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REVIEW ARTICLE

A review on modern seed delivery systems for sustainable agriculture and environmental restoration

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Abstract

Traditional sowing methods like direct seeding may not always be optimal, particularly for unfamiliar species, necessitating tailored approaches for different seed types and qualities. Thus, the delivery of essential materials along with seed necessitates time and cost saving which ultimately enhances overall seed performance in the planting. Some of the novel seed delivery techniques for agricultural and environmental restoration include seed pellets for mechanized planting, incorporates the seed pellets with biofertilizers improves soil microbiome health and reduce the use of chemical fertilizers. Seed balls for afforestation to promote agroforestry, pollinator support and soil regeneration in degraded soil, seed cube for vegetable gardening and reduction in usage of land and increasing food security, seed mats for ensuring uniform seed distribution and vegetation restoration, seed tapes in precision planting and drone seeding for afforestation are gaining momentum. Similarly, it also looks at the possible uses of seed capsules for delivery of inputs along with seed. These seed delivery systems like seed pellet, seed capsule, seed tape, seed mat and drone seedling which reduces the seed wastage by 20 %, 40 %, 50 %, 60 % and 10 % respectively. These techniques seek to increase seed vigour, seedling survival rates, plant physiology and offer practical, affordable alternatives for crop production and land restoration. Therefore, this review emphasizes the variety of materials and methods that the system employs for agricultural sustainability.

Keywords

drone seeding; seed ball; seed capsule; seed cube; seed mat; seed tape

Introduction

Seed is a mature ovule containing nutrients, the embryo being the most important part of it, which is enclosed by husks and used for planting crop seeds (1). Seeding is an important part of agriculture, in which direct seeding and transplanting are the two main ways of planting crops. Nevertheless, planting techniques are getting diversified by increasing technology for more intelligent agricultural production (1). Between the two methods, seeds are evidently more economical than plant transplants especially where large land have to be covered or in cases where a number of different species have to be planted at one time (2). Direct seeding is indeed a method used for sowing various crops, but depending on the unique qualities of the seeds and the circumstances necessary for their successful germination and growth, its efficacy may differ (3). On the other hand, new seed coating methods like film coating, encrusting and pelleting improve seed shape and surface area for better planting. They also add beneficial substances such as insecticides and nutrients, boosting crop health (4). The global market size for such seed coating technology is expected to reach USD 3.1 billion by 2028 from 2.0 billion in 2023 (5). The evolution of the seed coating market growth is propelled by technological advancements and innovative formulations, steering both growth and sustainability (5). Such seed treatments are the post harvest management practices that seek to improve the germination or seedling growth of seed or to assist in delivery of necessary components during planting, that is, before the seed is planted (6). Biologicals, also known as plant beneficial microbes (PBMs), may exhibit variability in pest management effectiveness across various field conditions encountered during sowing (7). From various studies it is observed that organic fertilizers release nutrients gradually into the soil solution, benefiting seed germination and nourish soil bacteria and crops, providing a balanced diet for optimal crop health. Such organic control-release fertilizers enhance plant productivity and reduce crop yield reduction (8). The recent trend in seed delivery system includes seed coating, seed pelleting, drone seeding, nano sensors-based seeding, seed cube, seed mate (9).

Therefore, we have prepared this review to discuss the use of specialized techniques for the delivery of the seeds as well as other inputs for better emergence, seedling vigour enhancement and subsequent plant growth. Also, these delivery systems aid in sowing, uniform distribution, bio-stimulation, nutrient provision and addressing stress factors, with broad applicability across various crop seeds.

1. Seed pelleting

Seed pelleting involves coating individual seeds with a considerable amount of inert material until the original seed shape becomes indiscernible (2). In addition, seed pelleting offers a remedy to address the challenge posed by the small, flat, or irregular size of seeds. This method effectively enlarges the seeds and imparts a more uniform shape, thereby facilitating their cultivation (10, 11). In simpler terms, the process involves applying adhesive to seeds, coating them with filler materials, rolling them for uniformity and then drying the pelletized seeds in the shade (12). Seed pelleting increased the seed yield upto 25 % than the unpelleted seeds in black gram (13). The incorporation of fertilizers, pesticides, or bio-stimulants into the pelleting material can reduce the need for additional field applications, lowering labor and material costs. Higher germination rates and uniform crop stands optimize land use, maximizing economic returns per unit area (13). From various studies it is observed that, seed pelleting by incorporating pesticides, insecticides, biologicals, micronutrients and growth regulators, crop protection from seed and soil-borne diseases is enhanced, which improves seed quality (14). Pelleting the paddy seeds with clay and calcium carbonate lead to improve the seed weight for mechanical planting in flooded fields (15). Wheat seeds were subjected to pelleting with polymers and it showed uniform emergence and provided resistant against loose smut diseases through which yield has been increased (16). Pelleted the seeds of legumes like soyabean with fungi mycorrizha which improved the symbiotic relationship and increased the nitrogen fixation (17).

1.1. Composition of pelleting material

Seed pelleting involves the use of two necessary materials: adhesive and filler (14). The effectiveness of seed pelleting hinges on several crucial components, including the matrix material, binder and active ingredients. Specifically, the matrix material plays a vital role in enlarging the seed size, facilitating growth while ensuring unimpeded water and air absorption (18). Many minerals, including calcium carbonate, limestone, bentonite, zeolite, pumice, gypsum, talc, charcoal, acacia powder, vermiculite and diatomaceous earth, are frequently used as matrix materials (11, 19). And also binder, 1.5 % aqueous solution of sodium carboxy-methyl cellulose (SCCS), complemented by inert materials such as bentonite (BT) and talcum powder (TP) (20). In which, basil and noni leaf powders serve as excellent filler materials for organic seed pelleting, demonstrating invigorating effects on seed quality characteristics that are maintained both in the field and during storage (21).

Preparing pelleted seeds include mixing ingredients with water to form slurry adjusted for surfactant or SAP content. This slurry was poured into molds measuring 11 cm in circumference and 1 cm deep, with a total volume of about 9.6 cm^3. Seeds were placed centrally in each mold and surrounded with additional slurry to encase them completely. For 2 days at room temperature the pellets were air-dried (22).

1.2. Seed pelleting - A trend set in precision planting and input delivery

Different methods like seed-dressing, polymer film coating, pelleting and encrustment enable the delivery of insecticides, pesticides, biologicals, micronutrients and growth regulators along with seeds, enhancing crop protection and enhancing seed quality to prevent soil- and seed-borne diseases (14). It also enhances the ease of planting small seeds in the field by enlarging their size and improving characteristics such as water absorption, oxygen diffusion, vigour and defense against diseases transmitted through both seeds and soil (23). The pelleted seeds resulted in enhanced photosynthetic efficiency and improved nodulation of the plant, both crucial for increasing productivity (21). It is also observed that the seed pelleting increases seed volume, weight and bulk density without significantly impacting seedling emergence or speed across different species (24). Apart from improving the functionality of seeding equipment, seed pelleting offers protection against unfavorable environmental conditions (10). In India small sized seeds poses problem for mechanical sowing. An experimental study conducted showed that pelleted seeds sown mechanically achieved better growth and yield and reduced the seed rate by 25 % for small sized seeds (12). In case of small seeded green gram variety, seed priming with 0.5 % manganese sulphate and pelleting with TNAU pelleting mixture added with imidacloprid 70 WS @ 7 g / kg enables seed drill sowing (Fig. 1), better field emergence, vigourous seedlings, optimum plant population and higher yield. The experimental study conducted showed

Fig. 1. Pelleted seeds in greengram enable seed drill sowing.

that pelleting of black gram seeds with nutrients improved the growth and yield parameters. Pelleted seeds had 13.5 % higher yield than the control (25). The continuous chemically pelleted seeds would alter the soil composition, microbial diversity which leads to reduced soil fertility over period (26). Long term use of synthetic polymers, binders to the seeds through pelleting which contributed for greenhouse gas emission (27). This technology has been followed in many countries like Netherlands, China, India, Canada etc. In China, seed pelleting research has been advancing to meet the demands of precision sowing particularly beneficial for the crops like vegetables, flowers, grains and medicinal plants (27).

1.3. Challenges and Opportunities

Developing pellet coatings that balance protection with the ability to break down for germination is complex. The pelleting process can add to seed costs, which may be a barrier for widespread adoption (11). The advantage of this technology is, it facilitates mechanical planting, allowing for precise seed placement and depth control. Pellets can include nutrients and protectants that boost early seedling growth, particularly in arid land restoration efforts (11).

2. Seed ball

Seed balls or seed bombs are one of the simplest and effective technique for native plant recovery since they help the seeds to grow and also give the seedlings more time to develop (28). In addition, the survival of seedlings may also be affected by water availability and thus planting seed balls during the rainy season is said to be ideal (29). Establishment of a seed ball with organic fertilizers substrate industry in every district in India, in the future, meet the oxygen needs of living organisms, increase biosphere land area from waste land. This is an efficient way of cultivating land without labour or plows or pills. Due to lack of farm machinery, this technique is more efficient in urban areas (30). On degraded marginal lands, where tillers cannot be used because of steep slopes, existing woods and the general rock, seeds have been employed to create perennial pastures (30). Seed ball technique is cheaper than the traditional tree planting. Direct seeding sometimes might be cheaper than the seed ball but survival rate due to seed predation and soil erosion (31).

2.1. Components of seed ball

Sand, loam, water and seeds are the fundamental raw materials (Fig. 2) of seed ball preparation, while the inclusion of nutrient additives is crucial for achieving a positive result (32). Microorganisms like mobilizers, P solubilizers and N fixers are recommended for germination and growth. Specifically, *Trichoderma sp.* are said to reduce disease and pest infestation (19). Seed balls can be made by mixing 500 g of soil, 500 g of organic matter, 5 g of adhesive and 200 mL of water, following the formula in Martabe gold mine 321). Durian, jackfruit and merbau seeds germinated most quickly on clay and compost (1:1), but velvet apple and white teak seeds germinated most quickly on clay, sawdust, bone meal and vermicompost (8:8:2:1) (32). On considering the benefits of red soil, they were mixed with the vermicompost at 2:1 and 4:2 ratio followed by shade drying for a period of 24 to 36 h which have high physical and physiological properties (33). Further, fertilizers like NPK (15-15-15) and ash were used to prepare seed balls, according to the formula: seed ball = sand + clay + ash or NPK + seed + water (34).The x-ray tomography of seeds revealed that seed ball with nutrient damage experienced a rapid development of fine roots on the other hand seed ball with nutrient release encouraged strong growth of fine

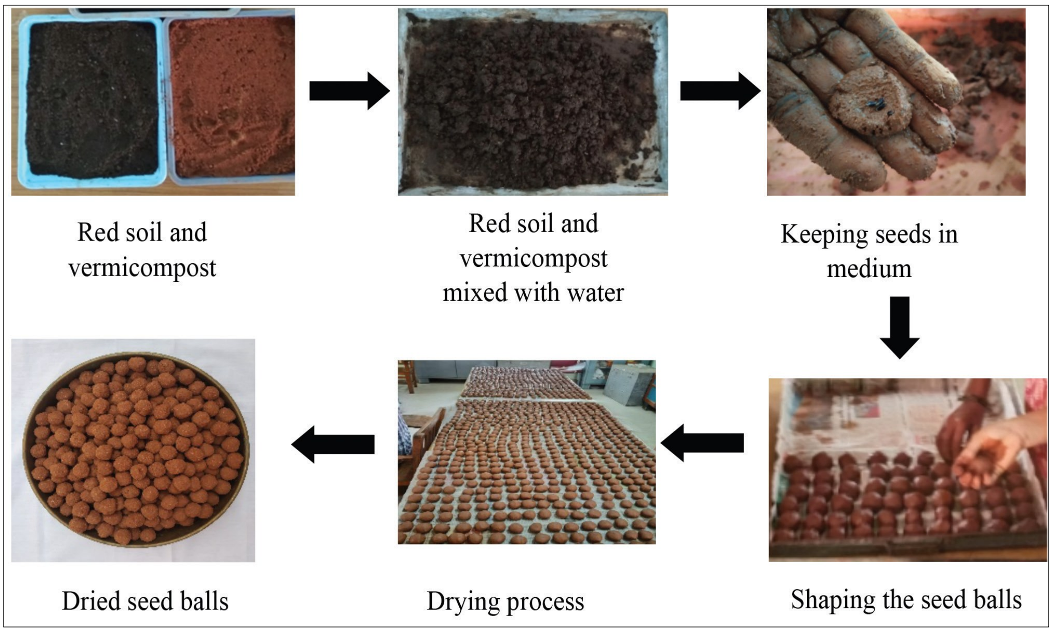

Fig. 2. Steps involved in seed ball preparation.

roots. These imply that increased root length density and occurrence of finer roots would be beneficial in early drought conditions on seedling survival (35).

2.2. Seed balls as an instrument for afforestation

In worldwide, the grasslands, the desert, the cut down forest and the farming fields are being revived by a cheap innovative technology known as seed ball. They protect against pests and other environmental adversities, enhance ecosystems and support healthier habitats by possibly receiving funds from independent and government sources (36). Further, seed sowing using seed briquette and seed ball are some of the alternative reforestation or land rehabilitation procedures for isolated areas (37). The seed ball technique is an effective and cost-efficient method for reforestation and land restoration but scaling it to large areas presents several challenges. Measuring the long-term success of seed ball projects requires systematic tracking of germination and survival rates. Traditional clay coatings may not be effective in all conditions. Innovations in biodegradable polymers or water-retaining gels could improve seed survival but increase costs (38).

The seed ball structures which should be employed are cuboidal rather than spherical to enhance the spread of trees and ecosystems restoration (Fig. 3). For example, *Albizia lebbeck* seedlings vigour and germination increases by 24 % and 134 % respectively through application of TNAU formulation (39). Further, dried seed cubes (Fig. 4) are also used for surface sowing in urban, rural and forest fallow areas, which promotes successful tree establishment with moisture from rainfall or irrigation. Effectively shielding the seeds from diverse stresses and supplying the requisite nutrients and growth hormones, the seed balls enhance the germination potential considerably for subabul (40). The seed ball with subabul seeds were tested at three different locations viz., roadside, forest area and in river side under both irrigated and non irrigated conditions. The results showed that vigourous seedlings were produced in treated seeds than the control under stress conditions. This might be due to the seed ball which provided additional nutrients and growth promoting factors for the establishment of plants under stress conditions (34). Comparative study of treated seed balls in arid and semi arid regions showed that increased germination was found in degraded land by 40 % than the direct seeding and the seed survival rates got improved under clay-based seed balls due to the more retention of moisture (34). One of the fascinating

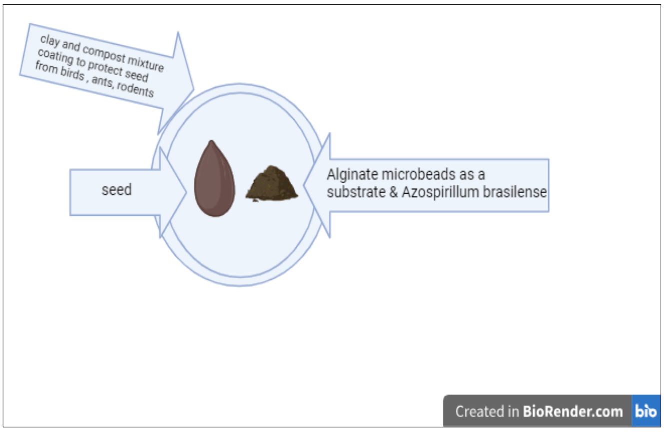

Fig. 3. Clay seed ball containing seed.

Fig. 4. Seed cube amenable for roof vegetable gardening.

methods of restoration of sea-grass beds is seed ball burial. The seeds are lodged in a moistened mud pellet and the unit becomes transplant buried sediment. An analysis of the data indicated those new plant establishments perform better in Qingdao than Tangshan and poor performance in large scale plantations restoration sites. This puts to light the effectiveness of seed ball method in sea-grass restoration (41).

Open-pit coal mining, heavy metal poisoning and soil erosion have negative impacts in natural resources which is evident in the developing countries like India. Thus, a new approach is developed as the use of seed biochar-bentonite balls with seeds of sorghum grass in the contaminated soil. It promotes plant physiological systems and minimizes both biotic and abiotic stresses (42). Thus, optimizing seed ball composition by adjusting clay, organic matter and microorganisms and adding slow-release fertilizers or biostimulants, could improve seed germination and seedling growth.

2.3. Challenges and opportunities

Several environmental constraints such as Infrequent precipitation, prolonged drought, seed predation and poor soil conditions can limit the effectiveness of seed balls in arid regions (30). Seed ball is a cost effective technology by utilizing readily available materials like sand, loam, wood ash and clay. By creating a microenvironment that captures moisture and provides nutrients, seed balls can enhance seedling establishment, especially in semi-arid areas (30).

3. Seed mat

For creating vegetation on land surfaces, dried compositions like sheets or rolled sheets are utilised. These mulch compositions, which are manufactured from dried plant material such as hay, straw, or wood fibre, are shaped into sheets with one or more layers and preferably contain fertiliser. Spraying a hydromulch containing viable seeds onto a layer of fibrous material, which is subsequently dried to form a sheet, is one method of creating a seed mat (43).

3.1. Fabrication of seed mat

The seed mat may be composed of two forms namely dried composition and suspension form. The dried compositions are in the form of sheets or rolled sheets or seed mat which is applicable for land surfaces like prepared soil and unprepared ground. These sheets may be precut to desired size and shape. The hydromulch or hydroseeding are applicable in landscaping and revegetation. This hydromulch contain appropriate amount of water which helps spraying for ease of manufacture (43). The nature of the carrier substrate can be of organic or inorganic origin or a mixture of both types of materials. Some of biodegradable materials used include jute, hemp, rock wool, wool fiber, cellulose, viscose, felt, textile fiber, synthetic fibers, Eucalyptus Jiffy®, Vitro-Plug TM and Oasis® Floral Foam (44). The paper-based seed tape with small seeds performed better and decomposed quickly which enriches the soil. Hydrogel based mats which are high in retaining moisture that promotes the higher seed germination in the arid regions (45). The adhesive utilized in the mentioned embodiments may be organic or inorganic based materials from starch or cellulose base. Also, there is no restriction in the adhesive material and it can take organic and inorganic forms. So, the seeds that are put into the carrier substrate may be almost any type of vegetable including the tomatoes, salad greens and herbs (44) (Fig. 5). Seed mat technology offers a promising solution for ecological restoration by facilitating vegetation establishment in degraded environments. Seed mats stabilized soil, reduced erosion caused by wind and water. This is particularly beneficial in post-wildfire landscapes, construction sites and coastal dunes (46). While initial production and material costs for seed mats may be higher, these expenses can be offset by the savings and increased yields. The precision placing of seeds in the mats reduced the seed rate by 60 % which also improved the yield upto 20 % in rapeseed cultivation (47).

Similarly, grass and legume have been used in vegetation restoration. Hence, according to the research findings it was clear that incorporating the annual herbs along with the perennial leguminous plants could rehabilitate the degraded sites (34, 35). This will promote good nitrogen regimes in the soil and the breaking down of plant litter comes with provision of nitrogenous mulch to the soil. For their part, grasses exhibit well-developed fibrous root systems that can effectively prevent soil erosion by securing the thin layer of loose soil on sloppy area, plus they are well adapted to unfavorable soils and form mystical covers on the surface when they dry (36). In addition, it is observed that the success of mechanical transplanting on mat type seedling depends upon the type of growing media used.

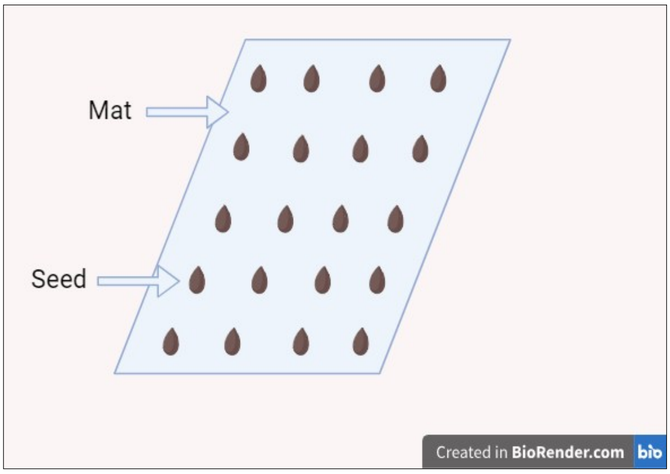

Fig. 5. Seed mat with seeds.

3.2. Seed mat - An innovative boom

When it comes to the rainy season, the plots covered with mat and regardless of the seed attachment did not show any sign of erosion. The assessment of vegetation also showed that the germination rate in the forest and grass-type mats was high during initial germination stage (51). The topsoil and straw-mats on the slopes are beneficial in vegetation growth which reduces evaporation losses, influence on temperature, and aesthetic satisfaction on the road environment. It also indicated improvements in the physicochemical characteristics of the soil and ecological values and therefore, economical and ecological benefits (52). It was expected that the water conservation would be achieved when using the rice straw seedbed with the sprinkler irrigation system (53). The modified mat nursery has excess benefits and has least costs on seeds which ranges between 85-90 %, fertilizer 90 % followed by labour which cost 34 % less compared to the rice wet nursery and water which cost 55 % less. Also, the seedlings from the newly developed rice mat nursery were comparatively younger and they performed better both in term of economic returns as well as growth and yield and they had less cost invested in them compared to the rest of the nursery grown plants. Hence it is one of the cheapest and most cost-effective form for farmers (54). On considering the above findings, advancements in seed mat technology could involve developing more biodegradable materials and incorporating targeted seed treatments or beneficial microbes to enhance their effectiveness and minimize environmental impact.

3.3. Challenges and opportunities

In seed mat choosing appropriate biodegradable materials that provide adequate moisture retention and protection for seeds is essential. Developing efficient methods for embedding seeds within mats while ensuring uniform distribution can be technically challenging (47). On the other hand, seed mats can stabilize soil, reducing erosion and promoting vegetation establishment in degraded areas. They allow for precise placement of seeds, leading to uniform crop stands and potentially higher yields (47).

4. Seed tape

Since the development of agrotechnology, planting methods are gradually shifting toward diversification and sophistication while the agricultural production is shifting toward sophisticated and intelligent production. Precision planting has been gradually adopted as a technique in planting since, it can reduce the seed costs and increase economic return (55). Precise seed placement at designated depths and spacing fosters optimal germination and growth, leading to reduced costs and minimized environmental impact. The emergence of integrated seed tape planters that combine land preparation, seed tape making, and sowing is essential for precision agriculture applications (55). Seed tape technology gained prominence in the United States and Europe before being introduced to Asian countries (55). Its initial application focused on the precision seeding of small seeds, offering advantages such as reduced seed consumption and improved economic efficiency. As precision agriculture continues to evolve, there is potential for increased adoption of seed tape technology globally, particularly as solutions to current challenges are developed and implement (55)."Seed tapes" are one among the diversified technology which is generally the rolls of biodegradable tissue paper (Fig. 6) that hold seeds in place while serving as a carrier. To guarantee that every seed is planted at an even interval, in a shallow trench the unrolled seed tape is covered with soil (56).

In seed tape, the seeds are sandwiched between two paper tapes or a vinyl tape that dissolves in water and the tapes installed on the rice fields. Paper tape works better than vinyl tape when it comes to direct rice seeding in paddy fields. Two machines are used for direct rice planting using the seed tape. The first machine encloses seeds between tape. The second equipment is a tape seeder, which is used to apply seed tape on paddy fields (57). Seeds and fertilizers are loaded together into a tape carrier constructed from suitable material, enabling the use of a single planter for multiple crop sowings (1). There is also a probability of increasing rice output by almost 8 % utilizing seed tape technology in collaboration with the direct seeded method and reducing cost by 25 %. It also shortens the growing season, reduces the number of workers per hectare, lowers the cost per kilogram of white rice produced by 11, 30 and 26 % respectively and 2.2 % increase in the benefit-cost index (58). There are some limitations that is seed tapes may not perform uniformly across different soil types and moisture conditions. Inconsistent soil contact or moisture levels can hinder seed germination and early growth. The effectiveness of seed tapes can vary among different crop species, particularly those with larger seeds or specific planting requirements, limiting the technology's applicability (59).

4.1. Fabrication of seed tape

The composition of seed tape is among the key elements influencing crop development. Originally, seed tapes were made using paper or regular plastic as the carrier (60). Two primary categories of biodegradable materials were utilized in the fabrication of seed tape: biodegradable synthetic cellulose material and biodegradable cellulose fiber material (61). The findings demonstrated that a tissue paper substance that yields maximum rates of seedling penetration and that the rates of seedling penetration in 2 ply format seed tapes were higher than those in 4 ply format seed tapes made of the same material (56). To ensure proper positioning and to evaluate the impact of using sticky rice glue as an adhesive on the growth of rice seedlings, seed tapes require a specific amount of glue coating (62).

4.2. Suitability of seed tape

To improve the accuracy and consistency of plot sowing, a precision planter utilizing seed tape has been created, with multiple variations (62). Carrot seeds were sown with seed tape and the outcome proved that the method may work (63). Agronomical characters like the speed of seedling emergence and the quality of the seedling growth were not greatly impacted by chemical glue seed, although sticky rice glue seed tape was more environmentally friendly (64). Since seeds, fertilizer, and herbicide may all be weaved into seed tape, how much fertiliser and pesticide were applied on the tape, as well as where they are placed in relation to the seeds, will determine how quickly seedlings will grow (65). The degradation of agricultural plastic film can be speed up by incorporating starch-based biodegradable plasticizers (1, 61).

4.3. Seed tape seeding

Originally, minor crops like flowers and vegetables were planted using the seed tape method. In the interim, scientists discovered that other crops like corn and rice could still be produced using the seed tape method. The emergence rate, time and percentage of corn seed did not significantly differ (60). Further, crop transfer is possible with seed tape planting method. Typically, the way we cultivate crops with seed tape technology is by putting the seeds into the tape and then placing the tape down using laying equipment that is part of crop direct seeding. Transplanting is a major method of production for several crops, including rapeseed and rice. The first step in using seed tape for transplanting is allowing the seed within to germinate. Once the seedlings reach a specific size, specialized transplanting machinery places the seed tape containing the seedlings in the groove (66). The seed tape method includes two steps: seeds are placed on a tape, twisted into a rope around a roller indoors and then laid in

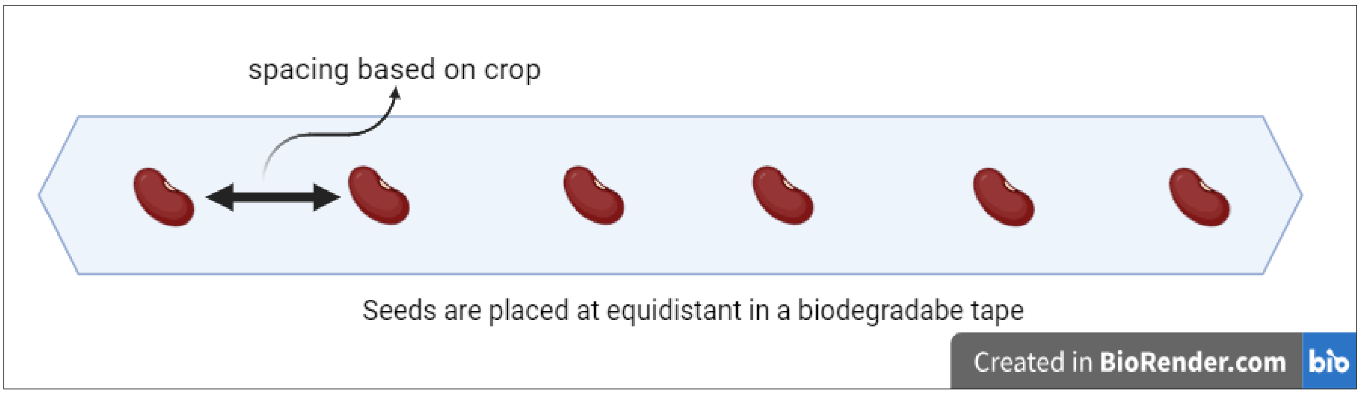

Fig. 6. Seed tape for precision vegetable seeding.

soil furrows in the field where they biodegrade in two to three days, facilitating germination (62). At present, agricultural landscape planting can make use of seed tape planting technique. Because of rice fields are often seeded by hand, their production is costly. If the seed tape seeding technique is used for paddy fields, the matching seeds can be rolled into the seed tape during seed tape production. Consequently, landscape planting in the field might be achieved by using seed tape mixed weaving of rapeseed and wheat seeds (67). The tiny and medium-sized mobile walk-behind planters will be popular with farmers who have little arable land. The benefits of rope planter include low cost, easy transportation, adaptation in and out of small fields and excellent flexibility (1). It is observed that seed tapes offer a cost-effective, uniform solution for precision planting. Future research is needed to optimize seed tape composition and explore integration with smart farming technologies like GPS-guided planters for improved precision and efficiency.

4.5. Challenges and opportunities

Developing high-speed, precise seed tape manufacturing equipment is necessary to meet agricultural demands is a major challenge in seed tape technology (55). Ensuring that the tape materials are durable enough to protect seeds during handling and planting, yet biodegradable in the field, is also a key concern. While, seed tapes simplify the sowing process, reducing labor costs and time. By maintaining optimal spacing and depth, seed tapes can improve germination rates and crop uniformity is the major advantage for this seed delivery system (59).

5. Seed capsules

In the pharmaceutical industry, a type of unit dose form is a capsule. It is composed of tiny, cylinder-shaped parts filled with a liquid or powder that are either soft or hard gelatin. Pharmaceutical capsules are a potential extension of seed coatings, allowing seeds and other beneficial components (or plant protectant chemicals) to be placed inside and planted as a single unit (68). This kind of seed encapsulation technique may combine the benefits of pelleting with film coating, minimising worker interaction with agricultural chemicals and delivering exact uniformity with less friction, allow for the use of mechanical planters and provide the necessary separation between protectant chemicals and seeds, thus reducing potential phyto-toxicity (66). Pharmaceutical-inspired nano-encapsulated pesticides, at concentrations ranging from 0.1 % to 0.5 %, provide controlled, targeted release, reducing environmental impact and improving pest control (59).

There are several kinds of capsules with diverse materials for their shells. Formulators should consider including the shell's reactivity, material composition and ability to withstand oxygen and water before selecting a capsule type. Hard gelatin and hard hydroxyl propyl methylcellulose, often known as hypromellose capsules are the two most common types of dry-filled capsules (69). Various substances can be used to make capsules, such as plant-based hydroxyl propyl methyl cellulose (HPMC) or gelatin, a collagen-based substance derived from animal bones or hide. Among the various types of capsules, the starch capsule proves to be an effective coating material for paddy seeds, facilitating their individual placement for use in the System of Rice Intensification (Fig. 7) direct seeding method (70). Further, plant growth and yield have been observed to be enhanced in a varietys of corps by gelatin, protein hydrolysates and other amino acid-based products, which have also been shown to behave as effective plant bio -stimulants (71). The breakdown of the dosage form is a crucial requirement for effective release of input materials and dissolution. Hard gelatin capsules have a specified maximum disintegration time of 15 min (72). Gelatin was observed to dissolve solely at temperatures exceeding 37°C, whereas starch capsules exhibited superior solubility at lower temperatures, aligning with the soil temperature under natural environmental conditions (70). Seeds from native species that grow in the same climate must be chosen for placing in capsule. Thus, the likelihood of germination is increased by this method. The size of the seed used for capsulation determines the size of the capsule to use. More appropriate species for this preparation include cereals like rice (70), legumes and vegetable species like tomatoes, brinjal and cucurbits (71).

Fig. 7. Smart input delivery through seed capsule.

5.1. Development of seed capsule

Depending on the size of the seed, capsules can offer ample empty space to accommodate larger quantities and/or various kinds of plant-beneficial substances. Regulatory agencies such as the Environmental Protection Agency (EPA, 2020) and the Food and Drug Administration (FDA, 2018) assess the toxicity of substances used in seed coatings or capsules. Gelatin alone has been demonstrated to act as a biostimulant (71) and supplementing it with other agricultural chemicals could potentially yield additional benefits without the worry of material wastage. Consequently, encapsulating seeds in gelatin capsules may offer distinct advantages not found in other approaches to seed enhancement (66). The seeds of cucumber with gelatin capsule achieved 40 % more leaf area than the control seeds and the yield of the plant recorded 28 % higher in gelatin encapsulated seeds than the control seeds (73). The improved growth and increased abiotic stress tolerance of gelatin seed capsules for cucumbers may be attributed in part to the increased expression of genes related to nitrogen transporter, amino acid transporter and the xenobiotic detoxification system. These genes may also be subject to transcriptional regulation through the two transcription factors (73). Pharmaceutical technology should be embraced for the industrial encapsulation of paddy seeds within starch capsules, aiming to automate the planting process of coated paddy seeds with conventional planters. Consequently, this will alleviate the labour burden experienced by farmers when adopting the SRI, leading to enhanced paddy yield and productivity (70). The study conducted said that the gelatine capsules filled with tomato seeds have performed well than the control which has more seedling emergence of 100 % and the plant height were also higher (16 %) compared to the control. The root development had also increased within 3 weeks whereas control plants took 12 weeks for the normal root development in tomato (74). From the above considerations, seed capsules effectively reduce agrochemical exposure and ensure precise input delivery. Further, it is necessary to explore increasing production scalability and integrating biostimulants, beneficial microbes, or slow-release fertilizers to improve their effectiveness in crop production.

6. Drone seeding

Drone seeding, also known as drone sowing, involves a drone with a container holding seeds and a mechanism for releasing them, providing control and guidance for seed dispersal (75). Unmanned Aerial Vehicle (UAV), an aircraft that operates without a human pilot is used for seeding in agricultural fields which employs wireless sensor networks to ensure minimal delays in information processing (76). Seed sowing is controlled manually and drones are equipped to detect and navigate around obstacles using IR sensors. They continuously scan for additional obstacles. However, the factors like wind strength and direction pose challenges to their operation (76).

Farming drones carrying sensitive technologies such as sensors and imaging are changing the face of farming with increased output, efficiency and productivity. Specific uses being crop inspection, application of pesticides, generating field plans, crop coating, planting, livestock inspection, watering and mechanical crop reaping (77).Using drones in agriculture significantly decreases the need for manual labour while substantially enhancing productivity. Advanced drones aid farmers in estimating crop yields, while technological advancements in drone technology enable soil fertility testing, delivering accurate and efficient results (78). The utilization of a quadcopter-type drone yielded more promising results in terms of accuracy compared to offline processing (79).

6.1. Drone for forest seeding

Drones are more efficient than manned aircraft for carrying out operations such as the restoration of forests at reasonable costs, especially in the difficult terrains. Seed enhancement technology has the possibilities of automatic forest rehabilitation by seed coat and seed pelleting (2). The true potential of drone seeding lies in its capacity to precisely deliver seeds to locations where recruitment is most likely to occur, thereby reducing seeding rates and optimizing success (80). This precision can be achieved by depositing seeds in specific areas, such as particular microhabitats, where the chances are enhanced by improving microclimatic conditions or fostering positive biotic interactions. Achieving this requires detailed mapping of habitat and microhabitat suitability at a submeter scale, a task made possible by current remote sensing technologies (80, 81). Unmanned Aerial Vehicles (UAVs) raise public awareness, contributing to the promotion of sustainable concepts and decisions in restoration initiatives. Diverse forest ecosystems play a crucial role in carbon sequestration within both biomass and soil, serving as a means of mitigation and adaptation to climate change, while also offering a multitude of ecosystem services (82).

Drone Seed, the company that was founded in 2019, stating about the seed bomb that does not let animals eat seeds and, therefore, raises the efficiency of planting trees by planting different seeds in one bomb. Aerial seeding, the action of placing seeds through a drone, an airplane, or a helicopter, is applied to refrain from the growth of invasive plants and to prevent erosion. This method was introduced in almost eight decades with the vision of restoring ecosystem functions rather than establishing ecological resilience (83). Drone seeding technologies (Fig. 8) offer several advantages, including precise sowing, minimal environmental impact and the ability to sow in challenging terrain, lower costs compared to conventional methods and increased seeding speed per hectare (80). Drone seeding technologies has been followed in countries like United States, India, China, Canada, Australia, Brazil for large scale precision farming of crops like paddy, wheat, barely, sorghum, mustard and for pulses (77).

Fig. 8. Quick seeding by drone seed spreader.

Drone seeding can expedite forest regeneration, especially in areas affected by wildfires or deforestation. By accelerating the establishment of vegetation, drones contribute to carbon sequestration efforts and enhance the resilience of ecosystems to climate change. Drones, primarily powered by electricity, generally produce lower carbon emissions compared to traditional machinery like tractors and planes (82). This reduction in emissions contributes to a smaller carbon footprint in agricultural and reforestation activities (82). However, practical implementation of drone seeding faces challenges such as regulatory compliance, limited payload capacity, short battery life, seed size variations affecting distribution, and the need for precise flight planning to navigate obstacles and complex field layouts (83). While traditional seeding methods may offer lower per-hectare costs, drone seeding provides benefits in efficiency, precision and soil health. The choice between methods should consider factors like field size, terrain complexity and available resources. As drone technology advances and becomes more cost-effective, it is expected to play an increasingly significant role in modern agriculture (77, 78).

Combining the advantages of different input delivery systems, such as seed balls, seed mats, seed tapes, and seed capsules, could lead to the development of more comprehensive and efficient solutions for sustainable agriculture. Integrating these technologies with precision farming techniques and smart farming tools may enable the creation of tailored input delivery systems that cater to specific crop and environmental needs.

6.2. Challenges and opportunities

Drone seeding requires high initial investment for drone, software and maintenance. Most drones can carry only a few kilograms of seed per flight, making large-scale seeding time-consuming (76). Wind and weather conditions can affect seed dispersion. Not all crops were suited for drone seeding. Despite of these many challenges, it is having opportunities like Drones enable precise seed placement, reducing seed wastage and optimizing resources. It reduces dependency on manual labor, especially in aging farming populations. Advancements in battery life, AI automation, and seed delivery mechanisms will enhance its scalability and efficiency in the coming years (77).

Conclusion and Future perspectives

Sowing seeds has become challenging due to a labor shortage, necessitating innovative methods to enable mechanized sowing. Techniques like seed pelleting, seed balls, seed capsules, seed tapes and seed mats offer precision planting and ease of use. Advancements in sowing technology have revolutionized modern agriculture by enhancing efficiency, precision and sustainability. Digital innovations are ensuring seed quality, traceability and authenticity through the block chain system. The modern seed delivery system is undergoing a technological revolution with drone seeding, AI-driven machines, space-based monitoring, biodegradable seed coatings and climate -resilient genetics. These advancements will help address food security, reforestation, and ecosystem restoration on a global scale. Seed pelleting enhances seed size and uniformity, improving germination rates. Seed balls ensure easy dispersal with nutrient-rich coatings, making them suitable for dryland farming. Seed capsules safeguard seeds from harsh conditions, enabling controlled release. Seed tapes ensure precise spacing, minimizing the need for thinning. Seed mats promote uniform planting and better crop management. Drone seeding technology also allows efficient sowing over large areas with minimal labor, making these input delivery systems highly effective. Mechanized sowing reduces labor reliance and lowers operational costs. Such innovations drive sustainable and efficient global agriculture. Development of Smart seeds viz., coated or genetically enhanced seeds that improve resilience to environmental stressors. Integration of these modern seed delivery systems with IoT and AI tool can improve the using real time data for adaptive sowing strategies, optimizing seed rates, depths and moisture conditions. Smart seed delivery systems will enhance affordability and accessibility of advanced sowing technologies for small-scale farmers.

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Authors' contributions

DG made substantial contributions to the conception and design. KR was involved in drafting the manuscript or critically revising it for important intellectual content. RU gave final approval for the version to be published. TA assisted in collecting the data and RK contributed to editing and reviewing. All authors read and approved of the final manuscript.

Compliance with ethical standards

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