



Review

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

Irfan Afzal <sup>1</sup>, Talha Javed <sup>1</sup>, Masoume Amirkhani <sup>2</sup> and Alan G. Taylor <sup>2,\*</sup>

<sup>1</sup> Seed Physiology Lab, Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan; iafzal@uaf.edu.pk (I.A.); talhajaved54321@gmail.com (T.J.)

<sup>2</sup> Cornell AgriTech, School of Integrative Plant Science, Horticulture Section, Cornell University, Geneva, New York, NY 14850, USA; ma862@cornell.edu

\* Correspondence: agt1@cornell.edu

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**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.

**Table 1.** Seed treatment and coating materials grouped as active components, liquids and solid particulates. Each group of material is further classified by function and composition. Abbreviations for material source/origin: Synthetic Chemicals—SYN, Natural products or derivatives—NP, Biologicals—BIO, Mineral—MIN, substances may be Organically approved—OR.

Active Components	Liquids	Solid Particulates
<b>Biostimulants</b> <ul style="list-style-type: none"> <li>• SYN, NP, BIO (OR)</li> </ul> <b>Plant nutrients</b> <ul style="list-style-type: none"> <li>• SYN, MIN (OR)</li> </ul> <b>Abiotic stress:</b> Drought and Salinity <ul style="list-style-type: none"> <li>• SYN, BIO (OR)</li> </ul> <b>Plant Protectants</b> <ul style="list-style-type: none"> <li>• SYN, NP, BIO, MIN (OR)</li> </ul> <b>Inoculants</b> <ul style="list-style-type: none"> <li>• BIO, MIN (OR)</li> </ul>	<b>Water</b> <b>Colorants</b> <ul style="list-style-type: none"> <li>• SYN, NP (OR)</li> </ul> <b>Adjuvants</b> <ul style="list-style-type: none"> <li>• SYN (OR)</li> </ul> <b>Binders</b> <ul style="list-style-type: none"> <li>• Polyvinyl alcohol (PVOH) and Polyvinyl acetate (PVAc): SYN</li> <li>• Methyl cellulose: SYN</li> <li>• Carboxymethyl cellulose (CMC): SYN</li> <li>• Plant starches: NP (OR)</li> <li>• Gum Arabic: NP (OR)</li> </ul>	<b>Binders</b> <ul style="list-style-type: none"> <li>• Also, under Liquids</li> <li>• Soy flour: NP (OR)</li> </ul> <b>Fillers</b> <ul style="list-style-type: none"> <li>• Diatomaceous earth (DE): MIN (OR)</li> <li>• Limestone: MIN (OR)</li> <li>• Gypsum: MIN (OR)</li> <li>• Bentonite: MIN (OR)</li> <li>• Vermiculite: MIN (OR)</li> <li>• Talc: MIN (OR)</li> <li>• Zeolite: MIN (OR)</li> <li>• Silica: MIN (OR)</li> <li>• BaSO<sub>4</sub>: MIN</li> </ul>

### 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).

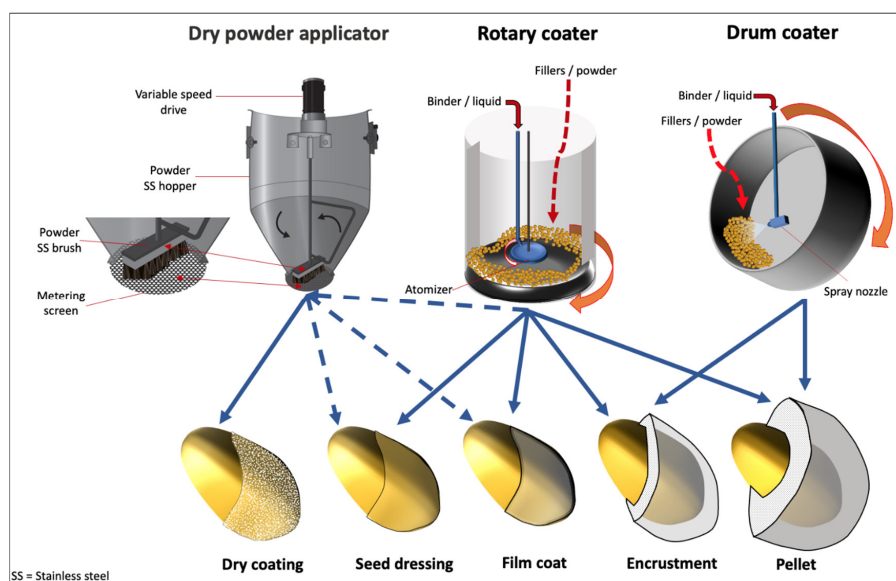
### 2.3. Solid Particulates

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].



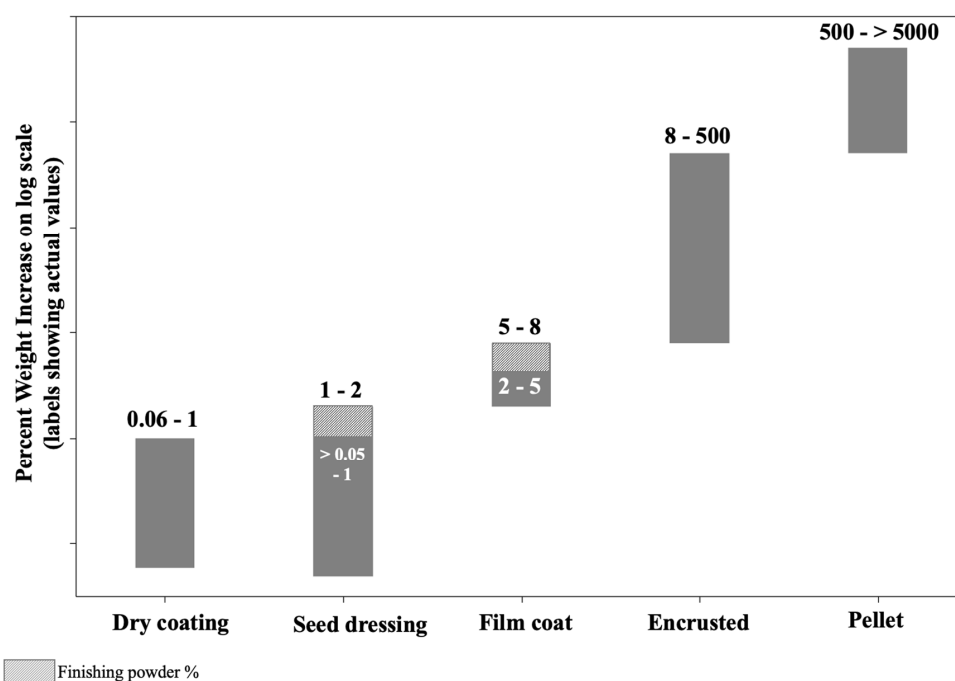
**Figure 1.** The three major types of seed coating equipment: dry powder applicator, rotary coater and drum coater used to produce five seed coatings: dry coating, seed dressing, film coat, entrustment and seed pellet.

### 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 a 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.



### 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

seed [49]. The amount of binder used in producing encrusted coatings changes mechanical properties including integrity, compressive strength and time to disintegrate after soaking [50].

### 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
<i>Paraburkholderia phytofirmans</i> 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 <sup>-1</sup> )	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— <i>Rhizophagus irregularis</i>	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— <i>Pseudomonas libanensis</i>	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 <i>R. irregularis</i> 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% ( <i>w/v</i> ) chitosans solution applied to 100 g seeds	4% ( <i>w/v</i> ) 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 (H <sub>3</sub> BO <sub>3</sub> ) SYN (OR)	Rice	Application of H <sub>3</sub> BO <sub>3</sub> at 1, 1.5, 2, 2.5 and 3 g/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) SYN	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 (KH <sub>2</sub> PO <sub>4</sub> ) SYN	Pearl millet	Application of KH <sub>2</sub> PO <sub>4</sub> at a rate of 400 g P ha <sup>-1</sup> 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 SYN	Wheat	Application of mixture of manganese, copper and zinc micronutrients by polymer coating	Seed coating with 395 mL 100 kg seeds <sup>-1</sup> improved dry matter yield (23%), N uptake (25%), P uptake (23%) and grain yield (2%) over control	[81]
Micronutrients SYN	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 <sup>-1</sup>	[82]
Micronutrients SYN	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 (ZnSO <sub>4</sub> + H <sub>3</sub> BO <sub>3</sub> ) SYN (OR)	Soybean	Seed coating with the dose 0.8 kg of H <sub>3</sub> BO <sub>3</sub> + 0.8 kg of ZnSO <sub>4</sub> /kg seeds.	Significantly improved growth and reduced shoot dry matter production	[77]
Zinc sulfate and Zinc chloride (ZnSO <sub>4</sub> + ZnCl <sub>2</sub> ) ZnSO <sub>4</sub> SYN (OR), ZnCl <sub>2</sub> SYN	Wheat	Application of ZnSO <sub>4</sub> + ZnCl <sub>2</sub> at 1.25 g Zn/kg by seed coating	Improved chlorophyll a and b contents. Enhanced grain yield and Zn contents	[78]
Zinc sulfate (ZnSO <sub>4</sub> ) SYN (OR) Borax SYN (OR) Arappu leaf powder (OR)	Cowpea	Application of ZnSO <sub>4</sub> , 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 ZnSO <sub>4</sub> improved yield parameters	[70]
Zinc sulfate and Boric acid (ZnSO <sub>4</sub> + H <sub>3</sub> BO <sub>3</sub> ) SYN (OR)	Stylosanthes	Application of ZnSO <sub>4</sub> with 90 g and H <sub>3</sub> BO <sub>3</sub> 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 harziannum* 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 (PBMs) 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 nematocides [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 pairing 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, fluxofenim was effective on field soil treated with the herbicide, metolachlor on switchgrass (*Panicum virgatum*) [95]. Biologicals also known as plant beneficial microbes (PBMs) [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 captan, 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.

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