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Cotton seed management: traditional and emerging treatment approaches for enhanced productivity

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Abstract

Cotton, a crucial commercial fibre crop, depends heavily on seed-associated characteristics like germination rate, vigour, and resistance to post-harvest deterioration for both production and lint quality. Serious cellular damage during post-harvest processes such as delinting, prolonged seedling emergence periods, decreased viability, increased susceptibility to infections, and lipid peroxidation during storage pose serious problems to seed quality. The performance of seeds and total crop productivity are adversely affected by these problems. Traditional methods of seed improvement, like physical scarification and seed priming, have demonstrated promise in raising cotton seed vigour and germination rates. Furthermore, modern approaches including plasma therapies, magnetic water treatments, and nanotechnology-based treatments have shown promise in improving seed quality and reducing environmental stresses. By offering sustainable substitutes for conventional approaches, these cutting-edge procedures lessen the need for fungicides and other agrochemicals that pollute the environment. This review explores various conventional and emerging strategies to address the detrimental factors impacting cotton seed quality. It emphasizes the importance of integrating classical and advanced approaches to enhance germination, ensure robust crop establishment, and achieve higher yields. In addition to promoting sustainable cotton production, this kind of integration helps preserve the ecosystem and create resilient farming methods.

Keywords Cotton, Seed vigour, Physical scarification, Seed priming, Plasma treatment, Magnetic water treatments, Nanotechnology-based treatments

Background

Cotton, the economically significant global crop, has been mainly cultivated for its natural fibre and oilseed. Cotton seeds are remarkable in that they have economic value in both maternal tissues (such as the seed coat) and filial tissues (such as the embryo and endosperm). The global cotton lint production is expected to reach 28.1 Mt by 2032 as per The Organisation for Economic Co-operation and Development-Food and Agriculture Organization (OECD-FAO) agricultural outlook report. India is the third largest exporter of textiles worldwide, currently valuing $223 billion in the market (Noreen et al. 2020). Seed vigour is one of the physiological parameters that

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are influenced by environmental and genetic factors. Seeds with high vigour can grow under diverse environmental conditions with rapid and better crop establishment. The most crucial step in cotton production is the stand establishment of cotton seedlings (Finch-Savage et al. 2016). Cotton seeds are reported to be "more sensitive to conditions of germination than the seed of most field crops" (Toole et al. 1924). Cotton seed germination poses a significant problem for farmers where developing countries have achieved a germination rate of 40%–45% and developed countries have achieved a germination rate of 95%. Cotton seedlings with an early emergence exhibited higher survival and yield compared with late emerging crops. In addition, early seedling vigour decreases the crop's susceptibility to weeds, and insects, and but increases the crop's growth, resource acquisition, and canopy light interception (Liu et al. 2015).

Post-harvest processing of cotton involves two processes, ginning and delinting. Cotton ginning is a process of removing the lint from the seed without affecting the fibre quality. Cotton ginning causes mechanical damage to the seed coat and the extent of damage depends on the ginning rate, and moisture content of the seed (Byler 2006). After ginning, seeds are subjected to a delinting process which removes the lint/fuzz that are remnants on the seed coat and it is a crop-specific seed management for cotton crops alone. There are three types of delinting: mechanical, acid delinting, and gas delinting. The mechanical method usually has 1%—2% of residual lint on the seed after treatment, whereas acid delinting completely removes all the lint. However, mechanical delinting causes seed coat damage, initiates embryo necrosis, and affects both seed viability and shelf-life. Such damaged seeds are more prone to soil-borne microbes as they can easily enter into the seed coat through cuts and fractures. Acid delinting with sulfuric acid rapidly burns the fuzz, and disinfects the seed. Though acid delinting is an effective method, it has drawbacks such as seed damage, disposal of spent acid, disposal of rinse water, safety issues, damage of equipment exposed to acid, and prone to environmental stresses. The third type is gas delinting, which uses compressed anhydrous hydrochloric acid (AHCL) to remove the lint. In this case, if the seed is already damaged or cracked, the gas can easily kill the seed, also this process can only be done in an environment where the humidity is low (Balešević-Tubić et al. 2005; Kalbande et al. 2009).

Post-processing, the cotton seeds are stored in cold and dry conditions to preserve the quality of the seed (Finch-Savage et al. 2016). Maintenance of seed quality during storage depends upon the genetic characteristic of the seed, initial seed quality during storage, moisture content, and harvesting steps of picking and processing of the seeds (Bradford et al. 2016; Delouche et al. 1973). Cotton seeds contain about 20% oil content, and are more prone to deterioration due to lipid peroxidation of the high fatty acid content (Basra et al. 2000; Eevera & Pazhanichamy 2013). As this process causes cellular damage and loss of seed viability, deteriorated seeds will result in retarded seedling emergence and are prone to the transmission of pathogens (Mohammadi et al. 2011; Zhang et al. 2021). To enhance the cotton field establishment, seed quality enhancement treatment can play an indispensable role in improving the seed quality and early seedling vigour. This review will discuss the seed quality enhancement treatments that are suitable for cotton seeds such as physical methods, seed coating, seed priming, and other advanced methods (Fig. 1).

Physical seed treatment methods

Although most modern agriculture uses chemical compounds, using physical factors could be an excellent substitute to increase agricultural production yield while enhancing storage and crop protection. Physical treatment methods have various advantages such as: (i) reduced usage of chemical fertilizers prevents environmental hazards, (ii) can be used for disinfecting seeds pre-sowing and during storage (Aladjadjiyan 2012; Araújo et al. 2016; Monga et al. 2018). Commonly used physical treatment methods for cotton seeds to enhance growth and seed vigour are hot water treatment, scarification, and radiation methods. Figure 2 depicts the types of physical treatments used for cotton seeds.

Hot water treatment

Few domestic and most wild varieties of cotton produce seeds with hard seed coats which restrict the water uptake and delay the germination. However, modern varieties of cotton do not produce hard seeds as that trait is eliminated through selection and breeding. The microscopic structure study revealed that the chalazal area in the hard coat seeds is highly compact compared with soft coat seeds. A hard seed is defined as one that can resists water uptake for 24 h at 27 °C. Among the cotton varieties cultivated in India, one example of a hard seed coat variety is 16B7-2H and a soft seed coat variety is DES 8948. Additionally, a hard seed line of cotton is derived from breeding between the upland cotton and 'Glandless 38–6' variety, while the Brazilian cotton cultivars IAC-19 and IAC-20 also have hard seed coats (Christiansen 1960; Christiansen et al. 1959; Lee 1975; Usberti et al. 2006). These hard seeds can be treated with hot water to increase water absorption and enhance the germination rate. Hot water treatment is one of the traditional treatment methods, which uses a temperature hot enough to kill various pathogens but not hot enough to kill or

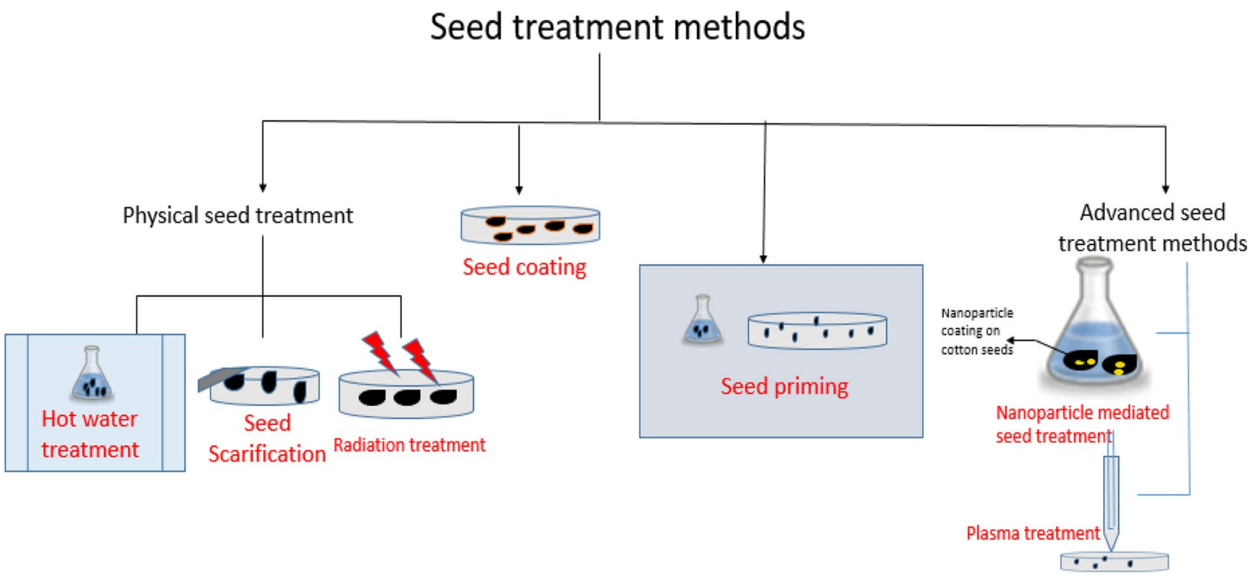

Fig. 1 Seed quality enhancement treatment methods for cotton seeds

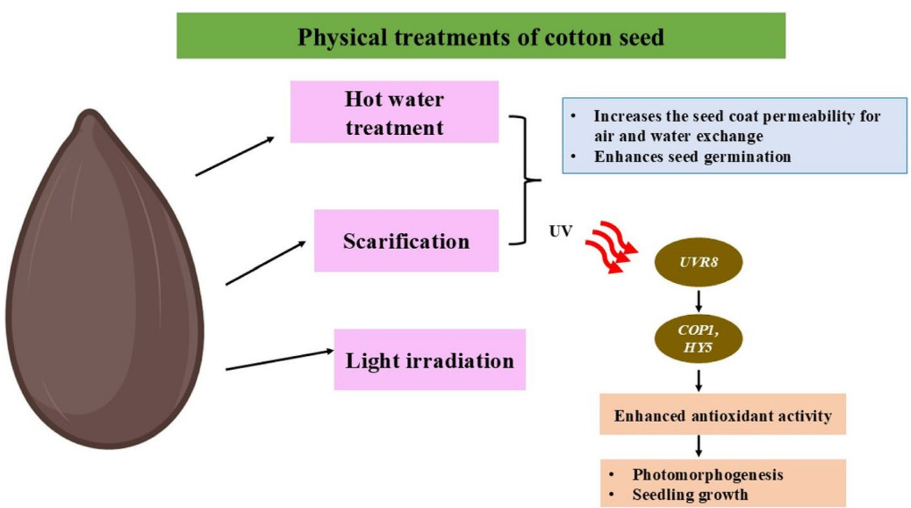

Fig. 2 Physical seed treatment methods for enhancing germination, growth, and vigor in cotton seeds

damage the seed (Bennett et al. 2010; Walhood 1956). First, seeds are wrapped in a cotton bag and pre-warmed for 10 min at 37 °C. Seeds are further heated in hot water for 20–25 min at a temperature based on the crop type, cooled down for 5 min, and finally dried. The precision of time and temperature is critical as the seed embryo might die in hot water or return to partial dormancy in cold water. Hot water treatment of cotton seeds for 10 s at 96 °C increased the seed germination rates for the varieties Maraş-92 and Sayar-314 by 27% and 71%, respectively, and the treatment for 60 s increased the seed germination rate of Stoneville-468 by 7% (Bolek et al. 2013). Hot water treatment also enhanced the seedling emergence compared with the control. Similarly, Abd-el-rehim et al. (1969) reported that hot water treatment at 60 °C for 10 min increased the seed germination and growth of the cotton cultivars Karnak and Ashmouni. Hot water treatment enhances seed germination by increasing the seed coat permeability for water and air exchange (Bolek et al. 2013; Sharma et al. 2008). In the study reported by Khan et al. (2019), hot water treatment of cotton seeds at 70 °C for 10 min increased the germination percentage by 75%. Thus hot water treatment of cotton seeds with a hard seed coat enhances the seed germination which can aid in increasing cotton production.

Scarification

A viable seed that is unable to germinate in an environment offering favourable conditions is known as seed dormancy. Seed dormancy can be of two types: physical dormancy and embryo dormancy. Cotton seeds that are stored in extremely dry conditions or maintained at a moisture content below 6% have a high chance of having a hard seed coat. Such a hard seed coat of cotton results in physical dormancy, and the embryos can undergo rapid germination when the hard seed coat is removed. However, mature cotton seeds benefit from moderate dormancy as it prevents the seed from sprouting before harvest. To overcome physical dormancy, scarification can be used as a pre-treatment for cotton seeds to enhance seed germination. Scarification makes the seed coat permeable for air and water to enter the seed and stimulate germination without damaging the seed embryo. Heat, chemical, and mechanical scarification are commonly used for seed treatment. Mechanical scarification makes the seed coat permeable by perforating the seed coat via nicking, filing, and cracking, using tools such as hammer, sandpaper, or other equipment (Baskin et al. 2004; Simpson et al. 1940). Acid scarification of seeds has been shown to be an effective method for breaking the dormancy of hard-seeded crops, including Indian grass, legumes, asparagus, and cotton. Research has shown that pre-sowing heat treatment of cotton seeds at elevated temperatures is an efficient and practical method to boost crop germination (Khan et al. 1973; McDonald et al. 1983). Table 1 describes the methods of scarification on cotton seeds and its effect on germination and seed vigour.

Radiation

Several studies have shown that exposure to radiation on seeds or plants has stimulated plant growth at various developmental stages and increased the growth, yield, and flowering of the plant (Sax 1963). Electromagnetic radiation such as gamma ray, X-ray (Babina et al. 2020), microwave (Talei et al. 2018), ultraviolet (UV) radiation (Sadeghianfar et al. 2019), ultrasonic radiation (Liu et al. 2016), electron beam (Waje et al. 2009), proton beam (Kim et al. 2012), and ion beam (Ling et al. 2013) have been used for pre-sowing seed treatments. Light irradiation for pre-treating seeds has also been studied (Hasan et al. 2020). Through light irradiation, seeds absorb light energy via photoreceptors and convert it to chemical energy which further activates biochemical and physiological processes that are required for germination (Hernandez et al. 2010). It was reported that UV irradiation activated the antioxidant activity which increased the seedling growth compared with non-irradiated seeds (Dana et al. 2020). Table 2 describes the effects of radiation treatment of cotton seeds and its effect on growth, germination, and yield.

Seed coating

Seed coating with exogenous materials such as chemicals, biological agents like plant growth hormones, and microbials enhances the seedling germination, growth, and protection from pathogens. The earliest report on seed coating was the first seed patent on improving the cotton seed with a coating of gypsum and glutinous compound which was filed in 1868. In recent decades, seed coating technology has evolved rapidly as a cost-effective method for seed enhancement, particularly for horticultural and agronomic seeds. Seed coating technologies aid in the mechanical sowing of seeds to achieve uniform spacing of crops and it also gives protection to the crops by acting as a carrier of protective agent. Seed coating technology is mainly of three types, namely film coating, encrusting, and pelleting. The commonly used seed coating types of equipment are rotary pan, dry coating, and pelleting pan. Those kinds of equipment can be used

Table 1 Scarification treatment of cotton seeds

S. No	Method of scarification	Result	Reference
1	Pre-sowing high temperature stress (50–70 °C, 24–48 h)	• Heat treatment of cotton seed at 50–70 °C stimulated the seedling emergence and growth of cotton plants • Untreated seeds have a germination rate of 21% whereas treated seeds have a germination rate of 40%–50% after 7 days of planting	(Khan et al. 1973)
2	Pre-sowing high temperature (60 °C, 10 min)	• Heat treatment of cotton seed at 60 °C increased the seedling emergence	(Basra et al. 2000)
3	Pre-sowing heat stress (60 °C, 8 h)	• Pre-sowing heat treatment of cotton seeds increased the seed vigour to 86% at 60 °C which is similar to the untreated seeds • Heat treatment at 70 °C increased the germination rate to 80% almost near to that of control (86%) • Pre-sowing heat stress at 70 °C also decreased the fatty acid content of the treated seed compared with control which indicates the enhanced oil quality	(Basra et al. 2004)

Table 2 Radiation treatment of cotton seeds and its effect on growth, germination, and yield

S. No	Radiation treatment	Result	Reference
1	X-Radiation of soaked cotton seeds	• X-radiation dose of 500 r gave the highest growth stimulation and yield of cotton seeds • The untreated cotton seeds had a yield of 12.89 g/plant whereas the treated cotton seeds had a yield of 18.77 g/plant	(Mukhanova et al. 1968)
2	Irradiation of seeds by helium–neon laser	• Cotton seeds irradiated by He–Ne laser stimulated the growth rate of stem and flowering systems • Seeds that were irradiated 8 times had the highest effect compared with the control during the three-year experiment	(Delibaltova et al. 2006)
3	Combined UV-A, B, and C radiation	• Combined UV-A, B, and C irradiation for 8 min on cotton seeds increased the germination rate compared with non-irradiated seeds • UV irradiation activated stress related genes *DEH* and *VPP* (ROS scavengers)	(Dana et al. 2020)
4	Ultraviolet (UV) radiation	• Pre-sowing UV treatment of cotton seeds increased the germination and yield by 20% and 35%–40%, respectively • The untreated cotton seeds had a germination rate of 72% whereas the UV treated cotton seeds had a germination rate of 92% • It also increased the export of products from the treated plants as it is grown chemical-free	(Anarbaev et al. 2021)
5	Gamma treatment of seeds	• Ganja-160, Ganja-182 cultivar seeds treated with a radiation dosage of 400 Gy resulted in the maximum number of bolls • The amount of protein, proline, antioxidant enzymes, and melondialdehyde (MDA) depends on the radiation dose	(Jafarov et al. 2022)
6	Light treatment with light emitting diode (LED)	• Light treatment of cotton seed increased the germination and yield by 37% and 74%, respectively, in field trials • Among various light sources, blue LED is the best, followed by diode laser, UV-B, and UV-C • With blue LED light treatment, the four varieties of cotton (control) have a germination rate of 30% whereas the treated seeds have an increased germination rate of 80% compared with the control	(Atta et al. 2023)

for performing various types of coating such as dry powder, film coating, seed dressing, pelleting, and encrusting (Hakeem et al. 2019; Pedrini et al. 2017; Taylor et al. 1998; Zhang et al. 2022). Seed pelleting is the process of coating the seeds with a binder or filler to increase the size and shape of the seed. This technique is particularly used for small sized seeds for better handling and sowing (Sharma et al. 2008; Singh et al. 2015). Seed encrusting is the process of coating in which the size of the seed is increased by 8%–500% without affecting the shape of the seed. The encrusting process consists of two phases such as before the coating phase and after the coating phase. During the before-coating phase, the initial weight of the seed, binder, and powder is measured. Small amounts of powder and binder are added during the coating phase. Seed dressing involves the application of less chemical coating agents in the form of powder or slurry. Following the coating procedure, the seeds are allowed to dry and undergo a quality check to make sure they fulfill the necessary requirements before being sowed (Afzal et al. 2020; Pedrini et al. 2018).

Through seed coating, active ingredients or stimulators can be incorporated as a kind of seed protectant or improve seed germination. Incorporating pesticides in the coating can decrease the number of pesticides used in the fields. Similarly, nutrients can also be applied as a coating agent to minimize the application of nutrients in the fields. The recent trend in the market is to apply pesticides and nutrients directly onto the seeds as coating agents in order to avoid the usage of pesticides/nutrients in the field thereby preventing environmental pollution (Pedrini et al. 2018; Weissmann et al. 2023). To ensure the success of the seed coating, the coating material must be coated on the seeds with minimum damage during the whole process and the seeds must be spun at uniform speed in the coating equipment. Factors affecting the coating process are porosity, particle size, water retention capacity, speed of the rotator, and properties of the binder (Afzal et al. 2020). Table 3 describes the types of seed coating on cotton seeds and its effect on germination and seed vigour.

Types of coating

Polymer coating

Polymer coating of seeds increases the binding affinity of the chemical to the seed and the treated seeds will be dust-free. Functionalized polymer coating can be used for even application of chemicals on the seed, increase the efficiency of chemicals used, and reduce environmental pollution. The polymer coating is very

Table 3 Cotton seed coating treatments

S. No	Types of seed coating	Result	Reference
1	Imidacloprid seed treatment	• Imidacloprid treatment of cotton seeds enhanced the seedling vigour and yield compared with the untreated seeds	(Patil et al. 2003)
2	Natural amino polysaccharide in seed film coating	• Cotton seeds coated with amino polysaccharide increased seed germination, plant growth, and yield • Untreated cotton seeds had a germination rate of 85% and treated cotton seeds had a germination rate of 88%	(Zeng et al. 2011)
3	Novel environmentally friendly cotton seed coating agent	• Seed coating made up of natural polysaccharides and other compounds increased the yield by 9%, decreased the cost by 35%, and were safer compared with conventional coating agents • The untreated cotton seeds had a germination rate of 80% and the treated cotton seeds had a germination rate of 96% • Among various concentrations, 1% of natural polysaccharide gave the highest germination rate of 97%	(Zeng et al. 2011)
4	Seed coating agent from combination of plant growth promoting rhizobacteria	• Biological seed coating agents increased the germination rate by 11%, plant height by 14%, fresh weight by 19%, dry weight by 25%, and leaf area by 47% compared with chemical seed coating agents • The chemical seed coating agent had a germination rate of 58% and the biological seed coating agent had an increased germination rate of 69%	(Wu et al. 2012)
5	Synthetic polymer coating and seed treatment chemicals	• Seeds coated with a synthetic polymer (polykote) and chemical (vitavax) increased the germination rate, vigour index, and electrical conductivity • During 2 months of storage, the germination rate of untreated and treated seeds was 85% and 88%, respectively • After 10 months of storage, the germination rate of untreated and treated seeds was 61% and 72%, respectively	(Bharamaraj Badiger et al. 2014)
6	Microencapsulated *Bacillus subtilis* SL-13 seed coating	• Cotton seeds treated with encapsulated microbial seed coating (ESCA) increased the germination rate by 28% • MDA content of ESCA coated seedlings was decreased indicating reduced lipid peroxidation and increased seedling and root growth	Tu et al. 2016
7	Seed polymer coating with micronutrients	• Polymer seed coating with micronutrients and two foliar sprays during the flowering stage increased the yield of cotton by 16%, pigeon pea by 19%, chickpea by 16%, and groundnut by 13% compared with the control • The treated cotton seeds recorded higher germination rate (87%) and seed vigour index of 2 613 when compared with untreated seeds	(Vasudevan et al. 2016)
8	Nutrient based seed coating	• Seed coating formulation increased the plant growth, boll yield, seed yield, chlorophyll content, and branching pattern • Among the three dosages that were tested, 40 $g \cdot kg^{-1}$ showed the highest improvement on cotton • The untreated seeds had a germination rate of 79% and the treated seeds had a germination rate of 84% • The untreated plant gave a seed cotton yield of 1 188 $kg \cdot hm^{-2}$ and the treated plant gave a yield of 2 575 $kg \cdot hm^{-2}$	(Bhaskaran 2017)
9	Polymer seed coating, fungicide seed treatment	• Seeds treated with polymer and fungicide (thiram) increased the germination rate, seedling length, seedling vigour indices, and dry weight compared with the untreated seeds	(Mahantesh et al. 2017)

Table 3 (continued)

S. No	Types of seed coating	Result	Reference
10	Micronutrients and potassium humate	• Foliar application along with seed coating treatment gave the highest yield, seed index, boll weight, and number of open bolls. • Seeds coated with micronutrients and potassium humate gave the highest yield, fibre strength, and a significant increase in seed index, boll weight, and the number of open bolls	(El-Ashmouny et al. 2018)
11	Carboxin from seed coating formulation	• The untreated seeds had a germination rate of 84% and the treated seeds had a germination rate of 85% initially • After 6 months of storage, untreated seeds had a germination rate of 70% and treated seeds had a germination rate of 79% indicating that the coating increased the germination rate even after storage • Carboxin seed coating enhanced the seed vigour, germination rate, seedling growth, and the ability to resist low temperature climates	(Xiao et al. 2019)
12	Micronutrient seed treatment	• Nutrient seed dressing (100% NPK + Zn ethylene diamine tetra acetate (EDTA)) of cotton seeds increased the germination, plant height, root density, leaf area, and number of leaves compared with other treatments and controls • The control (100% NPK) had a germination rate of 95% and the cotton seeds with nutrient seed dressing (100% NPK + Zn EDTA) had a germination rate of 99%	(Kale et al. 2022)
13	Lentinan and fluopimomide	• Cotton seeds coated with lentinan and fluopimomide increased the seedling growth, germination rate, expression of plant defence genes but reduced the incidence of damping off disease • The control had a germination rate of 88% and the coated cotton seeds of three varieties (Lumian 28, 38, 338) had a germination rate of 86%, 93%, and 93%, respectively	(Sun et al. 2022)
14	Bio stimulant and Bio insecticidal	• Cotton seeds coated with *B. bassiana* increased the growth parameters such as the number of shoots, leaves, and apical buds, plant height, stem diameter, fresh and dried biomass, and total chlorophyll content compared with uncoated seeds • *B. bassiana* coating also significantly reduced the infestation caused by *Aphis gossypii* after 5 weeks compared with the control • After 144 h of coating treatment, the control seeds had a germination rate of 96% and the coated seeds had a germination rate of 100%	(Mantzoukas et al. 2023)

simple, it diffuses quickly and does not harm the seed during germination (Ekebafe et al. 2011). Cotton seeds treated with polymer and thiram as fungicides, increased the seedling length, vigour indices, germination rate, and dry weight compared with uncoated seeds (Bharamaraj Badiger et al. 2014). The film coating around the seed will act as a physical barrier which may limit the embryo's ability to absorb oxygen and reduce the leaching of inhibitors from the seed. High germination was observed in polymer coated seeds due to the increase in the rate of water uptake. The fine particles in the seed coating act as moisture attracting layer which increases the rate of water uptake of the seed (Mahantesh et al. 2017). Polymer coating gives protection against water stress and these hydrophilic polymers maintain elevated water potential in the seeds which enhances their germination. Cotton seeds coated with a synthetic polymer (polykote) and chemical (vitavax) increased the germination rate, vigour index, and electrical conductivity. Polymers have also been used as an effective carrier of biological control agents for cotton seeds, which can sustain protection for four months (Bharamaraj Badiger et al. 2014; Bhaskaran et al. 2017; Manonmani et al. 2019). Polymer-based film coating is the application of a thin layer of coating agent on the seed which does not alter its size, shape, or performance. This approach provides an accurate treatment and minimal dust is produced during the process, making it a refined version of slurry coating (Pedrini et al. 2017; Zaim et al. 2023).

Nutrient coating

Early plant growth depends heavily on nutrients, and the amount needed for coating varies according to the size of the seed (Ali et al. 2008). The macronutrients required for cotton growth are nitrogen, phosphorous, potassium, calcium, sulphur, and magnesium and the micronutrients are iron, zinc, boron, copper, and manganese (Ahmed et al. 2020a b). Micronutrients are essential for the major physiological processes of respiration and photosynthesis and hence their deficiency can affect the crop's yield (Clarkson et al. 1995). Micronutrients can be supplied to the plant either via soil, foliar application, or through seed coating. Though foliar application has been effective in increasing the yield, it can only be applied after stand establishment, and due to its high cost, it is not affordable to the farmers. In this case, the application of micronutrients through seed coating is a more economically viable option which requires less dosage of agent and effectively improves the seedling growth (Farooq et al. 2012). Polymer seed coating with micronutrients combining with foliar sprays during the flowering stage increased the yield of cotton by 16%, pigeon pea by 19%, chick pea by 16%, and groundnut by 13% compared with the control (Vasudevan et al. 2016). Nutrient coating of cotton seed made up of Murashige and Skoog medium, gelatin, carboxy methyl cellulose, bone meal, glycerol, pectin, or dicalcium phosphate along with synthetic polymer and pigment increased the plant growth, chlorophyll content, and seed yield (Bhaskaran et al. 2017). Cotton seeds coated with salts containing nitrogen, phosphorous, potash, and zinc ethylene diamine tetra acetate (Zn EDTA) increased seed germination, plant height, root density, leaf area, and the number of leaves compared with other treatments and controls (Kale et al. 2022). Cotton seeds coated with micronutrients and potassium humate exhibited the highest yield, fibre strength, and a significant increase in seed index, boll weight, and the number of open bolls (El-Ashmouny et al. 2018).

Microbial coating

Plant beneficial microbes help in increasing productivity, reducing the usage of chemical pesticides and fertilizers, reinstating soil fertility, and overcoming issues caused by biotic and abiotic stresses (Malusá et al. 2012). Excessive fertilization, over usage of pesticides, and soil tillage affect the natural soil microbes and their interaction with plants (Tsiafouli et al. 2015). Plant beneficial microbes can be applied in liquid form or as dry formulations in the field. However, large-scale application of microbial inoculants to crops, especially broad-acre crops, is not feasible as it requires a large number of inoculums per plant. An effective and cost-efficient way is to supply microbial inoculants to the plants by seed inoculation. The application of microbes directly to seeds helps to colonize the seedling roots and interact with invertebrate pests that feed on the plant (O'Callaghan 2016; Vosátka et al. 2012). Coating seeds with microbial species requires a binder (adhesive compound) and in some cases, it requires a filler (bulking agent), acting as a carrier. Cotton seeds coated with encapsulated microbial coating increased the germination rate, plant height, shoot length, fresh weight and dry weight of the plant. The increase in germination rate can be achieved by the enhanced release of bacteria from the coating to the cotton's rhizosphere (Philippot et al. 2013; Tu et al. 2016).

Protective coating

Protective coating agents such as fungicides and biological agents can be used to give protection against seedling associated diseases (Baniani et al. 2016; Bhattiprolu 2017). The release of unbound chemicals is a major drawback in seed treatment with pesticides and fungicides. Therefore, pesticides or fungicides should be applied as a protective coating to safeguard the seed until planting (Ahmed et al. 2020c). Fungicide seed coating may deal with soil-borne and ectophytic seed diseases or create a protective zone around the seed (Nuyttens et al. 2013). Carboxin, a succinate dehydrogenase inhibitor fungicide, coated on cotton seeds demonstrated enhanced seed vigour, germination rate, seedling growth, and the ability to resist low temperature stress compared with untreated seeds (Xiao et al. 2019). Apart from chemicals, naturally existing biological compounds can be used for seed coating. Cotton seeds coated with natural amino polysaccharides (APS) increased seed germination, nutrient uptake, plant vigour, plant growth, photosynthesis, and yield. APS is extracted from shrimp, and it acts as an anti-feedant by disrupting the chemoreceptors in the insect's mouth and inhibiting their ability to form complexes with sulfhydryl or amine groups on the receptors. APS also acts as a plant growth stimulator and induces an immune response in roots which destroys nematodes without killing the beneficial microbes (Zeng et al. 2011). Similarly, another novel environmentally friendly cotton seed coating agent made up of natural polysaccharides has been reported. The natural polysaccharide forms a protective semi permeable layer on the seed which maintains the humidity of the seed and enhances the seedling germination. It also maintains a high concentration of carbon dioxide inside the seed which reduces nutrient consumption, and this coating also has beneficial compounds that stimulate plant growth and yield (Zeng et al. 2011). Biological cotton seed coating made up of sodium carboxymethyl cellulose, polyvinyl alcohol, and sodium bentonite along with growth promoting rhizobacteria such as BCL-8 and Rs-5 increased the germination rate by 11.3%, plant height by 14.4%, fresh weight by 19.1%, dry weight by 25.7% and leaf area by 47.4% compared with chemical seed coating agent (Wu et al. 2012). Cotton seeds coated with natural polysaccharide and fluopimomide fungicide increased the cotton seedling growth, germination rate, expression of plant defence genes, but reduced the incidence of damping off disease (Sun et al. 2022). Lentinan regulates plant growth and induces the expression of plant defence genes. Both lentinan and fluopimomide act as biological pesticides by controlling the cotton damping-off disease and reducing the usage of chemical pesticides.

Notably, the emergence of resistance against pesticides and fungicides necessitates the search for alternative natural substances as seed priming agents to control drug-resistant pests and diseases. Natural substances such as chitosan, insect repellent essential oils, ozone, vinegar, and mustard powder have also been proposed as alternative agents to pesticides and fungicides (Moumni et al. 2023).

Seed priming

Seed priming is a treatment that allows restricted hydration of seeds to activate the metabolic processes that mimic the early germination phase but prevent the seed from undergoing germination (Heydecker et al. 1977). After planting, seeds require water to grow for some period of time, and reducing this period by seed priming improves the seedling's germination and uniform growth (Nirmala et al. 2008). Seedlings emerging from primed seeds grow faster and can grow in diverse climatic conditions (Matthews 1999). Seed priming induces stimuli-related biochemical changes in the seed such as activating enzymes, synthesizing growth promoting compounds, metabolizing germination inhibitors, and repairing cell damage (Chatterjee et al. 2018). Seed priming consists of three stages: (i) imbibition phase, in which

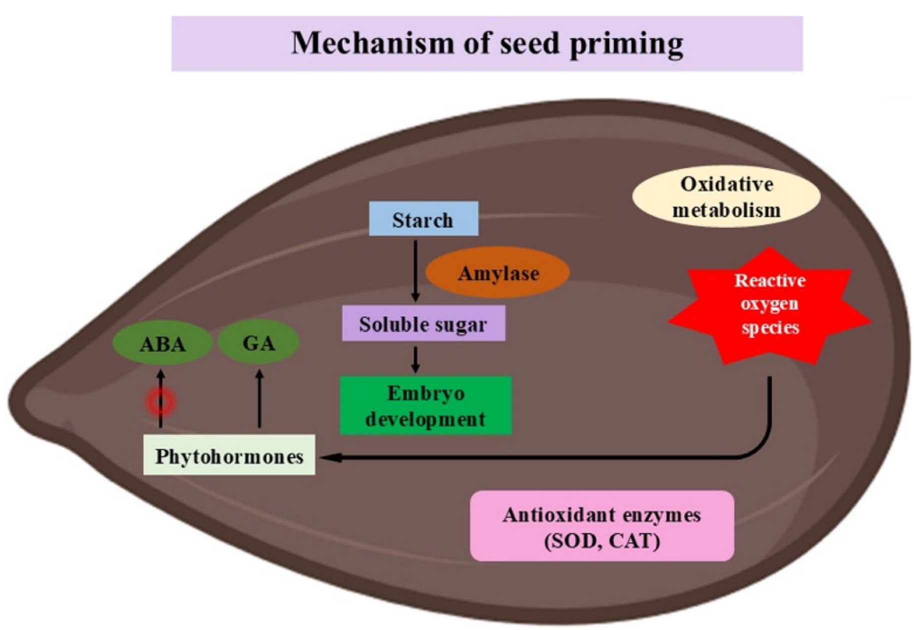

Fig. 3 Mechanism of seed priming in cotton seeds. SOD represents superoxide dismutase, CAT represents catalase

the seed increases its water uptake rate, (ii) activation phase, in which metabolic events happen such as synthesis of proteins, activation of enzymes, formation of mitochondria, and cell damage repair, (iii) germination phase, in which the water uptake is increased followed by the radical protrusion and the seed enters the growth elongation phase (Ibrahim 2016; Waqas et al. 2019). The different types of seed priming are osmopriming, hydropriming, halopriming, hormonal priming, biopriming, and organic priming.

Hydropriming is a simple, cost effective priming method that involves soaking of seeds in distilled water and osmopriming is the soaking of seeds in osmotic solutions (Bolek et al. 2013; Lin et al. 2006; Papastylianou et al. 2012). Hydropriming of cotton seeds activates the breakdown of metabolic reserves, increases the antioxidant activity of enzymes that protect the cell membrane from reactive oxygen species (ROS), and enhances seedling germination (Singh et al. 2018). Studies on the metabolic profiles of hydroprimed seeds revealed that the hydropriming of cotton seeds enhances lipid metabolism and activates the antioxidant enzymes to maintain the balance of ROS and minimize lipid peroxidation (Naguib 2019). Osmopriming of cotton seeds with mannitol for six hours increased the germination percentage due to the decrease in thermal time requirement (Papastylianou et al. 2012). Seed priming with phytohormones to induce seed metabolism is called hormonal priming. Cotton seeds primed with indole-3-acetic acid (IAA) increased seed germination by regulating endogenous phytohormones such as IAA, gibberellic acid (GA), and abscisic acid (ABA). In addition, IAA regulates the sucrose metabolism pathway and enhances seedling growth (Zhao et al. 2020). Priming of cotton seeds with brassinosteroid (BR) increased the seed germination by overcoming the ABA induced inhibition of germination under no stress as well as salt stress condition. BR also promotes lateral root initiation by overriding ABA mediated inhibition of lateral root via auxin independent pathway (Chakma et al. 2021). Cotton seeds primed with GA increase the endogenous GA content, inhibit the synthesis of ABA, and enhance germination under cold temperatures. During low temperatures, ROS increase, antioxidant enzymes such as superoxide dismutase get inhibited, and harmful compounds such as malondialdehyde (MDA) and hydrogen peroxide get produced which causes apoptosis/necrosis. Exogenous GA decreased the ABA synthesis by inhibiting*NCED6* expression in an ABI4-dependent manner and enhanced the superoxide dismutase activity which reduced the production of MDA and hydrogen peroxide (Xia et al. 2023). Halopriming involves soaking the seeds in inorganic salt solutions such as sodium chloride, potassium chloride, KNO_3, and others. Halopriming of cotton seeds with KNO_3 increases seedling germination by 83% by the activation of the pre-germination enzymes, metabolite production, osmotic adjustment, and protein synthesis. KNO_3 priming also enhanced the nitrogen use efficiency and hence higher growth rate was observed (Awan et al. 2023). Cotton seed priming with KCl increased the germination rate and antioxidant enzyme activity, enhanced the cell water saturation, and acted as cofactors for various enzymes. Seed priming with H_2O_2 increased the activity of antioxidant enzymes such as catalase and peroxidase which scavenge the ROS produced during water uptake (Santhy et al. 2014). Biopriming is the application of plant beneficial microbes in the seeds to stimulate plant growth and maintain an environmental balance (Vurukonda et al. 2016). Using microbial inoculant as a biopriming agent has been reported to enhance enzymatic activity, nutrient cycling, rhizosphere stimulus, and improve the crop's growth and productivity under diverse climatic conditions (Razavi 2021; Singh et al. 2015). Endophyte based biopriming enhanced the germination, seed vigour index and also enhanced the catalase and peroxidase activity (Verma et al. 2022). Biopriming cotton seeds with plant growth-promoting rhizobacteria enhances plant growth by improving nutrient availability and stimulating phytohormone production, including auxins, cytokinins, and gibberellins (Ragadevi et al. 2021). Priming cotton seeds with organic compounds such as cow urine, known as organic priming (Kumar et al. 2022a), showed the highest seedling vigour and maximum germination percentage. Under drought stress, cotton plants inevitably produce ROS which can be overcome by seed priming. Cotton seed priming with elicitors like methyl jasmonate increased the activity of antioxidant enzymes such as catalase and superoxide dismutase which scavenges the ROS (Kumar et al. 2022b). Figure 3 depicts the common mechanism of seed priming that has been observed for cotton seeds. Table 4 describes the influence of different types of seed priming on cotton seeds and its effect on germination and seed vigour.

Table 4 Seed priming treatment of cotton seeds

S. No	Types of seed priming	Result	Reference
1	Hydropriming	• Hydropriming of cotton seeds increased the germination rate of 30% under low temperature stress condition (12 °C) when compared with untreated seed	(Casenave et al. 2007)
		• Hydropriming at 25 °C for 4–6 h increased the germination rates for Maraş-92, Sayar-314, and Stoneville-468 by 54%, 17%, and 6%, respectively • Hydropriming at 5 °C for a longer time decreased the germination rate	(Bolek et al. 2013)
		• Hydropriming of cotton seeds increased the germination by 43% at 32–38.5 °C and 34% at 25 °C	(Kumar et al. 2022b)
2	Halopriming	• Salt priming of cotton seeds improved seed germination and field emergence under salt stress, with the control showing a germination rate of 70% and emergence rate of 53.1%, while seeds primed with NaCl had germination and emergence rates of 89% and 84%, respectively	(Lin et al. 2006)
3	Osmo-priming	• Osmo-priming of cotton seeds with mannitol for six hours increased the germination percentage compared with control and more than six hours led to a decrease in germination percentage. • Osmo-priming with −0.5 MPa solution of mannitol at 16 °C for 6 or 12 h may be recommended for enhanced germination of cotton seeds under suboptimal conditions. • The control had a germination percentage of 64% and the seeds primed with mannitol for 6 h had a germination rate of 75% at 12 °C	(Papastylianou et al. 2012)
4	Hydropriming and KNO_3	• Hydropriming and KNO_3 priming increased the germination, seedling emergence, and dry weight • At normal conditions, the final germination percentage of control and treated seeds are 91% and 99%, respectively • At a salinity level of 8 dsm^{-1}, the control had a germination rate of 27% and the seeds primed with water and KNO_3 had a germination rate of 57% and 66%, respectively • Similarly, at salinity level of 8 dsm^{-1}, the control had an emergence rate of 20% and the seeds primed with water and KNO_3 had an emergence rate of 48% and 61%, respectively	(Ahmadvand et al. 2012)
		• Seed priming with KNO_3 (1.5%, mass fraction) for 20 h increased the germination index, percentage, and decreased the mean germination time	(Narejo et al. 2023)
5	Hydrogen peroxide	• Seed priming with H_2O_2 and KCl enhanced seedling germination and growth under moisture stress, with the control showing a germination rate of 35%, while seeds primed with hydrogen peroxide and KCl exhibited germination rates of 45% and 42%, respectively, on the 3rd day	(Venoor et al. 2014)
6	KNO_3 priming	• Among different priming agents, KNO_3 induced the highest seed germination and developed vigorous cotton plants at low temperatures • At 18 °C, the control had a germination rate of 93% and the seeds treated with KNO_3 had a germination rate of 98%	(Çokkizgin et al. 2015)
		• Cotton seeds primed with KNO_3 (4%, mass fraction) demonstrated maximum germination index • Cotton seeds primed with distilled water showed increased root length, fresh weight, dry weight, and germination index under low temperatures	(Çokkizgin et al. 2015)
		• Halopriming with KNO_3 increased seed germination (83%), seedling emergence (90%), and yield (17%) • The control had a germination rate of 60% and the seeds primed with KNO_3 had a germination rate of 83% • It was observed that five days after sowing, the control had a seedling emergence of 65% and the seeds primed with KNO_3 had a germination rate of 92%	(Awan et al. 2023)
		• Cotton seed priming with KNO_3 (5 $g \cdot L^{-1}$) and glycine betaine (100 $mg \cdot L^{-1}$) significantly increased the germination, yield, and growth rate under drought stress conditions. • Compared with the control, seeds primed with KNO_3 showed increases of 54%, 36%, and 125% in dry shoot matter, cotton yield, and net photosynthetic rate, respectively, while seeds primed with glycine betaine exhibited corresponding increases of 31%, 11%, and 79%	(Khalequzzaman et al. 2024)

S. No	Types of seed priming	Result	Reference
7	Warm water and gibberellic acid	• Among different priming agents, gibberellic acid gave the highest germination compared with the control • Gibberellic acid and coconut water increased the height, flowering, and germination compared with the control • After 2 weeks of sowing, the control had a germination rate of 41% and the seeds primed with gibberellic acid had a germination rate of 83%	(Chuwang et al. 2018)
9	Osmo-priming and hydro-priming	• Hydropriming of cotton seeds for 16 h maintained its effect after 6 months of storage • Osmo-priming of cotton seeds for 41 h in mannitol maintained its effect after 12 months of storage • Osmo-priming of cotton seeds in mannitol gave the highest germination rate and vigour index • The mean germination time for control, seeds hydro-primed for 16 h, and seeds primed with mannitol for 41 h are 2.63, 2.17, and 2.17 days at 25 °C	(Toselli et al. 2014)
		• Osmo-priming of cotton seeds gave the highest growth percentage, growth rate, and dry weight of seedlings compared with the control • Under drought stress, the control had a germination percentage of 71% and a vigour index of 200, while seeds osmo-primed with Si showed the highest germination percentage of 95% and vigour index of 1000	(Mehrabadi 2020)
10	IAA	• IAA priming increased seed germination, seedling growth, and vigour growth • The control had a germination rate of 48% and the treated cotton seeds had a germination rate of 76% on the first day and 83% on the seventh day	(Zhao et al. 2020)
11	Brassinosteroid	• Brassinosteroid treatment increased seedling vigour, growth, dry matter weight, lateral root, and cotyledon opening • At a salt concentration of 200 $mmol \cdot L^{-1}$, the control had a germination rate of 40% and the seeds treated with 1 $\mu mol \cdot L^{-1}$ of brassinosteroid had a germination rate of 80%	(Chakma et al. 2021)
12	Biopriming	• Cotton seeds bio-primed with plant growth promoting rhizobacteria increased the growth, boll number, yield, and quality • The untreated seeds had a shoot and root length of 36.3 cm and 13.5 cm. The bio-primed seeds had an increased shoot and root length by 29% and 45%, respectively.	(Ragadevi et al. 2021)
13	Cow urine	• Cotton seed priming with cow urine (6%, mass fraction) demonstrated highest seed vigour and maximum germination • The control had a germination rate of 70% and the seeds primed with cow urine had a germination rate of 83% • Similarly, the control had a seed vigour index mass of 77.46 and the seeds primed with cow urine had a seed vigour index mass of 137.72	(Kumar et al. 2022a)
14	Endophyte biopriming	• Endophyte priming of cotton seeds improved seed germination and vigour, with the Phule Dhanwantary cultivar showing a germination rate of 90% compared with 46% in the control, and the Suraj cultivar showing 93% compared with 80% in the control	(Verma et al. 2022)
15	Sodium nitroprusside and hydrogen peroxide	• Cotton seeds primed with sodium nitroprusside and hydrogen peroxide enhanced the germination under stress • Stress conditions induced oxidative stress in the seed which activated the antioxidant system and hence enhanced growth	(Guaraldo et al. 2023)
16	Gibberellin	• Seed priming with gibberellin increased the germination potential, index, rate and decreased the mean time of germination at low temperatures • At a temperature of 12–15 °C, the control had a germination rate of 30% and the seeds treated with gibberellin had a germination rate of 62%	(Xia et al. 2023)

Advanced seed treatments

Nanotechnology has gained attention in recent years due to its wide range of applications in fields such as medicine and industries. In agriculture, nanotechnology provides nano-formulations that enhance crop productivity and reduce the usage of chemical pesticides/fertilizers (Alaa et al. 2019). Nano-materials with unique properties such as large surface area, high reactivity, enhanced absorption by plants, and protection to crops by penetrating pathogens (Banerjee et al. 2019). New techniques are constantly being developed to deal with issues related to seeds and one of them is nano-materials. Nanotechnology in seed research is a developing new field that involves using nano-materials for seed treatment. Nano

Table 5 Advanced cotton seed treatments

S. No	Types of treatment	Result	Reference
1	Pulsed electromagnetic field	• Magnetic field treatment of cotton seeds increased the germination percentage by 85% compared with the control • Treated seeds also performed better in the fields. • In the case of 1-year old seeds, the control had a germination rate of 59% and the treated seeds had a germination rate of 72% • Similarly, in the case of 2-year-old seeds, the control had a germination rate of 30% and the treated seeds had a germination rate of 55%	(Bilalis et al. 2012)
2	High voltage pulsed electric field	• The frequency of the electric field at 10 Hz improved the germination rate, germination potential, germination index, and vigour index • Above 10 Hz frequency, the effects were decreased. • Compared with the two voltage treatments, treatment at 16 kV gave better results than 20 kV	(Yan et al. 2017)
3	Extremely low frequency high voltage pulsed electric field	• Cotton seed vigour after electric treatment increased initially and later decreased with increasing frequency and voltage • At the optimum condition of pulsed voltage at 16.25 kV and frequency at 10.90 Hz, increased the germination potential by 44%, germination rate by 56%, germination index by 64%, and vigour index by 81% compared with the control. • The control had a germination rate of 44% and the treated seeds had a germination rate of 69%	(Yan et al. 2017)
4	Cold plasma treatment	• Cold atmospheric pressure plasma (CAP) treatment for 27 min improved germination, water absorption, and chilling tolerance • In the warm germination test, the control had a germination rate of 65% and the treated seeds had a germination rate of 90% after 10 days • In the cold germination test, the control had a germination rate of 79% and the treated seeds had a germination rate of 82% after 10 days	(de Groot et al. 2018)
5	High-voltage pulsed electric field treatment system with super-low-frequency	• Pulsed electric field treatment by arc shaped prick electrode increased the germination potential by 27%, germination rate by 45%, germination index by 42%, and vigour index by 71% • Pulsed electric field treatment by plate electrode increased the germination potential by 22%, germination rate by 20%, germination index by 35%, and vigour index by 64%	(Song et al. 2020)
6	High voltage electric field	• High voltage electric field treatment increased the germination rate by 43%, germination potential by 19%, germination index by 29%, and vitality index by 48% compared with the control • The control had a germination rate of 63% and a vigour index of 695, while among 25 treatments, the treated seeds achieved the highest germination rate of 84% and the highest vigour index of 981	(Song et al. 2021)
7	Electromagnetic field	• Pre-sowing electromagnetic treatment increased the germination rate by 19% and germination energy by 24% compared with the control • The control had a germination rate of 85% and the treated seeds had a germination rate of 88%	(Koleva et al. 2022)
8	Metal-based nanoparticles	• ZnONP (200 $mg \cdot kg^{-1}$) and TiO_2NP (400 $mg \cdot kg^{-1}$) exhibited maximum seed germination, seedling establishment, and seed vigour index • For both the nanoparticles, the control had a germination rate of 71% and the nano-primed seeds had a germination rate of 75%	(Singh et al. 2022)
9	Magnetic water treatment	• Magnetized fresh and brackish water increased the cotton seed germination by 13% and 41%, respectively	(Zhang et al. 2022)

Table 5 (continued)

S. No	Types of treatment	Result	Reference
10	Metal oxide nanoparticles	• Cotton seeds primed with ZnONP and TiO_2NP maintained the seed vigour and quality during the storage period • After 12 months of storage, the cotton variety H1300 showed a germination rate of 57% in the control, with ZnONP and TiO_2NP nano-primed seeds achieving rates of 63% and 63%, respectively, while in the cotton variety H1098-I, the control had a germination rate of 56%, and the nano-primed seeds with ZnONP and TiO_2NP had rates of 64% and 62%, respectively	(Singh et al. 2022)

agrochemicals for seed treatment are more effective and environment friendly compared with traditional methods (Neme et al. 2021). Nano-priming of seeds has been reported to be effective in achieving higher yields compared with traditional priming methods (Kandhol et al. 2022). Nano-materials can enhance seed germination by creating pores in the seed coat, stimulating the production of ROS, and increasing enzyme activity (Guha et al. 2018). When seeds are treated with nanoparticles, it causes ROS accumulation on the seed which is important for cell communication within the endosperm and the breakdown of glycosidic bonds of polysaccharides (El-Maarouf-Bouteau et al. 2008; Oracz et al. 2016). During this process, the superoxide dismutase(SOD) permits the interaction between hydrogen peroxide and gibberellic acid in the embryo. Further, GA activates alpha amylase enzyme for the hydrolysis of starch into soluble sugars which are used for embryo development and hence enhance seed germination and vigour (Kandhol et al. 2022; Yavari et al. 2023). Singh et al. (2022) reported that ZnO and TiO_2 nanoparticles increased germination, seedling establishment, and seedling vigour by enhancing the production of antioxidant enzymes such as SOD and hence improving the seed's defense system. Cotton seeds primed with ZnONP and TiO_2NP increased the germination and seed quality parameters by activating oxidation–reduction reactions through superoxide ion radicals. This priming led to quenching of free radicals in aged seeds and hence the oxygen produced can be used for the seed's germination. These nanoparticles also aid in repairing damaged organelles and activate enzymes in the seed that are vital for germination (Singh et al. 2022).

Another new method for the treatment of seeds is using plasma technology. Plasma is produced by a discharge in gas and has been proposed to aid in crop germination and survival (Randeniya et al. 2015). Plasma treatment on peanuts and wheat has shown to enhance the shoot growth, root growth, and germination (Jiang et al. 2014; Li et al. 2016). Cold atmospheric-pressure plasma (CAP) treatment in cotton seeds for 27 min with air enhanced the germination, water absorption capacity, and chilling tolerance (de Groot et al. 2018). Fourier transform and emission spectroscopy of plasma treated cotton seeds revealed that the biologically reactive nitrogen and oxygen species interact with the seed surface, penetrate the seed, and activate biochemical processes required for germination (Wang et al. 2017). High voltage electric field treatment has also been used for seed treatment as it can alter the permeability of the seed membrane, activate the intracellular enzymes, stimulate cell mitosis and cell metabolism, and improve seed vigour (Song et al. 2021). The first research on using a pulsed electric field as a pre-sowing seed treatment was studied on 20 different seeds such as corn, cotton, rice, rapeseed, etc., and studied their effect on seed germination, viability, and growth. Pulsed electric field (PEF) treatment increased the germination rate, yield, stress tolerance but decreased the degradation of the seed and plant growth cycle. When the frequency of the electric field was kept at 10 Hz in PEF, the cotton seed germination rate, germination potential, germination index, and vigour index were improved (Song et al. 2020). This study also reported that among two selected voltage treatments, the treatment at 16 kV gave better results compared with 20 kV. Electric and magnetic field treatment affects the biological processes by activating enzymes and proteins of the seed that increase the seed vigour (Molaforad et al. 2013; Morar et al. 1999). Electromagnetic field as pre-sowing seed treatment increased the germination rate by 19.5% and germination energy by 24% compared with the control (Koleva et al. 2022).

Magnetic water treatment is a new potential technology that is widely used in agriculture (Abobatta 2019). Water being magnetized by a magnetic field undergoes physical and chemical changes, which enhance its activity such as reaction rate, solubility, and other factors (Pang et al. 2008). Magnetized water for irrigation has been demonstrated to enhance seed germination and growth (Aghamir et al. 2016; Morejon et al. 2007). Magnetized fresh and brackish water increased cotton seed germination by 13% and 41%, respectively (Zhang et al. 2022). Magnetic fields have also been used as a pre-sowing seed treatment which has been studied to enhance the seed germination and vigour of various crops (Anand et al. 2019; Bhardwaj et al. 2012; Shine et al. 2011). It was reported that pre-sowing seed treatment with pulsed electromagnetic field as a pre-sowing seed treatment and observed that magnetic field treatment of cotton seeds increased the germination percentage by 85% and also performed better in the field compared with the control (Bilalis et al. 2012). Magnetic field treatment makes the seed membrane permeable to ions and free radicals, and this ion movement activates the metabolic pathway by activating the biochemical and physiological response (Atak et al. 2007; Jamil et al. 2012; Sun et al. 2014). Table 5 describes the types of electric field, magnetic field, plasma, and nano-based treatments on cotton seeds and their effect on germination and seed vigour.

Conclusion

Cotton seed production encounters persisting issues in terms of seed quality and viability, owing mostly to mechanical damage during post-harvest procedures such as ginning and delinting. These harms hasten the decay of seeds, especially in subtropical areas like India where ambient storage conditions are common. Moreover, lipid peroxidation-induced rancidity during storage significantly lowers the germination potential and reduces the seed vigour. This study emphasizes the significance of several conventional as well as modern methods for addressing these problems in order to maintain seed vigour and germination ability. Among the traditional approaches, methods like hydropriming, osmopriming, and biopriming are useful and efficient for enhancing cotton seed quality. Furthermore, seed coating techniques offer effective nutrient delivery to seeds in addition to giving protection against harmful mechanical and environmental impacts. Despite present apparatus and technical competence constraints, emerging technologies such as magnetic, plasma, and nanoparticle-based treatments have interesting potential. With advancements in technology, these approaches are expected to become cost-effective and precise, offering robust solutions for enhancing cotton seed quality before sowing. In addition to improving seed quality, using either conventional or advanced methods will encourage agricultural resilience and environmental sustainability. By implementing these strategies into practice, farmers can maintain high-quality seed stock levels, which improve crop productivity and yield financial gains. In conclusion, the seed quality enhancement strategies outlined in this review serve as a critical foundation for sustainable cotton production, addressing current challenges while paving the way for innovative practices in the future.

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Authors' contributions
Mylsamy P prepared the initial draft of the review, Tamilmani E developed of concept and preparation of the final manuscript, Venugopal R preparation of this manuscript concept-oriented pathway and schematic representation of the main crux of this review paper, Murugaiyan S added information corresponding to the role of microbes in cotton seed vigour improvement through seed treatment and Ranganathan U added information corresponding to how seed coating technology improve seed vigour in cotton and helped to arrive the final manuscript.

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