. 257–286.
11. Porter, F.E.; Scott, J.M. Seed coating methods and Purposes: A status report. In *Proceedings of the Short Course for Seedsmen*; Mississippi Agricultural and Forestry Experiment Station: Prairie, MS, USA, 1979.
12. Scott, J.M. Seed coatings and treatments and their effects on plant establishment. *Adv. Agron.* 1989, 42, 43–83.
13. Hill, H.J. Recent developments in seed technology. *J. New Seeds* 1999, 1, 105–112. [CrossRef]
14. Pedrini, S.; Balestrazzi, A.; Madsen, M.; Bhalsing, K.; Hardegree, S.; Dixon, K.W.; Kildisheva, O.A. Seed enhancement: Getting seeds restoration-ready. *Restor. Ecol.* 2020, 28, S266–S275. [CrossRef]
15. Taylor, A.G.; Allen, P.S.; Bennett, M.A.; Bradford, K.J.; Burris, J.S.; Misra, M.K. Seed enhancements. *Seed Sci. Res.* 1998, 8, 245–256. [CrossRef]
16. Taylor, A.G. Seed storage, germination, quality and enhancements. In *The Physiology of Vegetable Crops*, 2nd ed.; Wien, H.C., Stutzel, H., Eds.; CAB International: Wallingford, UK, 2020; pp. 1–30.
Agriculture 2020, 10, 526

17. Seed Coating Materials Market by Type (Polymers, Colorants, Pellets, Minerals/Pumice, and Other Additives), Crop Type (Cereals & Grains, Oils & Edible Oils, Fruits & Vegetables, Flowers & Ornamentals), & by Region—Global Trends & Forecasts to 2020. Available online: https://www.marketsandmarkets.com/Market-Reports/seed-coating-materials-market-149045530.html (accessed on 18 September 2020).
18. Taylor, A.G.; Trimmer, M.; DunhamTrimmer International Bio Intelligence, Lakewood Ranch, Florida. Global chemical and biological seed treatments market. Personal communication, 2020.
19. Biological Products Markets around the World. Available online: http://www.bpia.org/wp-content/uploads/2018/03/Biological-Products-Markets-Around-The-World.pdf (accessed on 30 October 2020).
20. Buffington, B.; Beegle, D.; Lindholm, C. Seed Treatment a National Pesticide Applicator Manual; Pesticide Educational Resources Collaborative (PERC), University of California Davis: Davis, CA, USA, 2018.
21. Organic Materials Review Institute. Available online: https://www.omri.org/ (accessed on 14 September 2020).
22. Rocha, L.D.S.; Ma, Y.; Souza-Alonso, P.; Vossaka, M.; Freitas, H.; Oliveira, R.S. Seed coating: A tool for delivering beneficial microbes to agricultural crops. Front. Plant Sci. 2019, 10, 1357. [CrossRef]
23. Ma, Y. Seed coating with beneficial microorganisms for precision agriculture. Biotechnol. Adv. 2019, 37, 107423. [CrossRef]
24. Kalaivani, K.; Kalaiselvi, M.M.; Senthil-Nathan, S. Effect of methyl salicylate (MeSA), an elicitor on growth, physiology and pathology of resistant and susceptible rice varieties. Sci. Rep. 2016, 6, 34498. [CrossRef]
25. Klessig, D.F.; Manohar, M.; Baby, S.; Koch, A.; Danquah, W.B.; Luna, E.; Park, H.J.; Kolkman, J.M.; Turgeon, B.G.; Nelson, R.; et al. Nematode ascaroside enhances resistance in a broad spectrum of plant–pathogen systems. J. Phytopathol. 2019, 167, 1–8. [CrossRef]
26. Lee, M.W.; Huffaker, A.; Crippen, D.; Robbins, R.T.; Goggin, F.L. Plant elicitor peptides promote plant defences against nematodes in soybean. Mol. Plant Pathol. 2018, 19, 858–869. [CrossRef]
27. Tayyab, N.; Naz, R.; Yasnin, H.; Nosheen, A.; Keyani, R.; Sajjad, M.; Hassan, M.N.; Roberts, T.H. Combined seed and foliar pre-treatments with exogenous methyl jasmonate and salicylic acid mitigate drought induced stress in maize. PLoS ONE 2020, 15, e0232269. [CrossRef]
28. Madsen, M.D.; Petersen, S.; Taylor, A.G. Seed Coating Compositions and Methods for Applying Soil Surfactants to Water-Repellent Soil. U.S. Patent 9,554,502 B2, 31 January 2017.
29. Ryu, C.M.; Kim, J.; Choi, O.; Kim, S.H.; Park, C.S. Improvement of biological control capacity of Paenibacillus polymyxa E681 by seed pelleting on sesame. Biol. Control 2006, 39, 282–289. [CrossRef]
30. Chen, Y.; Turnblad, K.M. Insecticidal Seed Coating. U.S. Patent 0,177,526 A1, 28 November 2002.
31. Lopisso, D.T.; Kühlmann, V.; Siebold, M. Potential of soil-derived fungal biocontrol agents applied as a soil amendment and a seed coating to control Verticillium wilt of sugar beet. Biocontrol Sci. Technol. 2017, 27, 1019–1037. [CrossRef]
32. Kangsopa, J.; Hynes, R.K.; Siri, B. Lettuce seeds pelleting: A new bilayer matrix for lettuce (Lactuca sativa) seeds. Seed Sci. Technol. 2018, 46, 521–531. [CrossRef]
33. Kimmelshue, C.; Goggi, A.S.; Cademartiri, R. The use of biological seed coatings based on bacteriophages and polymers against Clavibacter michiganensis subsp. nebraskensis in maize seeds. Sci. Rep. 2019, 9, 17950. [CrossRef]
34. Javed, T.; Afzal, I. Impact of seed pelleting on germination potential, seedling growth and storage of tomato seed. Acta Hortic. 2020, 1273, 417–424. [CrossRef]
35. Danielson, B.; Gaul, A. Category 4, Seed Treatment—Iowa Commercial Pesticide Applicator Manual, CS16; Iowa State University Extension and Outreach: Ames, IA, USA, 2011; p. 40.
36. Sikhaao, P.; Taylor, A.G.; Marino, E.T.; Catranis, C.M.; Siri, B. Development of seed agglomeration technology using lettuce and tomato as model vegetable crop seeds. Sci. Hortic. 2015, 184, 85–92. [CrossRef]
37. Cho, S.; Seo, H.; Oh, Y.; Lee, E.; Choi, I.; Jang, Y.; Song, Y.; Min, T. Selection of coating materials and binders for pelleting onion (Allium cepa L.) seed. J. Korean Soc. Hortic. Sci. 2000, 41, 593–597.
38. Guan, Y.J.; Wang, J.C.; Hu, J.; Tian, Y.X.; Hu, W.M.; Zhu, S.J. A novel fluorescent dual-labeling method for anti-counterfeiting pelleted tobacco seeds. Seed Sci. Technol. 2013, 41, 158–163. [CrossRef]
39. Sooter, C.A.; Millier, W.F. The effect of pellet coatings on the seedling emergence from lettuce seeds. Trans. Am. Soc. Agric. Eng. 1978, 21, 1034–1039. [CrossRef]
40. Vereenigde, M.H.; Wittlana, J.; Haag, D.J.R. Seed Coating Composition. European Patent No. Eur. Patent 2229808 A1, 22 September 2010.
41. Hirsch, G.W. Powdered Seed Treatment Applicator. U.S. Patent 7,487,892, 10 February 2009.
Agriculture 2020, 10, 526

42. Hirsch, G.W. Powder Dispenser Assembly. U.S. Patent 8,556,129, 15 October 2013.
43. Changing Times, LLC. Available online: https://www.ctapplicators.com/ (accessed on 10 September 2020).
44. Marks, P.; Aginnovation LLC, Lodi, CA, USA; Taylor, A.G. Dry powder seed covering equipment. Personal communication, 2020.
45. Anderson, D. Talc and Graphite: What You Need to Know before you Plant Machinery. AgWeb J. 2014. Available online: https://www.agweb.com/article/talc_and_graphite_what_you_need_to_know_before_you_plant_NAA_Dan_Anderson (accessed on 14 September 2020).
46. Badua, S.A.; Sharda, S.; Strasser, R.; Cockerlin, K.; Ciampiatti, I. Comparison of soy protein based and commercially available seed lubricants for seed flowability in row crop planters. Appl. Eng. Agric. 2019, 35, 593–600. [CrossRef]
47. Avelar, S.A.G.; Sousa, F.V.D.; Fiss, G.; Baudet, L.; Peske, S.T. The use of film coating on the performance of treated corn seed. Rev. Bras. Sementes 2012, 34, 186–192. [CrossRef]
48. Olivera, M.E.; Ferrari, L.; Araoz, S.; Postulka, E.B. Improvements on physiological seed quality of Festuca arundinacea schreb by encrusting technology: Products and storage effects. Science 2017, 10, 33–37. [CrossRef]
49. Gorim, L.; Asch, F. Effects of composition and share of seed coatings on the mobilization efficiency of cereal seeds during germination. J. Agron. Crop Sci. 2012, 198, 81–91. [CrossRef]
50. Qu, Y.; Amirkhani, M.; Mayton, H.; Chen, Z.; Taylor, A.G. Biostimulant seed coating treatments to improve crop germination and seedling growth. Agronomy 2020, 10, 154. [CrossRef]
51. Amirkhani, M.; Mayton, H.S.; Netravali, A.N.; Taylor, A.G. A seed coating delivery system for bio-based biostimulants to enhance plant growth. Sustainability 2019, 11, 5304. [CrossRef]
52. Amirkhani, M.; Netravali, A.; Huang, W.; Taylor, A.G. Investigation of soy protein–based biostimulant seed coating for broccoli seedling and plant growth enhancement. Hortic. Sci. 2016, 51, 1121–1126. [CrossRef]
53. Mei, J.; Wang, W.; Peng, S.; Nie, L. Seed pelleting with calcium peroxide improves crop establishment of direct-seeded rice under waterlogging conditions. Sci. Rep. 2017, 7, 1–12. [CrossRef] [PubMed]
54. Nwankwo, C.I.; Blaser, S.R.G.A.; Vetterlein, D.; Neumann, G.; Herrmann, L. Seed ball-induced changes of root growth and physico-chemical properties—A case study with pearl millet. J. Plant Nutr. Soil Sci. 2018, 181, 768–776. [CrossRef]
55. Madsen, M.D.; Davies, K.W.; Williams, C.J.; Svejcar, T.J. Agglomerating seeds to enhance native seedling emergence and growth. J. Appl. Ecol. 2012, 49, 431–438. [CrossRef]
56. Gornish, E.; Arnold, H.; Fehmi, J. Review of seed pelletizing strategies for arid land restoration. Restor. Ecol. 2019, 27, 1206–1211. [CrossRef]
57. Ben-Jabur, M.; Khiri, Z.; Harbouai, K.; Belguemsi, K.; Serret, M.D.; Araus, J.L.; Hamada, W. Seed coating with thyme essential oil or Paraburkholderia phytofirmans PsJN strain: Conferring septoria leaf blotch resistance and promotion of yield and grain isotopic composition in wheat. Agronomy 2019, 9, 586. [CrossRef]
58. Ma, Y.; Látr, A.; Rocha, I.; Freitas, H.; Vosátka, M.; Oliveira, R.S. Delivery of inoculum of Rhizophagus irregularis via seed coating in combination with Pseudomonas labinensis for cowpea production. Agronomy 2019, 9, 33. [CrossRef]
59. Rocha, I.; Duarte, I.; Ma, Y.; Souza-Alonso, P.; Látr, A.; Vosátka, M.; Freitas, H.; Oliveira, R.S. Seed coating with arbuscular mycorrhizal fungi for improved field production of chickpea. Agronomy 2019, 9, 471. [CrossRef]
60. Wilson, H.T.; Amirkhani, M.; Taylor, A.G. Evaluation of gelatin as a biostimulant seed treatment to improve plant performance. Front. Plant Sci. 2018, 9, 1006. [CrossRef] [PubMed]
61. Choohkongkha, N.; Sopondilok, T.; Photchanachai, S. Effect of chitosan and chitosan nanoparticles on fungal growth and chilli seed quality. In Proceedings of the International Conference on Post-harvest Pest and Disease Management in Exporting Horticultural Crops-PPDM2012 973, Bangkok, Thailand, 21 February 2012; pp. 231–237.
62. Ziani, K.; Beatriz, U.; Juan, I.M. Application of bioactive coatings based on chitosan for artichoke seed protection. Crop Prot. 2010, 29, 853–859. [CrossRef]
63. Michalak, I.; Dmytryk, A.; Schroeder, G.; Chojnacka, K. The application of homogenate and filtrate from Baltic seaweeds in seedling growth tests. Appl. Sci. 2017, 7, 230. [CrossRef]
65. Ben-Jabeur, M.; Vicente, R.; López-Cristoffanini, C.; Alesami, N.; Djebali, N.; Gracia-Romero, A.; Serret, M.D.; López-Carbonell, M.; Araus, J.L.; Hamada, W. A novel aspect of essential oils: Coating seeds with thyme essential oil induces drought resistance in wheat. *Plants* **2019**, *8*, 371. [CrossRef]

66. Jardin, D.P. Plant biostimulants: Definition, Concept, Main Categories and Regulation. *Sci. Hortic.* **2015**, *196*, 3–14. [CrossRef]

67. Calvo, P.; Nelson, L.; Kloepper, J.W. Agricultural uses of plant biostimulants. *Plant Soil* **2014**, *383*, 3–41. [CrossRef]

68. Taylor, A.G.; Trimmer, M.; DunhamTrimmer International Bio Intelligence, Lakewood Ranch, Florida. Global market value of biostimulant seed treatments. Personal communication, 2020.

69. Farooq, M.; Wahid, A.; Siddique, K.H. Micronutrient application through seed treatments: A review. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 125–142. [CrossRef]

70. Masuthi, D.A.; Vyakaranahal, B.S.; Deshpande, V.K. Influence of pelleting with micronutrients and botanical on growth, seed yield and quality of vegetable cowpea. *Karnataka J. Agric. Sci.* **2009**, *22*, 898–900.

71. Peltonen, S.P.; Kontturi, M.; Peltonen, J. Phosphorus seed coating enhancement on early growth and yield components in oat. *Agron. J.* **2006**, *98*, 206–211. [CrossRef]

72. Rehman, A.U.; Farooq, M. Boron application through seed coating improves the water relations, panicle fertility, kernel yield, and biofortification of fine grain aromatic rice. *Acta Physiol. Plant.* **2013**, *35*, 411–418. [CrossRef]

73. Guan, Y.; Song, C.; Gan, Y.; Li, F.M. Increased maize yield using slow-release attapulgite-coated fertilizers. *Agron. Sustain. Dev.* **2014**, *34*, 657–665. [CrossRef]

74. Dong, Y.J.; He, M.R.; Wang, Z.L.; Chen, W.F.; Hou, J.; Qiu, X.K.; Zhang, J.W. Effects of new coated release fertilizer on the growth of maize. *J. Soil Sci. Plant Nutr.* **2016**, *16*, 637–649. [CrossRef]

75. Adhikari, T.; Kundu, S.; Rao, A.S. Zinc delivery to plants through seed coating with nano-zinc oxide particles. *J. Plant Nutr.* **2016**, *39*, 136–146. [CrossRef]

76. Shivay, Y.S.; Kumar, D.; Prasad, R.; Ahlawat, L.P.S. Relative yield and zinc uptake by rice from zinc sulphate and zinc oxide coatings onto urea. *Nutr. Cycl. Agroecosyst.* **2008**, *80*, 181–188. [CrossRef]

77. Acha, A.J.; Vieira, H.D.; Freitas, M.S.M. Perennial soybean seeds coated with high doses of boron and zinc. *Afr. J. Biotechnol.* **2006**, *15*, 1998–2005.

78. Rehman, A.; Farooq, M. Zinc seed coating improves the growth, grain yield and grain biofortification of bread wheat. *Acta Physiol. Plant.* **2006**, *38*, 238. [CrossRef]

79. Xavier, P.B.; Vieira, H.D.; Amorim, M.M. Physiological potential of *Stylosanthes* spp. seeds cv. Campo Grande in response to coating with zinc and boron. *J. Seed Sci.* **2016**, *38*, 314–321. [CrossRef]

80. Ullah, A.; Farooq, M.; Hussain, M.; Ahmad, R.; Wakeel, A. Zinc seed coating improves emergence and seedling growth in desi and kabuli chickpea types but shows toxicity at higher concentration. *Int. J. Agric. Biol.* **2019**, *21*, 553–559.

81. Wiatrak, P. Influence of seed coating with micronutrients on growth and yield of winter wheat in Southeastern Coastal Plains. *Am. J. Agric. Biol. Sci.* **2013**, *8*, 230.

82. Wiatrak, P. Effect of polymer seed coating with micronutrients on soybeans in Southeastern Coastal Plains. *Am. J. Agric. Biol. Sci.* **2013**, *8*, 302–308. [CrossRef]

83. Vasudevan, S.N.; Doddagoudar, S.R.; Sangeeta, I.M.; Shakuntala, N.M.; Patil, S.B. Augmenting productivity of major crop through seed polymer coating with micronutrients and foliar spray. *J. Adv. Agric. Technol.* **2016**, *3*, 150–154. [CrossRef]

84. Karanam, P.V.; Vabez, V. Phosphorus coating on pearl millet seed in low P Alfisol improves plant establishment and increases stover more the seed yield. *Exp. Agric.* **2010**, *46*, 457–469. [CrossRef]

85. Chandrika, K.P.; Prasad, R.D.; Godbole, V. Development of chitosan-PEG blended films using *Trichoderma*: Enhancement of antimicrobial activity and seed quality. *Int. J. Biol. Macromol.* **2019**, *126*, 282–290. [CrossRef]

86. Quastel, J.H. ‘Krilium’ and synthetic soil conditioners. *Nature* **1953**, *171*, 7–10. [CrossRef]

87. Tsujimoto, T.; Sato, H.; Matsushita, S. Hydration of Seeds with Partially Hydrated Super Absorbent Polymer Particles. U.S. Patent 5,930,949, 3 August 1999.

88. Leinauer, B.; Serena, M.; Singh, D. Seed coating and seeding rate effects on turfgrass germination and establishment. *HortTechnology* **2010**, *20*, 179–185. [CrossRef]
89. Gorim, L.; Asch, F. Seed coating with hydro-absorbers as potential mitigation of early season drought in sorghum (Sorghum bicolor L. Moench). *Biology* 2020, 9, 33. [CrossRef] [PubMed]

90. Berdahl, J.D.; Barker, R.E. Germination and emergence of Russian wildrye seeds coated with hydrophilic materials. *Agron. J.* 1980, 72, 1006–1008. [CrossRef]

91. Chen, H.W.; Jiang, S.T.; Zhou, J.Q.; Zhao, Y.Y.; Wang, J.H. Super absorbent polymer seed coating and its effect on physiological features of corn seed. *J. Hefei Univ. Technol. (Nat. Sci.)* 2004, 27, 242–246.

92. Su, L.Q.; Li, J.G.; Xue, H.; Wang, X.F. Super absorbent polymer seed coatings promote seed germination and seedling growth of *Caragana korshinskii* in drought. *J. Zhejiang Univ. Sci.* 2017, 18, 696–706. [CrossRef]

93. Yildirim, E.; Taylor, A.G.; Spittler, T.D. Ameliorative effects of biological treatments on growth of squash plants under salt stress. *HortTechnology* 2006, 11, 1–6. [CrossRef]

94. Mastouri, F.; Björkman, T.; Harman, G.E. Seed treatment with *Trichoderma harzianum* alleviates biotic, abiotic, and physiological stresses in germinating seeds and seedlings. *Phytopathology* 2010, 100, 1213–1221. [CrossRef]

95. Rushing, J.B.; Baldwin, B.S.; Taylor, A.G.; Owens, V.N.; Fike, H.J.; Moore, K.J. Seed safening from herbicidal injury in switchgrass establishment. *Crop Sci.* 2013, 53, 1650–1657. [CrossRef]

96. Nault, B.A.; Straub, R.W.; Taylor, A.G. Performance of novel insecticide seed treatments for managing onion maggot in onion fields. *Crop Prot.* 2006, 25, 58–65. [CrossRef]

97. Wilson, R.G.; Orloff, S.B.; Taylor, A.G. Evaluation of insecticides and application methods to protect onions from onion maggot, *Delia antiqua* and seedcorn maggot, *Delia platura* damage. *Crop Prot.* 2014, 67, 102–108. [CrossRef]

98. Moretti, E.; Nault, B.A. Onion maggot control in onion, 2019. *Arthropod Manag. Tests* 2020, 45, tsaa007. [CrossRef]

99. Mbega, E.R.; Mortensen, C.N.; Mabagala, R.B.; Wulff, E.G. The effect of plant extracts as seed treatments to control bacterial leaf spot of tomato in Tanzania. *J. Gen. Plant Pathol.* 2012, 78, 277–286. [CrossRef]

100. Findura, P.; Hara, P.; Szparaga, A.; Kocira, S.; Czerwińska, E.; Bartoš, P.; Tredter, K. Evaluation of the effects of allelopathic aqueous plant extracts, as potential preparations for seed dressing, on the modulation of cauliflower seed germination. *Agriculture* 2020, 10, 122. [CrossRef]

101. Mancini, V.; Romanazzi, G. Seed treatments to control seedborne fungal pathogens of vegetable crops. *Pest. Manag. Sci.* 2014, 70, 860–868. [CrossRef]

102. Dogan, T.; Zeybek, A. Improving the traditional sesame seed planting with seed pelleting. *Afr. J. Biotechnol.* 2009, 8, 6120–6126.

103. Carvalho, M.L.M.; Lopes, C.A.; Ribeiro, A.M.P.; Vasconcelos, M.C. Could packing and pelleting keep the quality of forage and seed of berseem clover (*Trifolium alexandrinum* L.) and its impact on soil fertility and smallholder farmer’s income. *J. Anim. Plant Sci.* 2018, 25, 1493–1500.

104. Deaker, R.; Roughley, R.J.; Kennedy, I.R. Legume seed inoculation technology—A review. *Soil Biol. Biochem.* 2004, 36, 1275–1288. [CrossRef]

105. Tufail, M.S.; Krebs, G.L.; Ahmad, J.; Southwel, A. The effect of *Rhizobium* seed inoculation on yields and quality of forage and seed of berseem clover (*Trifolium alexandrinum* L.) and its impact on soil fertility and smallholder farmer’s income. *J. Anim. Plant Sci.* 2018, 28, 1493–1500.

106. Głodowska, M.; Schwinghamer, T.; Husk, B.; Smith, D. Biochar based inoculants improve soybean growth and nodulation. *Agric. Sci.* 2017, 8, 1048–1064. [CrossRef]

107. Belles, D.; Seed Care, Syngenta Crop Protection, Phoenix, Arizona; Taylor, A.G. Rhizobia compatibility. Personal communication, 2020.

108. Tripathi, B.; Pandey, A.; Bhatia, R.; Walia, S.; Yadav, A.K. Improving soybean seed performance with natural colorant-based novel seed-coats. *J. Crop Improv.* 2015, 29, 301–318. [CrossRef]

109. Sikha, P.; Teeraponchasit, P.; Taylor, A.G.; Siri, B. Seed coating with riboflavin, a natural fluorescent compound, for authentication of cucumber seeds. *Seed Sci. Technol.* 2014, 42, 171–179. [CrossRef]

110. Taylor, A.G.; Salanenka, Y.A. Seed treatments: Phytotoxicity amelioration and tracer uptake. *Seed Sci. Res.* 2012, 22, S86–S90. [CrossRef]

111. Taylor, A.G.; Eckenrode, C.J.; Straub, R.W. Seed treatments for onions: Challenges and progress. *HortTechnology* 2001, 36, 199–205.
112. Kanampiu, F.K.; Kabambe, V.; Massawe, C.; Jasi, L.; Friesen, D.; Ransom, J.K.; Gressel, J. Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls Striga spp. and increases yields in several African countries. *Crop Prot.* 2003, 22, 697–706. [CrossRef]

**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).