PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(sp1): 01–11
https://doi.org/10.14719/pst.8047

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REVIEW ARTICLE

A comprehensive review of advanced seed treatment techniques to enhance Amaranthus cultivation and productivity

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OPEN ACCESS

ARTICLE HISTORY
Received: 03 March 2025
Accepted: 25 March 2025
Available online
Version 1.0 : 15 April 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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CITE THIS ARTICLE
Ravichandran G, Malarkodi K, Eevera T, Thangamani C, Pon Sathya M, Kavitha S, Marimuthu E. A comprehensive review of advanced seed treatment techniques to enhance Amaranthus cultivation and productivity . Plant Science Today. 2025; 12 (sp1): 01–11.
https://doi.org/10.14719/pst.8047

Abstract

Amaranth is a highly valued leafy vegetable known for its exceptional nutrient profile, including high-quality protein, dietary fiber and essential vitamins and minerals. The seeds of amaranth are particularly rich in calcium, magnesium, phosphorus and vitamin C, making them a valuable component of a healthy diet. Additionally, amaranth is well-suited for terrace gardening and sustainable agriculture. However, despite its nutritional benefits, the consumption of amaranth in daily diets remains limited. One of the major challenges in amaranth cultivation is the imbibition issue caused by the tannin -rich testa and exotegmen cells in the seed coat. These factors contribute to poor seed quality, delayed germination and prolonged dormancy, which can last several years, ultimately reducing crop productivity. Seed treatment plays a crucial role in overcoming these limitations by improving seed viability and enhancing germination rates. Effective seed treatment methods help eliminate non-viable seeds, break dormancy and improve the physico-chemical properties of seeds. Furthermore, seed treatments can enhance seedling vigor, provide resistance against biotic and abiotic stresses and improve overall crop establishment. Conventional techniques such as priming, scarification and chemical treatments, as well as advanced methods like hydropriming, biopriming and nano priming, have shown promising results in enhancing amaranth seed quality. This critical review explores various seed treatment strategies, comparing their effectiveness and highlighting their potential to improve amaranth production. A better understanding of these techniques can help optimize amaranth cultivation and contribute to its increased adoption in sustainable food systems.

Keywords

Amaranth; seed treatment; dormancy breaking; germination; seed quality

Introduction

Amaranth (*Amaranthus* spp.), a dicotyledonous pseudocereal, is one of the New World's earliest crops (1). It has a high genetic diversity and a wide spectrum of phenotypic flexibility, which enable it to thrive on marginal ground and provide substantial potential for additional adaptation and development (2). It is a third-millennium crop (3) which is known as a "superfood" due to its high nutraceutical value, including high-quality protein, unsaturated oils, squalene, dietary fiber, tocopherols, tocotrienols, phenolic compounds, flavonoids, vitamins and minerals (1). Amaranth seeds have a high protein content (13-19 %) and an excellent balance of important amino acids (3). It is a crop that can be used to prevent malnutrition, obesity and diet-related disorders. Dry amaranth seeds have roughly 14 % protein, 65 % carbohydrate, 7 % fat and 2 % fiber (4). It also found that it has anticancer, antidiabetic (5), antioxidant properties (6) and high nutraceutical value in it (7). It has twice the calcium of milk, five times the iron of wheat and more potassium, phosphorus, vitamins A, E, C and folic acid than cereal grains (8). Because of balanced amino acid composition of grain amaranth, it has been stated that the protein content is extremely close to the standards advised by the Food and Agriculture organization (FAO) and World Health Organization (WHO). Extruded amaranth protein hydrolysates have been shown to prevent inflammation in humans by activating bioactive peptides and reducing pro-inflammatory markers (9).

Amaranthus hypochondriacus sprouts have a high fiber content and are a source of proteins with possible antihypertensive and antioxidant properties, we may view them as a diet that promotes health (10). It is a crop that can meet the urgent dietary and nutritional needs of rural populations in agriculturally fragile areas (11). It is a green vegetable that is grown in great abundance throughout India during the summer and kharif seasons. This crop formerly grown in many regions but then abruptly disappeared from cultivation for many years, is making a comeback and showing promise for global food and nutrition security (12). With the ability to thrive in a variety of climates, amaranth is still an underutilized food crop. It is a crop that can withstand drought and has great market and industrial potential that has not been completely realized (13).

There is a lack of data on amaranth production globally and the FAO does not have any records so far. Amaranth is mostly grown in tropical regions of South America, Africa (mainly for its leaves), Central and Southeast Asia (particularly China, India and Nepal) and North America, including Kenya. Peru and Bolivia were the top exporters, with per-ton values ranging from USD 360 in 2009 to USD 640 in 2011. During the same period, Germany, France, Lithuania, Poland and China had the highest amount of business transactions. The producing area in Europe is fairly small, only about 1000 ha. Production of amaranth is mostly concentrated in Slovakia, Hungary and Italy (8). The reported yields ranging from 50 to 7200 kg/ha of seed (14). South and Middle America have the highest agricultural yields (4600-7200 kg/ha), while Africa has lower yields (50-2500 kg/ha). Yields in Europe are moderate, ranging from 1200 to 6700 kg/ha, particularly in Mediterranean regions (14).

Although the crop has high nutritional value and wider economic importance there is a problem with amaranth seed production because it sheds once it matures. So, the time of harvest is crucial and there is a problem of uneven maturation is also seen in the amaranth crop (15). Histological analysis of amaranth seed shows tanniniferous testa and exotegmen cells which greatly affect the imbibition and result in the reduction of germination or lead to uneven germination (16). Tanniniferous testa and exotegmen cells contribute to seed dormancy by limiting water absorption and enzyme activity. The testa, rich in tannins, reduces imbibition and oxygen diffusion, delaying germination (17). Tannins also inhibit hydrolytic enzymes like amylases, preventing nutrient mobilization. Exotegmen cells add structural rigidity, further restricting embryo expansion (18).

The dormancy of amaranth seeds can extend up to 1 year (19). On average, each inflorescence of an amaranth crop can yield approximately 50000 seeds. However, not all of these seeds are viable for germination after harvest. This is largely because the seeds are enclosed in a delicate, single-layered perisperm that is susceptible to post-harvest damage (20). Such damage heightens the risk of pathogen attacks, further compromising seed viability. The seed longevity of *Amaranthus* spp. is only about 19-40 days (21). Therefore, it is essential to protect the seeds to extend their longevity and minimize pest and disease issues.

Techniques such as pelleting and priming with various chemicals can enhance seed quality and improve their resilience. Pelleted seeds offer significant protection against external environmental factors. The presence of flavonoids on the surface of the seed coat reduces the germination of amaranth because these flavonoids cause dormancy to these seeds (22). So, there is a need for advanced technologies in the seed treatment of amaranth to enhance its quality of seed to boost amaranth seed production harness its nutritional power and fight against malnutrition effectively. This review study will examine the technologies used in seed treatment to improve the quality of amaranth seeds.

Different methods of seed treatment in amaranth

Physical treatment : Physical seed treatment methods involve majorly in breaking the outer seed coat by various methods which includes scarification, magnetized seed treatment, radiation seed treatment and hot water treatment (Fig. 1). Physical seed treatment exports energy into the targeted cells of seeds and induces seed germination by the activation of enzymes and biochemical processes. Energy introduced into the seed is converted into chemical energy and enhances the metabolism of the seed. Radiation treatment, magnetic treatment, dry heat treatment, electromagnetic treatment, ultrasound treatment and scarification are effective physical seed treatments (22). This treatment is majorly focused on breaking the outer seed coat or involves the loosening of the outer layer. So, it increases the imbibition rate of the seed and produces vigorous seedlings.

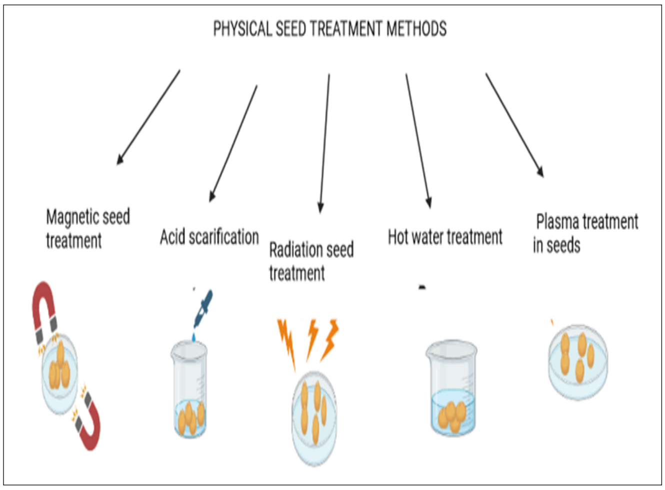

Fig. 1. Various physical seed treatment methods.

Heat treatment : Heat treatment can increase the seed germination rate and reduce the pathogen attack over the surface of the seed (23). Germination of amaranth of about 60 % is only at the temperature above 16 °C and attains maximum germination at 35 °C (24). Amaranth seeds are subjected to hot water, cold water seed treatment and their germination after 14 days of sowing, the seeds which are immersed in hot water showed 77 % seed germination but seeds in cold water showed only 44 % germination. The hot water increases the germination of the amaranth seed by breaking its outer seed coat (24). The effect of heat treatment effect on seed germination of amaranth was studied (Table 1).

The highest germination rates for amaranth seeds are obtained from the seeds which are treated in microwave ovens by using power densities between 0.13 and 6 W/g (25-27). Dry heat treatment for 15 days at 60 °C on seeds effectively controls *Fusarium graminearum* (28). The germination percentage of *A. hypochondriacus* and *A. creuntus* at different temperatures were studied and the results were observed that both species gave good germination percentages of 86 % at 28 °C (24). The temperature treatment of *A. retroflexus* seeds shows that the temperature above 60 °C causes a drastic reduction in the germination of *A. retroflexus*. A temperature above 80 °C leads germination to zero percent (25). Higher temperature drastically reduces the viability of the seed. Thermal processing such as autoclaving and blanching drastically reduces the phenolic compound present in the amaranth seeds (25).

A duration of five minutes of heat treatment at 120 °C and 180 °C treatments greatly decreased the germination. At the lowest temperature of 60 °C, seeds that had been heat-treated for 3 min showed 100 % germination. After 5 min of exposure, germination was totally suppressed in the 120 °C and 180 °C treatments (25). So, the temperature and the treatment duration play a major role in heat treatment. Thus, optimal heat treatment can improve the germination rate and break seed dormancy and stimulate the seeds to sprout more uniformly and vigorously and it reduce the moisture content of the seed which increases the seed viability. In some cases, heat treatment can also reduce pathogen occurrence (28). This heat treatment directly affects the seed coat and helps to reduce the seed coat density and increases the imbibition rate. Improving the heat treatment through microwave drying is a futuristic method because it is easy and time-consuming method.

Radiation treatment : Pre-sowing noninvasive radiation treatment in crop seeds not only increase in germination but it also shows a considerable increase in the nutritional value of amaranth seeds. Among physical treatments, the use of magnetic and electromagnetic seed treatments has become popular (29). Electromagnetic field treatment resulted a significant increase in the minerals, amino acid composition, zinc, iron and essential amino acids in amaranth crop seeds (29). Radiation study was conducted under different environmental conditions such as in pot condition, laboratory condition and field condition (30). In the pot study, He-Ne laser treatment (6 $mW{\cdot}cm^{-2}$) along with magnetic treatment (30 mT) for 30 sec gives a higher percentage of germination of 83 % (30-32). Under field conditions, He-Ne Laser treatment of 6 $mW{\cdot}\ cm^{-2}$ gives the highest germination percentage and growing pattern percentage (33). The germination of amaranth seeds was about 75-80 % when high voltage nanosecond pulse treatment of five shots was applied which is higher than the control germination percentage (34).

UV-B radiation treatment of 250-315 nm was conducted on both green plants and high beta cyanin plants of *A. tricolor*; the high influence of UV-B treatment of 315 nm shows influence on physiological, transcriptional and biochemical changes that occur in it. A high dosage of UV-B radiation at 315 nm negatively affects the properties of the seed (35). The UV-B radiation treatment reduces the ABA content of the seed. Decreased ABA content directly increases seed germination (36). The electromagnetic radiation treatment did not affect the chlorophyll and carotenoid content of the amaranth crop (31). Electromagnetic radiation treatment of amaranth seeds induced significant changes in the antioxidant enzymatic activities of sprouts, enhancing bioactive compound content (37). Ultrasonic sound treatment of about 20 min increased the germination of *A. retroflexus* (38). Nowadays, these ultrasonic sound waves from 20-100 KHz are greatly useful in the agricultural industry to stimulate seed germination (39).

Magnetic seed treatment : In this technique, the seeds are subjected to a magnetic field either by permanent magnets or PRISMA magnetic coil (40). The optimistic effect of magnetic seed treatment has been scientifically proven to increases seed germination (41), plant tissue development (42) and chlorophyll synthesis (43). Short-term exposure of amaranth seeds to low-frequency magnetic fields or laser light radiation influenced germination energy but not photosynthetic pigment content (42). Electromagnetic stimulation with laser light and magnetic fields influenced germination parameters of amaranth seeds, showing correlations with changes in chlorophyll and carotenoid content in seedlings (43). When comparing the treated group of *A. gengeticus* and *A. tricolor* to the typical magnetized water treatment. The seed germination vigor began a bit earlier (14 hr) when treated with magnetized water. With a similar vein, *A. blitum* showed greater germination after 36 hr of incubation with magnetized treatment. Furthermore, a clear indicator of the quick penetration of water molecules into seeds was the gradual increase in weight of the 50 seeds

Table 1. Effect of heat treatment on seed germination in *Amaranthus* spp.

Species Name	Method heat treatment	Effects	Reference
A. hypochondrious	Dry heat (28 °C)	Germination increased to 86 %	(24)
A. creuntus	Dry heat (28 °C)	Germination increased to 86 %	(24)
A. reteroflexus	Hot water treatment (60 °C)	Germination increased to 80 %	(25)
A. reteroflexus	Dry heating (60 °C)	100 % germination obtained	(25)

treated with magnets, from 30 to 140 µg (44).

Scarification treatment : Scarification is one of the physical methods of seed treatment which includes mechanical, acid and bio scarification methods. In amaranth, due to its strong seed coat mechanical scarification is usually practiced. Scarification is one of the dormancy breaking methods that promotes seed germination (45). *A. pumilis* seeds have tanniniferous testa and exotegmen cells, which reduce the imbibition efficiency and result in poor germination. So, scarification treatment should be carried out to loosen its seed coat and to increase the imbibition and germination percentage (16). Scarification is mainly known to increase the seed germination rate (45-47). These seeds are pierced with a needle and treated with 1 ppm GA_3 treatment, which increases the germination by about 99 %, pierced seeds alone produce 35 % germination, GA_3 treatment alone produces a germination percentage of about 14 %, untreated seeds produce only 1 % (16).

Plasma seed treatment : Charged gas molecules are said to be plasma. This plasma mainly consists of positive ions, negative ions, excited atoms and free radicals. Plasma is generally divided into high temperature plasma and low temperature plasma (48). Common plasma sources include the dielectric barrier discharge, corona and gliding arc. Cold plasma treatment is a new approach that has attracted interest in numerous industries since it is an economical and pollution-free procedure. It is also successful in reducing microbial contamination without altering seed quality features (49). Each plasma treatment and the duration applied to the seed had a great impact on seed germination (Table 2). Plasma treatment generates ROS such as superoxide anions (O_2^-), hydroxyl radicals (OH•) and hydrogen peroxide (H_2O_2), which act as signaling molecules in seed germination. ROS play a crucial role in breaking dormancy by activating oxidative signaling pathways that regulate gene expression related to germination (50). Controlled ROS production enhances seed metabolic activity by modulating the expression of antioxidant enzymes like catalase and superoxide dismutase, which maintain cellular redox balance (51).

This plasma is an innovative technique that can be applied to both beneficial and detrimental purposes, including cleaning and disinfection, as well as functional alterations, seed germination and plant development (52). This plasma seed treatment also involves the inactivation of bacteria on the surface of the seeds (53). It increases seed survival without causing any toxic residue in it. It has a 10 nm deeper penetration, so it reduces its surface functionalization (54). Plasma treatment for 10 sec provides a 100 % germination rate and Dielectric Barrier Discharge (DBD) plasma treatment for 900 sec provides 100 % germination rate. These plasma treatments increase the water uptake by seeds (55). The study also reported that there is an increase in gibberellic acid synthesis when the seeds are treated with plasma technology, which increase the germination of seeds (56).

Table 2. Various methods of plasma treatment, their duration and their effects

S. No	Duration of treatment (sec)	Method (56)	Effects
1	10	Cold plasma	100 % germination
2	30	DBD plasma treatment	80 % germination
3	60	Cold plasma	85 % germination
4	900	DBD plasma	100 % germination

Chemical seed treatment : Biological effects provoked in plants after the application of synthetic substances with a composition identical to natural hormones, auxins and gibberellins, have already been used in agricultural practice and horticulture for more than 50 years. Of synthetic auxins, the one that found wider application is indole acetic acid (IAA) and in the large group of gibberellins - gibberellic acid - GA_3 (57). The seed treatment of amaranth seed with GA_3 of 500 ppm increases the germination percentage to 62.1 % when compared to the control, which is only 46.4 %. GA_3 treatment not only increases the germination percentage and also the root length, shoot length, dry matter and vigor index of the crop (62). Potassium nitrate is generally used as a physical dormancy breaking chemical but in amaranth seed treatment with potassium nitrate at different concentrations (0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 %) it does not produce any significant difference in their germination percentage (58).

Amaranth seeds have primary dormancy. So, GA_3 application alone does not produce significant difference in the germination of the seeds along with cold stratification GA_3 significantly increases the germination of crops with an increase in the concentration of GA_3 (Table 3) (59). Seed treatment of amaranth with heavy metal lithium was conducted at a different concentration at 10 ppm germination increased up to 95 %, at a lower concentration of lithium germination of amaranth increased tremendously but at increasing concentrations the germination percentage goes in a decreasing trend (60). Similar to that of GA_3, ethephon treatment along with cold stratification gives better results in germination than ethephon treatment alone in amaranth seed treatment (59). The above result was obtained when the seed treatment was conducted at 25 °C. A similar experiment was conducted at the temperature of 35 °C then the germination percentage observed was much higher than that of germination observed at 25 °C (59). In amaranth, the chemicals that are applied are generally synthetic hormones to influence seed germination.

Priming of amaranth seeds : Seed priming is a physiological process of pre-germinative treatment to enhance their quality and germination and subsequent growth by activating certain metabolic process before sowing. Priming of seeds (Fig. 2) promotes germination and growth, particularly in environments with limited resources (61). This

Table 3. Gibberellic acid and Ethephon concentration with stratification period and their resulted germination percentage

Gibberellic acid (57)		
GA_3 Concentration	**Stratification period**	**Germination %**
10^{-4} M	-	45 %
3×10^{-4} M	20 weeks	70 %
10^{-3} M	4 Weeks	90 %
Ethephon		
10-4 M	-	45 %
10^{-4} M	8 weeks	80 %
3×10^{-6} M	20 weeks	90 %
10^{-5} M	20 weeks	90 %

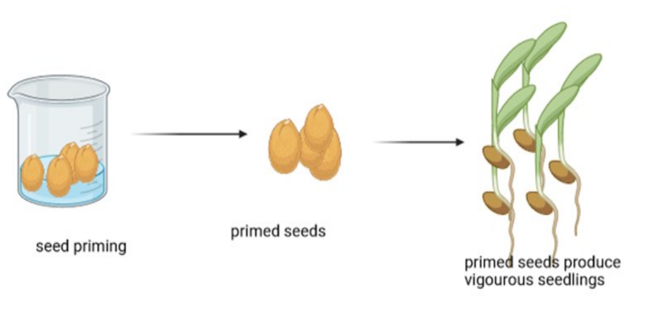

Fig. 2. Effect of priming on seeds.

priming technique can improve plant growth metrics, like germination rate and uniformity (62) and lead to increased yields and plant resistance (63). Main advantage of this techniques is more rapid germination than the unprimed seeds. Even the germination of aged seeds is also possible (64). Primed seeds are usually not suitable for long-term storage because primed seeds usually deteriorate faster than unprimed seeds even the primed seeds are stored after drying (64). This may be due to the conversion of complex polysaccharides into simpler forms.

Some of the most commonly available priming techniques are hydro, halo, osmo, bio hormonal, nano and solid matrix priming. Other seed priming includes nutrient priming, plant growth regulators and with plant extracts. To increase the seed water potential, seeds are soaked in a high osmotic potential solution before germination in order to activate or increase the metabolic activities of the seed (65). Hydropriming under stress conditions increases the germination of the seeds. Osmo-priming of the seeds with different priming agents majorly include polyethylene glycol, mannitol, sorbitol and different salts such as $NaNO_3$, KH_2PO_4, $KH_2(PO_4)$, K_3PO_4, KCl, KNO_3, $Ca(NO_3)_2$, $MgCl_2$ (64). The main advantage of osmo-priming is controlled hydration of seeds (66). Seed treatment with growth stimulant regulates the antioxidant potential through the increase of ascorbic acid synthesis, total content of water and alcohol soluble compounds this results in the reduction of negative effects of cold stress in amaranth crop (67). Different methods of seed priming of *Amaranthus* spp. and their effects are listed in Table 4. The main difference among hydro, bio and nano priming were discussed in Table 5.

Chemical priming : There are distinct priming agents such as KNO_3, KH_2PO_4 and polyethylene glycol (PEG 8000) that were used to prime freshly harvested *A. cruentus* seeds. The priming agents applied at varying doses over seven days at 20°C. Priming in 3 % KNO_3 enhanced *A. cruentus* seed germination at 20 °C, but not in KH_2PO_4 or PEG solutions (68). Standardization of the priming duration of *A. creuntus* was done. Priming the seeds with water for different durations (2, 4, 6 and 8 hr) among those different durations, priming for two hours shows better germination percentage than others (69). Analyzing the best concentration of KNO_3 as a priming agent. Among different concentrations of KNO_3 (0.5 %, 1 % and 2 %), the 0.5

Table 4. Different methods of priming in *Amaranthus* spp. and their observations

S. No	Method of priming	Species	Chemical used	Observations	Reference
1.	Osmo-priming	*A. creuntus*	3 μM methyl jasmonate and 3 % KNO3	The highest germination and metabolic activity	(62)
2.	Osmo-priming	*Amaranthus* sp.	10 % PEG 6000	Plant height, number of leaves, root length and leaf chlorophyll content increased under salinity condition and decreased proline, Ca oxalate and oxalic acid content	(67)
3.	Chemical priming	*Amaranthus* sp.	3 % KNO3	Increased germination percentage (37 %)	(62)
4.	Chemical priming	*A. tricolor*	138 ppm with succinic acid	Enhanced seed quality	(68)
5.	Chemical priming	*Amaranthus* sp.	Succinic acid 500 ppm	Increased germination percentage (62.1 %)	(69)
6.	Chemical priming	*Amaranthus* sp.	H_2O_2 50 mmol/L	Increased seed quality, improvement in seed cold resistance	(69)
7.	Osmo-priming	*Amaranthus* sp.	PEG 6000	Increased germination percentage under salinity conditions	(70)
8.	Halopriming	*A. caudatus*	100 mmol NaCl	Increased germination under saline and normal water condition (96 %)	(71)
9.	Osmo-priming	*A. caudatus*	-3 MPa PEG 6000	Improved germination (74 %) under saline condition	(71)

Table 5. Main differences among hydro, bio and nano priming of seeds

Characteristic	Hydropriming	Biopriming	Nano priming
Source	Soaking in water	Treated with beneficial microorganisms (e.g. Fungi & Bacteria)	Treated with nanoparticles or nanomaterials
Mechanism	Water absorption activates enzymes and metabolic pathways, promoting germination without fully starting the process	Microorganisms adhere to seed surfaces and provide growth-promoting effects, disease resistance and nutrient uptake improvements	Nanoparticles penetrate seed tissues, enhancing enzymatic activities, nutrient uptake and protecting against environmental stresses
Duration of treatment	Relatively short (Few hours to day)	Relatively long (Several hours to day)	Very short (few minutes to hours)
Common Application	Commonly used for vegetables, grains and legumes to obtain faster and uniform germination	Widely applied in crops requiring disease resistance, improved growth and enhanced performance under stressed conditions	Used in high-tech agriculture, especially for abiotic stress resistance/tolerance
Effect on seed dormancy	Breaks seed dormancy, especially seeds require moisture for germination	Breaks seed dormancy, especially seeds require specific microorganisms to trigger germination	Breaks seed dormancy by enhancing metabolic activity and seed readiness for germination
Scalability	Easy to scale up for huge number of seeds with minimal infrastructure	Can be scale up (care is needed for handling of microbial culture	Less scalable (require specialized equipment)
Advantage	Low cost, Accelerated and uniform germination by activating enzymes and metabolic process	Relatively high cost, improves seedling vigor, growth, stress tolerance and disease resistance	High cost, but still improves germination, enhanced nutrient uptake, promotes stress resistance and protection from pathogens
Disadvantage	Time consuming, prolonged soaking may cause seed damage	Time consuming and possible contamination or harm to seed from microbes	Require precise application and toxicity could harm seed or soil

% concentration of KNO_3 gave better germination than others (70). The germination process was further enhanced by adding methyl jasmonate (MeJA), 1-aminocyclopropane-1-carboxylic acid (ACC), or 6-benzylamino-purine (BAP) to the priming solution. All studied plant growth regulator (PGR) concentrations considerably enhanced seed germination, with the exception of the highest MeJA and ACC concentrations as compared to seeds primed in KNO3 alone (64).

Gibberellic acid (GA_3-300 mg/L), Succinic acid (ScA-500 mg/L), Calcium chloride ($CaCl_2$-3000 mg/L), Salicylic acid (SA-138 mg/L) and Hydrogen peroxide (H_2O_2-5 mM) were used as priming agents. The quality of amaranth seeds was enhanced by pre-sowing treatment with GA_3, ScA and $CaCl_2$, but seed treatment with SA and H_2O_2 resulted in a decrease in seed quality for both large and small fractions (70). When *A. tricolor* cv. Valentina seeds were treated with ScA, $CaCl_2$ and GA_3 and the amounts of amaranthine and photosynthetic pigments dropped in the seedlings, but their biomass increased than that of the control group, indicating that these substances function as growth regulators (70).

The negative effect of salicylic acid on the amaranth seeds is due to oxidative stress, which results in decreased germination of seeds (70). Among these, seed treatment with hydrogen peroxide gave better results than other stimulants for priming. Viability and biomass of amaranth seeds increased by the pre-sowing seed treatment of priming with gibberellic acid and succinic acid, but at the same time it reduces the amaranthine, carotenoid and chlorophyll pigments (70). Seeds that are soaked with succinic acid (ScA-500 mg/L), hydrogen peroxide (H_2O_2-10 and 50 m mol/L) and calcium chloride ($CaCl_2$-3000 mg/L) increase the seed quality and improve the seed cold resistance (71). Biomass, hypocotyl and root length morphological parameters were also significantly improved with seed treatment by growth stimulants such as SA, H_2O_2 and $CaCl_2$ (71). The maximum root length of amaranth seedlings can be achieved by the seed treatment of amaranth with succinic acid and calcium chloride (71). The presence of NaCl, $CaCl_2$ and K_2Cl in the water where the seeds are placed for growth might cause a reduction in the germination of the seeds due to the negative osmotic effect (72). This negative osmosis may cause a loss of water from the seed to outer environment.

Osmo-priming : Priming the seeds with poly ethylene glycol as an osmo-priming agent is the most commonly used chemical because it is an inert matter with large molecular weight and non-toxic to embryos (73). *A. caudatus* seeds, which are primed with PEG 6000 at a concentration of -1 MPa grown under saline condition, show low final germination percentage and germination index and extended minimum germination time (74). PEG 6000 with a lower concentration produces better result than that of with a higher concentration as a priming agent against saline conditions. PEG 8000 at -0.5 M concentration was applied to the *A. caudatus* crop in the presence of air inhibited the germination of seeds and it barely germinated for about 10-20 % but along with gas priming, ethylene may cause an increase in germination percentage of about 3-fold (75). Osmo-priming of amaranth seeds in 10 % PEG 6000 solution for 24 hr and the seeds are grown under saline conditions resulted, decreased in calcium oxalate and oxalic acid content (69).

Gas priming : Gas priming is one of the novel priming technologies emerging in recent trends. The gaseous form of ethylene, hydrogen cyanide and nitric oxide can be used as a gas priming agent these gaseous priming becoming a novel technology of priming of amaranth seed which results increase in germination percentage of both dormant and non-dormant seeds of *Amaranthus* spp. (75). Gas priming of amaranth seeds with ethylene, hydrogen cyanide and with nitric oxide for the period of 24 hr of treatment has significantly increased the germination of amaranth seed crop (75). Among different concentration (-10, -12 and -14 bars) and different duration (3, 6, 9 and 12 hr) of priming treatment on the amaranth crop it is found that -10 bars concentration and for 3 hr treatment shown to be an effective method for seed treatment because the amount of total protein content, peroxidase activity, polyphenol oxidase activity significantly increased during these seed treatment durations and concentrations (76).

Pelleting of amaranth seeds : The method of surrounding a seed with a small amount of inert material, just big enough to create a globular unit of uniform size, is known as seed pelleting (Fig. 3). This technique gives young seedlings a minimal amount of nutrients. The technique of pelleting involves covering seeds with inert substances to ensure that their size and shape are consistent (77). Seed pelleting is an important process to reduce seed rate and to increase the seed handling efficiency of seeds. Standardization of amaranth seed pelleting for CO-2 variety was done and they concluded that 14 layers of TNAU pellet mixture with 3.2 mm of pelleted seed size gives maximum germination of 79 % among 12 layers and 16 layers of seed pelleting and it also possible for mechanized sowing of seeds (78). Iron ore can be used as a binder for pelleting the which increases the binding efficiency and increases the germination of the seeds (79). Seed pelleting with spinetoram is an effective way to control stripped flea beetle infestation (80). For small seeded species the effective way mechanized seed planting is done by seed pelleting. It is helpful method to increase the seed size and germination percentage (81).

Seed coating : The application of foreign materials on the outer surface of seed for improving seed appearance and handling characteristics and delivering active compounds is generally known as seed coating (82). Amaranth is known for its high nutritious content, rich in proteins, essential amino

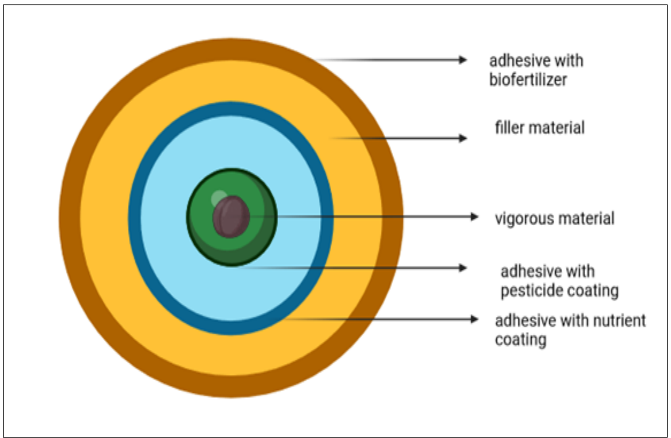

Fig. 3. Pelleted seeds.

acids and micronutrients like iron and calcium. However, its nutritional benefits can be limited by antinutritional factors such as phytates, oxalates and tannins, which reduce the bioavailability of minerals. Processing techniques like soaking, sprouting, fermentation and thermal treatments can help to reduce these compounds and enhance the digestibility and absorption of nutrients, thereby maximizing amaranth's nutritional impact on seed germination (83, 84).

The most important role of seed coating is to protect the seeds from pest and diseases (85). In amaranth, crop losses about 54.00 % and 43.76 % are mainly due to *Rhizoctonia solani* and *Fusarium oxysporum* to control these diseases by *Bacillus subtilis* strain BS58. It is also used as a seed coating material which reduces this mortality rate and increases the germination percentage of about 23 % when compared to control (86). Moreover, this *B. subtilis* by generating phytohormones like auxin, cytokinin, gibberellin and indole acetic acid (IAA), *B. subtilis* considerably enhanced the growth and development of the seedling. Additionally, it acted as a biocontrol agent and produced antibiotic substances like azine, oomycin, pyoluteorin, herbicolin and agrocin to protect against the pathogen (87). Another important disease caused by many biotic variables, particularly those that exist in soil, can induce damping-off illnesses by preventing seeds from germinating or seedlings from emerging (88).

Damping-off disease caused by *Pythium* spp. which greatly affects the germination of amaranth seeds and causes seedling death. When seeds are sowed, pathogens become active and can cause seed decay or damping-off disease in vegetables (89, 90). It can be effectively controlled by seed coating with *Gliocladium virens*, a biocontrol agent over the seed surface greatly controlling the occurrence of damping-off disease (91). *R. solani*, a root rot fungus causes the death of emerging seedlings. Using plant growth promoting bacteria (PGPBs) for seed coating to boost *A. hypochondriacus's* nutrient content is a crucial strategy for achieving food security and meeting the plant's demand for food, especially given the population's steady expansion (14).

Pest is another major constraint in amaranth production. Seeds of each selection were treated with either thiamethoxam (20 g/kg), metalaxyl-M (20 g/kg) and difenoconazole (2 g/kg) (1.25 ml ai/250 g seed) or imidacloprid (233 g/l), pentycuron (50 g/l) and thiram (3 ml ai/250 g seed). Coated seeds well performed by giving higher performance than the untreated controls in terms of germination (91). Individual amaranth hybrid seeds were treated with thiamethoxam (20 g/kg), metalaxyl-M (20 g/kg), difenoconazole (2 g/kg), imidacloprid (233 g/L), pencycuron (50 g/L) and thiram (107 g/L). The treated seeds were planted after 24 hr of treatment, the treated seeds are less infected by aphid attack than the control (92).

Seed treatment with nanoparticles : The application of nanomaterial over the surface of the seed is a new area of research they are more effective than conventional agrochemicals. These nano-coated seeds show greater catalytic activity due to their increased surface area. The reactivity of seeds can be affected by a greater amount of the nanomaterial contacting surrounding materials as its surface area per mass increases so this nanomaterial can be used to treat the seeds (93). Nano-priming can boost germination (94). It is mainly useful for nutrient delivery (95), pest and disease management (96), seed treatment (97) and enhanced nutrient uptake (98) (Fig. 4). TiO_2 photocatalytic activity helps the amaranth seed germination and helps to increase germination percentage by about 67 % when a concentration of 1 mg/cm^2 is applied (99). A high dose of more than 1 mg cm^{-2} TiO_2 causes tissue damage in amaranth seed crops. TiO_2 treated seeds influence gibberellic acid production which significantly increases the germination percentage of seeds (99).

CuO (0.12 µM) and ZnO (0.24 µM) nanoparticles are used in the amaranth seeds as a hydroponics system produce better germination result than the seeds grown as normal condition (100). GA_3 infused nanomaterial enhance the seed quality and seedling establishment. This nano seed treatment is a futuristic approach to increase production and it also has a higher percentage of success rate compared to others. Smaller quantity of nano material is enough to apply large quantity of seeds because it has high use efficiency. Seed treated with nanoparticles show increased germination and increased stress tolerance (Fig. 4). Seed treatment with nanoparticles should be increased because nano treated seeds shows uniform germination and increased field survival rate.

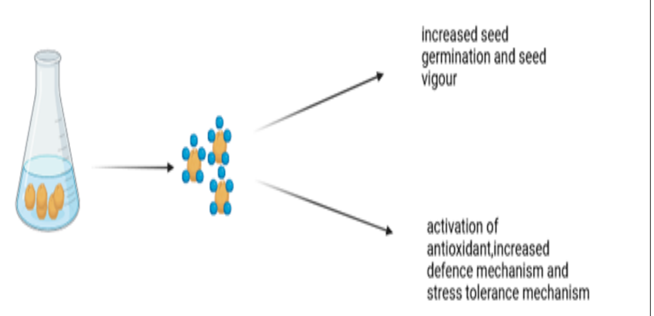

Fig. 4. Benefits of nano priming.

Conclusion

Enhancing amaranth seed quality through advanced seed treatment techniques is crucial for sustainable agriculture and global food security. These treatments, including seed priming, coating, pelleting and emerging technologies like cold plasma and nanoparticle applications, significantly improve germination, seedling vigour and crop resilience under varied environmental conditions. Methods such as hydropriming, hormonal priming and biopriming effectively mitigate abiotic stresses and boost crop performance, while seed coatings with microbial agents protect against soil-borne pathogens. Advanced innovations like plasma treatments and nanoparticles, such as TiO_2, demonstrate notable potential in promoting enzyme activity, germination and resilience to challenges like drought. Despite proven efficacy, adoption at the farm level remains limited due to a lack of awareness and accessibility. Bridging this gap requires policy support, enhanced extension services and targeted farmer education to facilitate widespread use of these techniques.

Future prospects

Future research on amaranth seed treatments should focus on understanding the molecular and biochemical mechanisms driving the effectiveness of techniques like priming, coating and nanoparticle applications. Investigating the physiological impacts of hydropriming, hormonal priming and biopriming can optimize their application for diverse environmental conditions. Advanced studies on innovative methods, such as cold plasma and nanoparticle treatments, are essential to refine protocols, ensure safety and enhance efficiency. Integrating emerging technologies like genome editing and bioinformatics with seed treatments holds promise for developing crops with superior stress resilience. Exploring the synergistic effects of combining traditional and advanced techniques can lead to customized solutions for specific challenges. Research should also prioritize creating cost-effective and scalable methods to increase accessibility for smallholder farmers. Additionally, studying the long-term effects on soil health and crop sustainability is critical. Collaborative efforts are needed to translate scientific advances into practical, sustainable solutions for amaranth cultivation and global food security.

Acknowledgements

Ravichandran Gomathi, acknowledges to Indian Council of Agriculture Research, New Delhi for providing ICAR-Junior Research Fellowship for writing this review on Amaranthus seed quality enhancement during her Masters' degree program.

Authors' contributions

RG contributed to the conceptualization, investigation, writing of the original manuscript and editing. ET was responsible for methodology, supervision and review. CT provided supervision and review, while PS contributed to supervision and review as well. SK was involved in methodology and review. ME played a key role in conceptualization, supervision, review and editing. KM contributed to conceptualization, methodology, supervision and review. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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