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SEED ENHANCEMENT FOR SUSTAINABLE AGRICULTURE: AN OVERVIEW OF RECENT TRENDS

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Abstract

Seed enhancements are post-harvest treatments that improve the performance of seeds such as germination, seedling growth and facilitate the delivery of seeds and other planting materials required at the sowing. Seed quality plays an important role in crop production and lack of quality seed is one of the major hindrances in bridging the yield gap. Seed enhancement process involves pre-sowing hydration treatments or priming, hardening, coating technologies, seed conditioning and pregermination but excludes treatments for control of seed borne pathogens. Some of the recent advances in seed enhancement techniques include nano-priming which involves soaking seeds in nano-particle solutions followed by drying and magneto priming which involves exposing of seeds to magnetic field. In magneto priming, magnetic field is used as a non-invasive physical stimulant to improve seedling vigour and stress tolerance of the crop in the field. Nanopriming can augment performance of seeds in many ways such as enhancing α-amylase activity, increasing soluble sugar content to support early seedlings growth, up-regulating the expression of aquaporin gene in germinating seeds, increased stress tolerance through lower ROS production, creation of nanopores for enhanced water uptake etc. This paper reviews the scope and relevance seed enhancement for sustainable agriculture with a special emphasis on recent advances in seed priming technologies.

Key words*:* seed enhancement, seed priming, germination, magnetopriming, nanopriming.

Introduction

Seed is the most important input for crop production. Availability of quality seeds of different crops is considered very crucial for achieving higher productivity of crops. The quality of seed is known to contribute greatly towards increase in yield and lack of quality seed adversely influences the production of food grains. Faster and uniform germination of seeds and seedling emergence are the vital factors that determines better field stand of crops (Mahakham *et al.*, 2017). The process of seed germination starts with uptake of water by the seed through imbibition and terminates with the protraction of the embryonic axis, typically the radicle, through the seed envelope resulting in the protrusion of root followed by shoot (Rajjou *et al.*, 2012; Mahakham *et al.*, 2017). The performance of seeds in terms of germination, seedling growth and vigour can be increased by seed treatments involving numerous invigoration techniques. The techniques of seed invigoration are not new and there is evidence of pre-sowing soaking of seeds in water and honey to invigorate them by the farmers of ancient Greek civilization (Evenari, 1980). Invigoration of seeds involving different organic and inorganic substances have been developed and practiced by the farmers over the years. Seed enhancement or invigoration includes a wide variety of treatments of seeds which improves their performance attributes like germination and early seedling growth. Some of the commonly used seed enhancement methods are priming, steeping, hardening, pregermination, pelleting, coating, encrusting, etc. but they exclude treatments for management of seed borne pathogens. This seed invigoration technology which includes a range of physical, physiological and biological treatments helps the seed to overcome different germination constraints and favours uniform crop stand, early development and higher yields of crops (Afzal *et al.*, 2016). While conventional seed treatments are intended to eradicate the seed borne pathogens and pests, seed enhancement aims at invigoration of seeds to

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improve germination and seedling growth. Priming is a technique of seed enhancement which partially hydrates seeds in the solution of natural or synthetic compounds under specific environment till the pre-germinative metabolism are initiated without emergence of radicle (Mahakham *et al*., 2017; Ibrahim, 2016). Seed priming is known to enhance germination, seedling establishment and yield of crops. Though a number of priming agents of diverse nature are used for priming of seeds, the effectiveness of the priming solution which varies from crop to crop depends on the optimization and suitability of priming agents. There is a growing need to find out newer priming agents as well as technologies to enhance seed germination and seedling growth of various crop plants. Magnetopriming and nano-priming are some of the recent advances in seed enhancement technology involving nonconventional and eco-friendly means. Green nano-particles, which can be developed through bioreduction of metal ions through plant extracts, are economical, eco-friendly, non-toxic and biocompatible for agricultural use. Agriculture is the main stay of majority of human populace around the world. This age-old practice is a fundamental operation required for the survival of mankind on earth. Rapid expansion of human population and technological advancement has gradually turned agriculture to more exploitative and exhausting natural resources with a concomitant degradation of environment (Poddar *et al*., 2018). Sustainable agriculture involves the effective management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources (CGIAR, 1978; Panda *et al*., 2012). Seed enhancement which involves improvement of performance of seeds through different treatments can improve germination, seedling vigour and yield of crops as well as induce biotic and abiotic stress tolerance in plants reducing the over dependence on harmful chemicals such as pesticides and fungicides.

Seed priming

Seed priming is one of the most important physiological seed enhancement method. It is a hydration treatment of seeds which involves controlled imbibition and induction of the pregerminative metabolism (activation), but radicle emergence is prevented (Kalaivani *et al*., 2010). The hydration treatment is withdrawn before desiccation tolerance of the seed is lost (Bose *et al*., 2018). Seeds can be primed by soaking seeds in solutions supplemented with plant hormones or beneficial microorganisms for a specific period of time (Araújo *et al*., 2016). The hydrated primed seeds can be reverted back to safe moisture content by drying for storage, distribution and planting. Seed priming is an easy and effective technique to get speedy and uniform emergence, high seedling vigour and higher yields of crops. This controlled hydration technique stimulates metabolic processes during early phase of germination before protrusion of radicle (Araújo *et al*., 2016). Higher rate of germination of primed seeds primarily happens because of reduction in the lag time of imbibition (Araújo *et al*., 2016), enzymatic activation, accumulation of germination enhancing metabolites (Hussain *et al*., 2015), metabolic repair during imbibition and osmotic adjustment (Hussain *et al*. 2016). The priming induces activation of cellular defense responses in plants, that imparts tolerance to subsequent exposure to environmental stresses (Jisha *et al*., 2013). Seed priming is also known to improve the germination of weak, damaged or aged seeds (Dragicevic *et al*., 2013). Seed priming can enhance germination and seedling establishment by curtailing dormancy, increasing desiccation tolerance and enhancing seedling growth resulting in better crop stands and yields. The positive effects of priming on the seeds are also attributed to the specific metabolic changes commencing inside the seed with onset of water uptake through imbibition (Bray, 1995). Subsequent rehydration of primed seeds during sowing triggers many cellular processes like *de novo* synthesis of proteins and nucleic acids and production of ATPs, accumulation of sterols and phospholipids, activation of antioxidant system and repair of DNA. Seeds are exposed to different environmental stresses during the developmental process, post-harvest period and germination in the field. These environmental stresses can damage different cellular biomolecules such as lipids, proteins and nucleic acids (Paparella *et al*., 2015). The repair mechanisms operational in primed seeds such as DNA repair plays a vital role preserving the seed vigour under adverse condition (Rajjou and Debeaujon, 2008). Proper repairing of DNA not only facilitates progression of cell cycle in the embryo cells but also replication of DNA (Ventura *et al*., 2012). DNA repair forms the major basis of pregerminative metabolism activated in the primed seeds with uptake of water and concurrent uncontrolled production of ROS. Most of the DNA repair pathways such as Base Excision Repair (BER), Nucleotide Excision Repair (NER) and Base and Nucleotide Excision Repair active during early phase of seed germination (imbibition) helps to maintain the genome integrity (Co´rdoba-Can˜ero *et al*., 2014). The activity of antioxidant enzymes such as Superoxide Dismutase (SOD, EC 1.15.1.1), Ascorbate Peroxidase (APX, EC 1.11.1.11), Catalase (CAT, EC 1.11.1.6) and Glutathione Reductase (GR, EC 1.8.1.7) are known to be enhanced during priming of seeds (Yao *et al*., 2012; Chen *et al*., 2014). The priming protocol of different seeds can be optimised by studying the effect of priming agents on DNA repair mechanisms of seeds (Balestrazzi *et al.*, 2015). Priming also decreases the storability of the seed and the primed seeds need cool storage temperatures. Prolonged treatment of seeds during priming may lead to increased oxidative injury to DNA irreversibly affecting the seed viability. Hence optimization of correct time of priming treatment is very important considering its critical role in seed enhancement and to prevent loss of viability due over soaking (Lutts *et al.*, 2016). Some of the commonly used methods of seed priming are hydropriming, osmo-priming, hormonal-priming, halopriming, matrix priming and pregerminated seeds.

Hydropriming or drum priming is a method of priming of seeds through pre-soaking in water. This method involves continuous addition of a small amount of water to the seeds (Leubner, 2019). A drum is often used for this purpose and the water also can be applied by humid air (Leubner, 2019). On-farm steeping is a low cost and useful hydropriming technique that is practiced by incubating seeds of cereals and legumes for a short span of time in warm water (Leubner, 2019). This method of seed priming helps the crop to cope with abiotic stresses faced by the crops in the field (ICAR, 2011; Leubner, 2019).

Osmopriming (osmo-conditioning) is the method of seed priming technique in which the seeds are incubated in well aerated solutions with low water potential followed by washing and drying (Leubner, 2019). Osmolytes such as mannitol, polyethylene glycol (PEG) or potassium chloride (KCl) are used to make solutions with lower water potential. Preconditioning through osmolyte priming invigorates the seeds resulting in uniform and higher vigour and field emergence leading to better crop stand (ICAR, 2011; Leubner, 2019). Halopriming is done by soaking the seeds in osmotic solutions such as Sodium chloride (NaCl), Potassium nitrate (KNO_3) and Potassium chloride (KCl).

Hormonal-priming involves soaking of seeds in different solutions of phytohormones and plant growth regulators such as auxins (IAA, IBA, α-NAA), gibberellins, cytokinin, brassinosteroid, abscisic acid etc. Priming with Gibberellins (GA_3) has been found to help in overcoming seed dormancy and enhance germination and early seedling growth of cereals (Karssen *et al.*, 1989).

Matrix priming or matriconditioning is done through the incubation of seeds in moist solid, insoluble matrices like vermiculite, cross-linked extremely water-absorbent polymers and diatomaceous earth (Khan *et al.*, 1990). However this method involves a process of slow imbibition.

Use of pregerminated seeds is another method of seed enhancement, which is possible in a few crop species. In contrast to normal priming, seeds are allowed to have radicle protrusion (Leubner, 2019). This technology involves soaking of seeds till the physical process of germination is initiated followed by planting of the wet seeds whereas priming involves seed soaking for short period followed by drying and subsequent storage of seeds (Leubner, 2019). Fast and uniform germination and seedling growth is possible through the use of pregerminated seeds.

The seeds hydrated by primed are dried back to optimum moisture content suitable of safe storage. The primed seed usually perform better in stressful conditions than non-primed seeds. Priming not only enhances general invigoration of seeds but also helps in overcoming many seed limitations such as post-harvest dormancy, photo-dormancy and thermo-dormancy.

On-farm seed priming in another method of priming in which farmers can prime their own seed by pre-sowing on-farm soaking of seeds by knowing the safe limits or maximum duration of time for the seeds can be soaked. Soaking of seeds beyond safe limits could lead to damage of the seed and young seedling. These safe limits are determined for each variety so that germination will not continue once seeds are removed from the water. In this method the seeds are generally soaked overnight (8-10 hours) by the farmers followed by surface drying and immediate sowing. However, some seeds like rice and maize require more soaking period (up to 16-18 h.) for better performance (Harris, 2004). This method of seed priming is known very effective in increasing yields of most of the cereals and legumes (Harris, 2004). On-farm seed priming is an indigenous technical knowledge known to farmers since ages. The farmers of Malwa plateau, Madhya Pradesh and Odisha had been practising it since long (ICAR, 2011).

Primed seed can germinate after getting additional moisture from the soil after sowing. Usually the seeds are primed by soaking the seeds overnight and surface dried before sowing next day. The primed seeds appear to be slightly swollen and weighs more than the non-primed seeds. However, these seeds can be treated in the same way during sowing. The primed seeds can be surface dried and can be stored for some time to avoid unfavourable weather condition such as heavy rain and can perform better than non primed seeds when sown latter (ICAR, 2011).

Table 1: Summary of the effects of nanoparticles (NPs) on seed and seedling performance.

Species	Nanoparticles (NPs) applied	Effects described	Reference
Alnus subcordata	100 mg /l	Nano priming of seeds with multi-walled carbon nanotubes (MWCNTs) enhanced seed germination and drought stress tolerance	Rahimi *et al.*, 2016
Boswellia ovalifoliolata	30 µg/ml	Silver nanoparticles (SNPs) enhanced germination and seedling growth	Savithramma *et al.*, 2012
Triticum aestivum L.	50ppm	TiO_2, ZnO and chitosan nanoparticles enhanced seed germination and seedling growth of wheat.	Rawat *et al.*, 2018
Alum cepa L.	-	Nanopriming with silver nanoparticles (AgNPs), gold nanoparticles (AuNPs) had a significant impact in seed germination, growth, quality and yield	Acharya *et al.*, 2017
Dodonaea viscosa L.	30 mg/ 150 and 100 mg/l	Priming with MWCNTs, (i) improved germination, mean germination time, seedling growth, (ii) increased drought tolerance	Yousefi *et al.*, 2017
Oryza sativa L.	5 and 10 ppm	Priming with silver nanoparticles (AgNPs) significantly improved germination parameters and seedling vigor	Mahakham *et al.*, 2017
Cajanus cajan L.	25 ppm	Seed coating with Fe NPs improved germination parameters such as germination percent, speed of germination, seedling growth and vigour index	Raju and Rai, 2017
Petroselinum crispum	30 mg/ml	Nano-anatase (TiO_2) increased germination parameters, seedling growth, vigor index and chlorophyll content of seedlings	Dehkourdi and Mosavi, 2013
Triticum aestivum	-	Seed treatment with metal nanoparticles (Zn, Ag, Fe, Mn and Cu) improved the tolerance against eyespot of wheat	Panyuta *et al.*, 2016
Spinacia oleracea	-	Seed treatment with iron pyrite (FeS_2) nanoparticles resulted in a greater number of broader leaves, increased biomass production and enhanced concentration of Ca, Mn and Zn in the leaves.	Srivastava *et al.*, 2014
Vigna radiata L.	0.02 %	Seed priming with Titanium oxide (TiO_2) nanoparticles improved germination and seedling growth of green gram.	Maroufi *et al.*, 2011
Oryza sativa L.	20 mg/ L	Germination seedling growth of aromatic rice cultivar Gobindabhog was enhanced by priming with zero valent iron (nZVI) nanoparticles	Guha *et al.*, 2018
Citrullus lanatus (Thunb.) Matsum. and Nakai	20, 40, 80 and 160 mg/ L	Seed priming with Iron oxide nanoparticles (Fe-NPs) modulated the antioxidant potential and jasmonate linked defences responses in watermelon seedlings	Kasote *et al.*, 2019
Triticum aestivum	300, 600, 900, 1200 mg/L	Seed priming with Silicon nanoparticles (SiNPs) improved growth, yield and chlorophyll contents of wheat and alleviated oxidative stress through increased activity of antioxidant enzymes.	Hussain *et al.*, 2019

Nanopriming

Nanotechnology, the technology involving manipulation of matters at nanoscale has immense potential in modern agriculture. This novel technology can transform modern agriculture and play a vital role in increasing productivity of crops. The use of various engineered nanoparticles (NPs) has become increasingly popular in past decade. Nanoparticles are incorporated into various agri-inputs such as pesticides, fertilizers and plant growth regulators to enhance their efficiency and to promote sustainable agricultural practices. Some of the recently developed nanofertilizers, nanopesticides, nanosensors and nano-formulated plant growth regulators are examples of increasing use of this technology in agriculture (Mahakham *et al.*, 2017). The use of several metal-based nanoparticles (NPs) such as silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), iron nanoparticles (FeNPs and FeS_2NPs), copper nanoparticles (CuNPs), titanium nanoparticles (TiO_2NPs), Zinc nanoparticles (ZnNPs, ZnONPs and nZVI), cerium oxide nanoparticles (CeNPs) and carbon-based NPs such as fullerene and carbon nanotubes for seed pre-sowing seed treatment to promote germination, early seedling growth and environmental stress tolerance in some crop plants has become popular in recent years (Mahakham *et al*., 2017; Guha *et al*., 2018). Nano priming is a novel and innovative technique of improving germination, seedling vigour and growth, through the use of nanoparticles such as silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), multi-walled carbon nanotubes (MWCNTs) and other nanoparticles for priming of the seeds (Table 1). Nanopriming can improve performance of seeds in different ways such as enhancing α-amylase enzyme activity, increasing soluble sugar content to support seedlings growth, stimulating the up-regulation of aquaporin genes in germinating seeds, increased stress tolerance through lower ROS production, formation of nanopores for increased water uptake, activating antioxidant systems in seeds, production of hydroxyl radicals for cell wall loosening and hastening hydrolysis of starch as a nanocatalyst (Mahakham *et al*., 2017). Seed priming with silver nano particles (AgNPs) accelerates seed germination and seedling growth by enhancing the activity of amylase enzyme in rice seeds (Mahakham *et al*., 2017). Priming of seeds influences the imbibition of seeds greatly at early stage of germination process. Primed seeds absorb water faster than the unprimed control seeds. Nanopriming not only affects the water metabolism but also starch metabolism of rice seedling. The total soluble sugar content of seedlings is known to increase by nanopriming owing to increased hydrolysis of starch by α-amylase. Nano-priming with AgNPs promotes dehydrogenase activity in rice seedlings, which is the indicator of vitality of seeds. Nano-priming with AgNPs is known to up regulate aquaporin gene expression in rice. The expression levels of aquaporin genes PIP 1;1 and PIP 1;2 increased by priming leading to high water uptake. Nano-priming is known to modulate the activity of antioxidant enzyme activity such as SOD and CAT. The process of nanopriming, possible mechanism of action and morpho-physiological effects on plant in presented in fig. 1.

However, the chemically synthesized nanoparticles are expensive, potentially harmful to the environment (Makarov *et al*., 2014) and not cost effective for agricultural use. Green nanoparticles can be produced

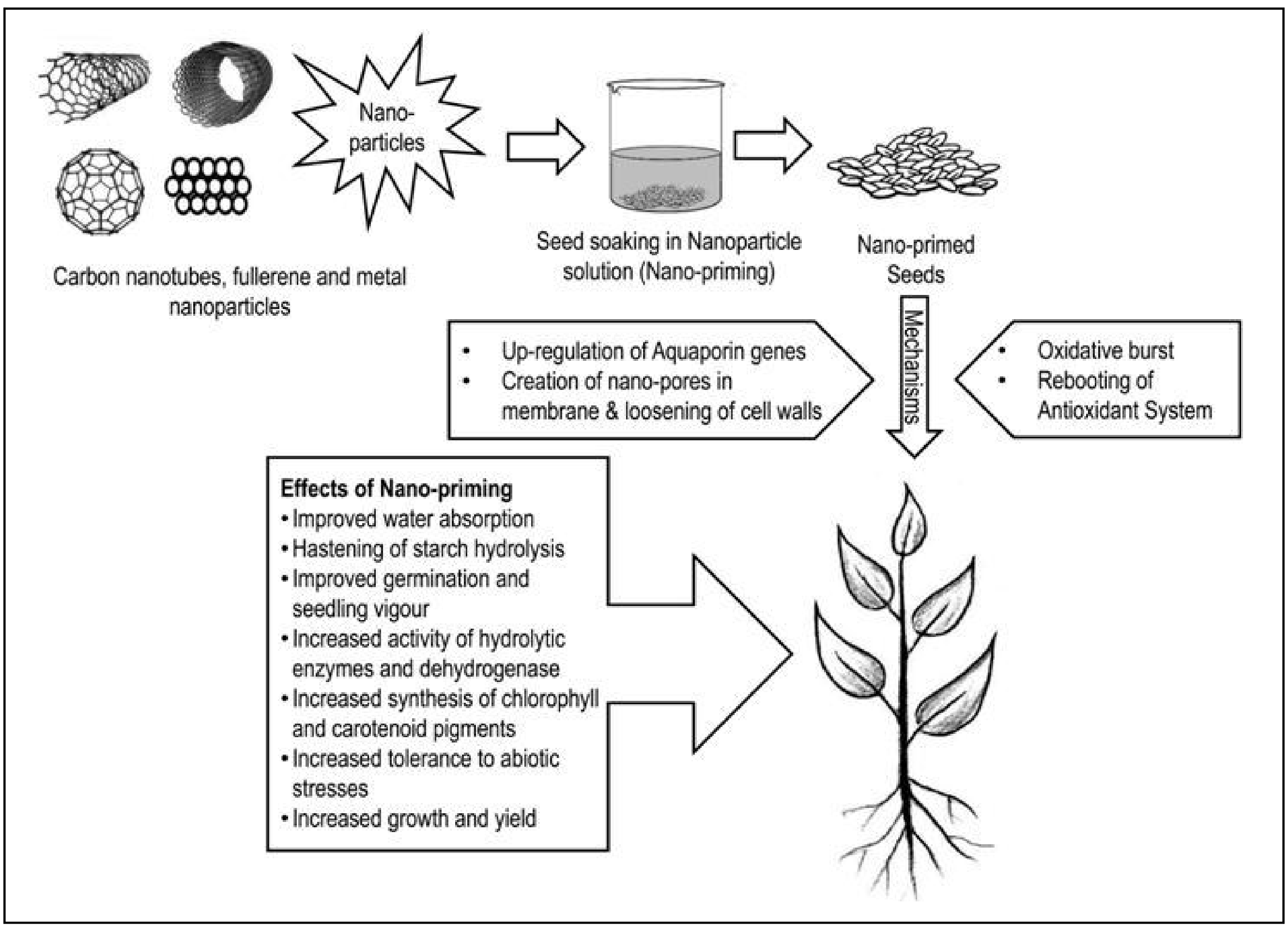

Fig. 1: Nanopriming: process, possible mechanism of action and morpho-physiological effects on plant

Table 2: Summary of the effects of magnetic fields (MFs) on seed and seedling performance.

Species	Magnetic fields (MFs) applied	Effects described	Reference
Triticum aestivum	30 mT	Enhanced antioxidative system of seedling under flooding stress, but did not improve germination and seedling growth	Balakhnina *et al.,* 2015
Tagetes patula	100 mT	Improved germination parameters, seedling vigour and promoted early growth, enhanced starch metabolism of seeds	Afzal *et al.* 2012
Vigna radiata	5 mT	Improved germination, and activity of α-amylase enzyme in seeds	Reddy *et al.,* 2012
Cucumis sativus	200 mT	Improved germination parameters, seedling growth, water uptake, activity of hydrolytic enzymes and antioxidant enzymes in seeds	Bhardwaj *et al.,* 2012
Zea mays	100 and 200 mT	Improved seedling growth, relative water content, stomatal conductance, chlorophyll content and photosynthesis and decreased levels of hydrogen peroxide and antioxidant enzymes under moisture stress.	Anand *et al.*, 2012
Glycine max	200 and 150 mT	Improved germination, seedling vigour and growth parameters, biomass accumulation, leaf area, photosynthetic efficiency, protein content of leaf. Improved performance index of Photosystem II in leaves and light harvesting efficiency of leaves and biomass accumulation	Shine *et al.* 2011; Baby *et al.*, 2011
Glycine max	10 and 100 Hz 1500 nT PMFs	Increased germination, fresh weight of shoots and roots, leaf leaf area, plant height, total soluble sugar, total protein and phenol content	Radhakrishnan and Kumari, 2013
Helianthus annuus	50 and 200 mT	Increased germination and seedling vigour, growth and biomass production; Improved membrane integrity of seed coat; Increased the activity of enzymes such as alpha-amylase, dehydrogenase and protease in germinating seeds.	Vashisth and Nagarajan, 2010
Lycopersicon esculentum	100 and 170 mT	Improved crop growth parameters such as leaf area, dry weight and relative growth rates. Increased tolerance to biotic stresses such as geminivirus and early blight	De Souza *et al.,* 2006
Vicia faba	100 iT	Improved growth of seedlings	Rajendra *et al.*, 2005
Quercus suber	50-Hz of 15-μT Sinusoidal Magnetic Field (SMF)	Improved sprouting rate and seedling growth parameters such as main shoot length, axillary shoot formation and seedling biomass	Celestino *et al.*, 2000
Lycopersicon esculentum	100 mT	Improved germination and seedling vigour	Anand *et al.*, 2019
Vigna radiata (L.) Wilczek	10Hz, 50Hz, 100Hz of 1500 + 250nT Sinusoidal Magnetic Field (SMF)	Increased calcium and total phosphorus content in the seeds	Nair *et al.,* 2018
Cicer arietinum L.	100 mT	Increased root volume and surface area which enabled the crop to utilize higher moisture during the active growth period under moisture stress. Improved water use efficiency, biomass production and radiation use efficiency	Mirdha *et al.,* 2016
Solanum tuberosum	75, 150 and 300mT	Reduced days of emergence and increased plant height and total chlorophyll content	Yildiz *et al.,* 2017
Lens culinaris Medik.	75, 150 and 300mT	Improved germination, seedling growth and total chlorophyll content	Yildiz *et al.*, 2017
Lathyrus sativus L.	75, 150 and 300mT	Improved germination, seedling growth, total chlorophyll content	Yildiz *et al.*, 2017

through *in vitro* approaches in which plant extracts are used for the bioreduction of metal ions to form nanoparticles. This inexpensive approach of nanoparticle production has been demonstrated using extracts from a variety of plant species in combination with different acids and salts of metals, such as copper, gold, silver, iron and platinum (Makarov *et al*., 2014). The green nanoparticles of gold and silver are known to be very effective in improving the performance of seeds through priming. The effectiveness of nanopriming has been demonstrated in different crops like rice, maize, onion, green gram and some other crops.

Magnetopriming

Magnetic field has been found to have profound effect on living organisms including plants. The earth's magnetic field (50 mT) is a natural component of the environment (Belyavskaya, 2004). The magnetic flux density is measured by the unit Tesla (T) which corresponds to $kgs^{-2}A^{-1}$, where A denotes Ampere. Both static magnetic field (SMF) generated by a permanent magnet like magnetic field of earth or by industrial processes and electromagnetic field (EMF) generated by electrically charged objects are utilized in agriculture for priming of seeds (Mitchell and Cambrosio, 1997; Baby *et al*., 2011). During magnetopriming process the seeds are exposed to magnetic field which is a non-invasive physical stimulant for a specific duration of time, to induce physiological changes in the seed. Unlike normal seed priming which involves soaking of seeds in priming solutions, the dry seeds are exposed to magnetic field for magnetpriming to improve germination, seedling vigour, yield and stress tolerance of crops (Anand, 2014; Kataria, 2017). Magnetopriming are often effectively used as a pre-sowing treatment for mitigating adverse effects of various environmental stresses such as drought, salinity, disease and pests during germination and early crop growth (Kataria, 2017).

Magneto-primed seeds show enhanced rate of germination, vigour, root and shoot growth and biomass production. This method of seed priming has been found to boost the performance of seeds of maize, wheat and chickpea and increased water absorption characteristics of seeds resulting in quicker hydration of enzymes such as amylase, protease and dehydrogenase, early germination and increased vigour of seedlings under water deficit and salinity stress (Table 2). The exposure the seeds of different strengths and durations of magnetic field on the germination, growth and physiology of various crops was previously reviewed by Araújo *et al*., (2016). This method of seed enhancement also increased germination and seedling growth and vigour of chickpea and was efficient in mitigating salinity stress at the stage of early crop growth (Thomas *et al*., 2013). Magnetopriming of tomato seeds (exposure to magnetic field of 100 mT for 30 minutes followed by imbibition for 12 hours) was found to increase production of H_2O_2 in seeds (Anand *et al*., 2019).

H_2O_2 signalling was found to plays a *vital* role during magnetopriming of seeds (Anand *et al*., 2019). Balanced H_2O_2 acts as a signalling centre for the regulation of seedling vigour in different ways. The antagonistic relationship between GA_3 and ABA is known to play an important role in dormancy as well as germination of seeds. The role of H_2O_2 as a signalling hub for regulation of dormancy and germination through concurrent activation of ABA catabolism and GA_3 biosynthesis is well known (Kucera *et al*., 2005; Razem *et al*.,

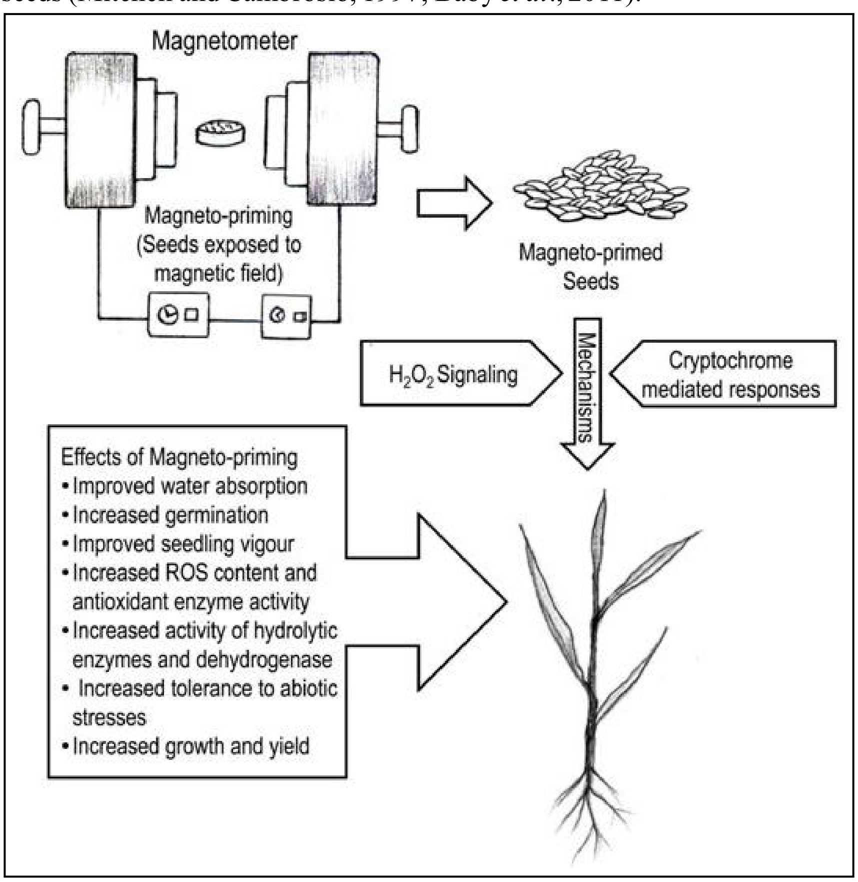

Fig. 2. Magnetopriming: process, possible mechanism of action and morpho-physiological effects on plant

2006; Weiss and Ori, 2007). According to Anand *et al*. (2019) metallothionein and receptor for activated C kinase 1 (RACK1) are also considered to play vital role in the oxidative signalling process as well as scavenging and production of hydrogen peroxide. Several genes associated with positive control of germination are known to be regulated by H_2O_2 through carbonylation of protein, activation and modulation of kinase transduction cascades along with concomitant change in cellular redox states. Increased levels of hydrogen peroxide found in faster germinating magneto-primed seeds, under both water deficit and salinity stress has been attributed for its role in oxidative signalling during seed germination process. The oxidative window formed by production of reactive oxygen species ensured that faster germination rate and vigorous seedlings from magneto-primed seeds. Improved root system integrated with higher photosynthetic efficiency and efficient partitioning of Na^+ increased yield from magneto-primed seeds under salinity stress (Anand, 2014). Unlike other conventional priming techniques, it avoids seed hydration and dehydration cycle, allows storage of the seed at room temperature and is eco-friendly (Anand, 2014; Kataria, 2017). Magnetopriming has been found to enhance the activity of hydrolytic enzymes such as α-amylase, dehydrogenase and protease in seeds during imbibition. The enhanced germination, seedling vigour and rooting traits of SMFs-treated seeds may be attributed to the higher activities of hydrolysing enzymes (Araújo *et al*., 2016). However, the mechanism of perception of MFs by plants and regulation of the signal transduction pathway is not fully understood. MF-perception/signaling in plants is considered to be mediated by the blue light photoreceptors-cryptochromes (Ahmad *et al*., 2007; Araújo *et al*., 2016). The process of magnetopriming, possible mechanism of action and morpho-physiological effects on plant is presented in fig. 2.

Seed Coating

Seed coating involves application of a layer of exogenous material around the natural seed coat (Pedrini *et al*., 2017). The seed coating is intended to modify the physical properties to improve handling of seeds through standardisation of seed weight and size and facilitate delivery of active ingradients such as protectants, nutrients, symbionts, soil adjuvant, phytoactive substances, growth regulators, colours and tracers etc. (Kaufman, 1991; Avelar *et al*., 2012; Halmer, 2008; Pedrini *et al*., 2017). There are three different types of seed coating namely film coating, encrusting and pelleting which are categorized according to their physical characteristics such as weight, size and sorting properties (Pedrini *et al.*, 2017). The film coating involves application of a thin layer of external material (usually < 10% of seed weight) around the seed, whereas encrusting involves application of a thick coating around the seed leading to significant increase in weight and volume of seed but without altering the original seed shape (Pedrini *et al*., 2017). The application of a very thin layer of high-quality polymer around the seed during film coating causes virtually no change in size and weight of seeds (Anonymous, 2019a). Though both encrusting and pelleting involves application of a thick layer of exogenous coating around the seed, pelleting differs from encrusting in the sense that encrusting does not alter the original shape of the seeds and pelleting changes the original shape of coated seeds. The film coated and encrusted seed are usually distinguished by weight whereas pelleted seeds are sorted by diameter (Pedrini *et al.*, 2017). The synthetic polymers used as binders during seed coating help in adherence and retention of active ingredients onto the seed and modify imbibition to facilitate early germination (Leubner, 2019). The temperature sensitive polymers regulate water uptake by the seed at specific temperature thresholds to limit germination of seeds only at the onset of favourable environmental conditions suitable for continued growth (Pedrini *et al*., 2017; Leubner, 2019).

Seed pelleting in involves application of a very thick coating around seed which can cover irregular seed shapes (Pedrini *et al*., 2017) usually resulting in spherical shape (irregular shaped seeds change into spherical shape) and the thicker artificial coating makes it impossible to discriminate the initial seed shape (Taylor *et al*., 1998). The irregular shape of seeds of some crops like lettuce and sugar beet etc. or smaller seed size of Begonia, Calceolaria and some other horticultural crops make it difficult sowing mechanically. The seeds become more uniform in shape, weight and size through pelleting which makes facilitates easier and precise planting through planters. Seed planters with adjustable for row spacing can help in planting at correct distances and depths with less seed loss (Anonymous, 2019a). Nutrients can be coated on the seeds through pelleting. The active ingredients as well as suitable protectants (fungicides and insecticides) can also be incorporated into the pellet to protect some species from diseases and pests (Anonymous, 2019a). Pelleting also favours placing of desired quantity of active chemical ingredients near the emerging seedling, which can be used more efficiently (ICAR, 2011). Pelleting not only increases the size of small seeds but also reduces the seed rate of crops. Hence seed coating serves as an important delivery system of active materials to the crop (Anonymous, 2019a). The seed coating or encapsulation technology has immense potential for effective control of both seed borne disease and pest through delivery pesticides onto the seeds directly. The use of chemicals for pest and disease management can be reduced greatly by the application of this environment friendly technology. Seed coating using natural or synthetic adhesive (*e.g.* starch gruel or carboxy methyl cellulose), natural filler (*e.g.* arappu leaf powder, neem kernel powder or vermicompost and Thiram 0.3% or $ZnSO_4$ (0.3 g/kg) enhances field emergence and crop growth in soybean. Storability of the coated seed is also satisfactory up to 3 months (ICAR, 2011).

Seed hardening

Seed hardening is a method of physiological preconditioning of the seed by hydration to tolerate drought under rainfed condition (ICAR, 2011). Seeds can be hardened to induce abiotic stress tolerance such as drought and cold tolerance in crops. The initial drought and cold stress of crops can be overcome by imposing these treatments to the seeds. These cold tolerance treatments, which are applied to germinated seeds are meant for only temperate crops and tree seeds. However, the seed: solution ratio (1:1), duration of soaking and method of drying are considered to be very important factors during hardening of seeds (Anonymous, 2019). Seed hardening is known to enhance the germination, vigour, seedling (root and shoot) growth and yield. It helps in the uniformity of seedling emergence and induction of early flowering and uniform seed setting and maturity. However, the success of this treatment is influenced by the method of seed hardening process (Anonymous, 2019). The amount of solution used for hardening process should never be higher than the amount of the seeds to ensure the imbibition of all the solution by the seeds. The solutions should be sufficient for the seeds and excess residual solution may cause leaching effect. The germination process starts after imbibition of water by the seeds. The seeds should be dried back to original moisture content after soaking process is over (Anonymous, 2019). The time required for completion of germination process by hardened seeds is lesser than that of non-hardened seeds. The chemicals commonly used for seed hardening are Calcium chloride ($CaCl_2$), KCl (Potassium chloride) and Potassium dihydrogen phosphate (KH_2PO_4). The method of seed hardening involves soaking of seed in water or solution for limited period in suitable seed to solution ratio followed by drying in shade to restore the original moisture content of the seed.

Seed fortification

It is a process of seed invigoration which helps in augmenting the vigour or initial strength of the seed to improve the initial field establishment and consequently final yield of the crop (Vishwanath *et al*., 2015). It is the impregnation of the seeds with beneficial substances such as of inorganic nutrients, growth regulators and vitamins through the imbibition phase to enrich the endogenous level of bioactive substances. In this process, seeds are partly hydrated to let metabolic activities to occur but prevent germination of seed. The partly hydrated seeds are then dried back to their original moisture content and weight for routine handling. The fortified seeds are found to germinate earlier than non-fortified seeds. Seed fortification favours supply nutrients to seeds and to achieve the high vigour under unfavourable of soil reactions conditions. In this method, the moisture content of seeds is increased up to 20-25% by soaking the seeds in solutions of equal volume for a duration of 6 to 24 hours to facilitate endogenous impregnation of chemicals. However, the choice of chemicals, their concentration and duration of seed soaking varies from crop to crop. Seed fortification with 0.5 to 1% of $MnSO_4$ is known to improve oxidation-reduction potential of seeds ultimately leading to higher germination (ICAR, 2011).

Seed conditioning

The harvested seeds from the field are rarely pure and contains impurities such as crop seeds, weed seeds and inert materials including poor quality seeds (Taylor *et al*., 1998). The main objectives of conditioning are removal of these impurities from the seed lots as well as upgradation or elimination of the poor quality from the high-quality seeds (Copeland and McDonald, 1995). The immature, damaged or off-sized seeds are considered poor quality seeds. This method of upgrading enhances the quality of seeds by improving germination and seedling growth characteristics of the seed lot. Seed conditioning commonly involves the exploitation of the physical parameters such as shape, size and weight (Brandenburg, 1977), while other parameters such as colour and surface texture are used as secondary techniques (Brandenburg and Park, 1977). In the process of seed conditioning dry seeds are usually conditioned on the basis of different physical characteristics by a number of steps involving different equipments (Taylor *et al*., 1998). This is also a useful practice for mid-storage correction of seeds. There are two different methods of seed conditioning such as moist sand conditioning-drying and moist sand conditioning and soaking-drying.

Moist sand conditioning-drying

The invigoration of seeds through moist sand condition conditioning involves thorough mixing of seeds with pre-moistened sand. In this method seeds are mixed with three times of air-dried sand to facilitate slow and progressive uptake of moisture. Required amount of water should be added to the prewashed and dried fine-grained sand to maintain the moisture content of the sand in the range of 5-10%. The amount of water added to the sand should be sufficient to start metabolic reactions but insufficient to initiate germination. The mixture of dry seed and pre-moistened sand is usually kept at room temperature for 16-36 hours depending on the material and moisture content (Anonymous, 2019). The seeds are found to absorb moisture from the moistened sand during incubation. The hydrated seeds are separated from sand by sieving and dried back to the original weight (Renganayaki and Sripunitha, 2010).

Moist sand conditioning and soaking-drying

This method of seed conditioning involves two steps. The first step involves conditioning of seeds by mixing with moist sand for 24 hours following the method of moist sand conditioning-drying (Anonymous, 2019). The second step involves again soaking of moistened seeds in water for 2 hours followed by drying back to its original moisture content (Renganayaki and Sripunitha, 2010).

Conclusion

In advent of global warming and consequent climate, sustainable crop production can only be achieved through a good crop stand. Seed enhancement technologies which involve a range of seed treatment approaches such priming, hardening, pelleting, conditioning etc. has immense application in modern agriculture. It is not only useful for improving crop stands through better germination rates and seedling vigour but also improves crop yields under different biotic and abiotic stresses. This low cost and eco-friendly technology can be a commercially viable option for the farmers as seed enhancement reduces the use of chemical fertilizers and other agrochemicals. Recent advances in seed priming technologies such as nano-priming and magneto-priming, can also augment crop growth and yield and improve the tolerance of crops to different environmental stresses. Bio priming involving different microorganisms like bacteria and fungi can also be useful for control of diseases and growth promotion of plants. Seed invigoration and nutripriming can also improve the growth of crops through availability of essential nutrients to the crops. However, integration of physiological and molecular approaches with seed enhancement technologies can contribute greatly to the performance of crops.

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