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Recent developments in physical invigoration techniques to develop sprouts of edible seeds as functional foods

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For nutritional security, the availability of nutrients from food sources is a crucial factor. Global consumption of edible seeds including cereals, pulses, and legumes makes it a valuable source of nutrients particularly vitamins, minerals, and fiber. The presence of anti-nutritional factors forms complexes with nutrients, this complexity of the nutritional profile and the presence of anti-nutritional factors in edible seeds lead to reduced bioavailability of nutrients. By overcoming these issues, the germination process may help improve the nutrient profile and make them more bioavailable. Physical, physiological, and biological methods of seed invigoration can be used to reduce germination restraints, promote germination, enhance early crop development, to increase yields and nutrient levels through sprouting. During sprouting early start of metabolic activities through hydrolytic enzymes and resource mobilization causes a reduction in emergence time which leads to a better nutritional profile. The use of physical stimulating methods to increase the sprouting rate gives several advantages compared to conventional chemical-based methods. The advantages of physical seed treatments include environment-friendly, high germination rate, early seedling emergence, uniform seedling vigor, protection from chemical hazards, and improved yield. Different physical methods are available for seed invigoration viz. gamma irradiation, laser irradiation, microwaves, magnetic field, plasma, sound waves, and ultrasonic waves. Still, further research is needed to apply each technique to different seeds to identify the best physical method and factors for seed

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species along with different environmental parameters. The present review will describe the use and effects of physical processing techniques for seed invigoration.

KEYWORDS

seed germination, gamma irradiation, laser irradiation, microwaves, magnetic field, plasma, sound waves, ultrasonic waves

Introduction

Edible seeds including cereals, pulses, and legumes are globally used as a staple food and possess several functional properties like antioxidant, antidiabetic, anticancer, and antitumor effects. They are a rich source of vitamins, minerals, and fiber and also contain enough amount of bioactive components such as phenolics, carotenoids, lignin, β-glucan, inulin, resistant starch, sterols, and phytates. According to several studies, the controlled germination process is a valued technique to improve the nutritional and medicinal values of edible seeds (Hayat et al., 2014; Verspreet et al., 2015; Özer and Yazici, 2019) (Figure 1). Sprouts are germinated seeds of cereals, pulses, and legumes that grow into seedlings, and are characterized by nutrient bioavailability and their profile including phenolic profile, antioxidant profile, vitamins, minerals, along with other micro and macronutrients. As compared to the un-sprouted grains the sprouted grains are considered an important functional ingredient due to having major nutritional, textural, and tasteful, advantages. The edible sprouts can help to provide essential nutrients, maintain health status, and to prevent disease. Currently, interest in the use of sprouted grains as functional ingredients and food is growing with increased interest from food researchers, nutritionists, producers, and consumers (Aloo et al., 2021; Pires et al., 2021).

The germination process can improve the levels of simple sugars, free amino acids, and organic acids through the catabolism of macronutrients like carbohydrates, protein, and fatty acids (Wang et al., 2005; Shi et al., 2010; Benincasa et al., 2019). It can also decrease different anti-nutritional factors and indigestible components, like lectin and protease inhibitors (Saithalavi et al., 2021). Moreover, through germination secondary metabolites such as vitamin C and polyphenols can accumulate in edible seeds (Toro et al., 2021).

Sprouting is the crucial phase in the plant at which fast germination and seedling emergence are vital aspects that can be stimulated in seeds (Sharififar et al., 2015; Lai et al., 2016). Germination stimulation has been achieved through several methods such as fertilizers, light, seed scarification, seed stratification, salinity, temperature, humidity, and regulatory hormones (Rifna et al., 2019b). As a substitute for chemical invigoration techniques for plant growth stimulation, the use of physical methods attracts more and more attention. The physical techniques can improve food quality without imparting any safety concerns, thus the applications of these methods have increased to affect plant growth and germination (Bose et al., 2018).

Now sprouted grains are becoming popular and consumed all over the world. To increase the nutritional value of foods and to improve the sensory properties of sprouted grains flour is used in different products. Despite several efforts to explore the utilization of sprouted grains, limited products have been produced and introduced into the market. Thus, it is required to conduct more research and incorporate seed sprouts into different food industries to introduce them into the food chain (Liu et al., 2017; Yilmaz et al., 2020).

Therefore, different physical methods have been developed to facilitate the germination process and to improve the plants' growth and production. This paper gives a brief overview of such physical processing technologies including gamma irradiation, laser irradiation, microwaves, magnetic field, plasma, sound waves, and ultrasonic waves. Additionally, mechanisms of seed germination promotion by processing treatments and how they impact germination have also been discussed.

Physical seed invigoration techniques

Throughout the transient activation of the pre-germination metabolic activities, seed priming is a well-known and established way to improve seed quality (good nutritional composition along with reduction of seed dormancy, the breakdown of the complex of anti-nutrients, and the release of nutrients and their improved bioavailability) (Chakraborti et al., 2021). Under adverse environmental circumstances (abiotic stresses like water deficit, high salinity, high temperature, submergence, etc.) seed priming has arisen as a constructive way of improving seed vigor, germination synchronization,

Abbreviations: MWs, Microwave radiations; US, Ultrasonic waves; IR, Infrared; WLAN, Wireless router; MFs, Magnetic fields; DNA, Deoxyribonucleic acid; ROS, Reactive oxygen species; RF, Radio-frequency; SMF, Static magnetic field; EMF, Electric magnetic field.

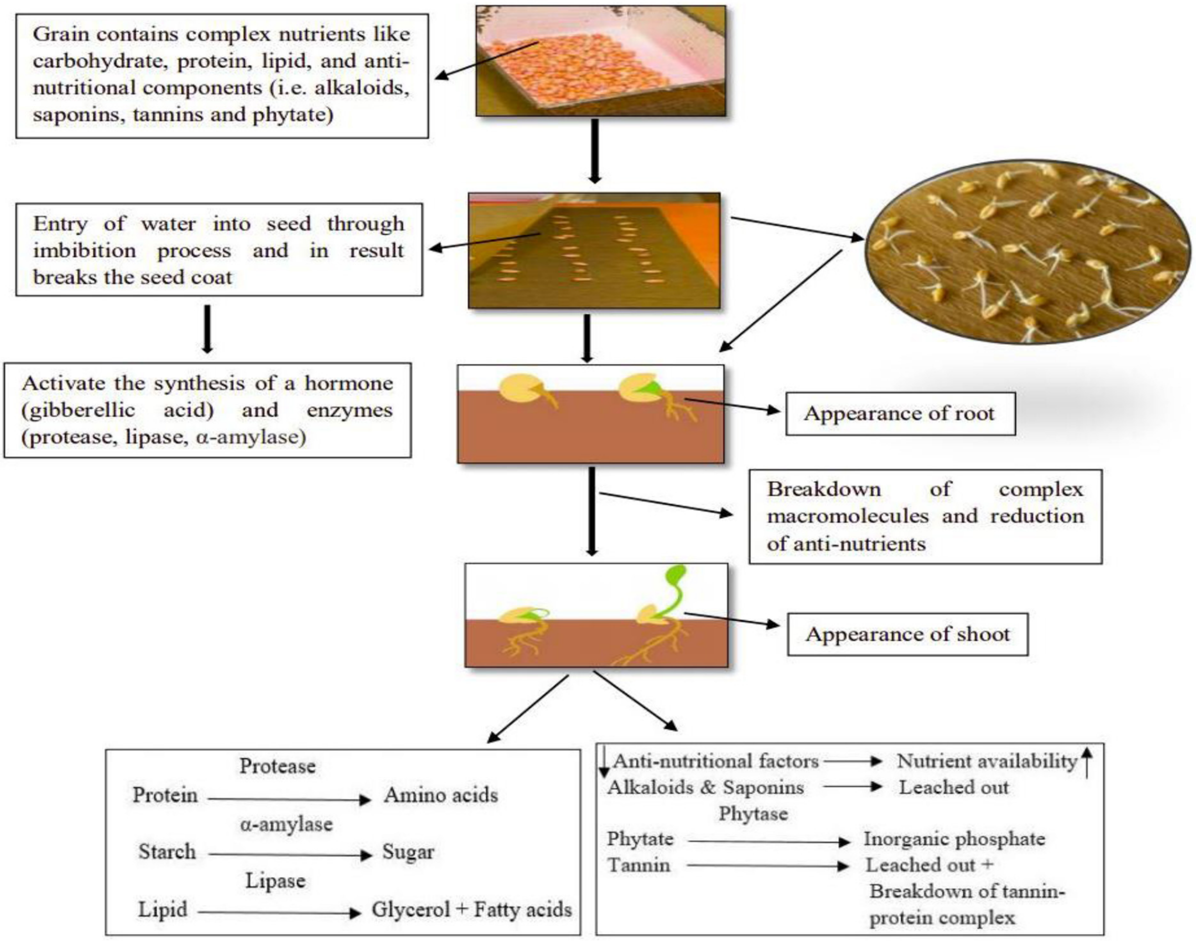

FIGURE 1
Schematic diagram of the germination process.

and seedling growth (Marthandan et al., 2020). A variety of priming techniques is available, and some of them are properly categorized such as hydro-priming and osmo-priming. As compared to osmo-priming and chemical-based conventional treatments, physical processing techniques have shown several advantages. Due to their less damaging effects on the environment like anthropogenic changes in the soil, water, and atmosphere, recently the use of physical methods for plant growth stimulation is becoming more popular (Table 1) (Bilalis et al., 2012; Rifna et al., 2019a). In chemical-based methods, the required chemical compounds are directly injected into the cell while in physical methods, energy is introduced into the cell which generates conditions for different transformations at a molecular level (Govindaraj et al., 2017). Different positive biological changes can be introduced in plants without influencing their biology through the application of various physical factors. These physical techniques decrease the on-farm pollution of raw materials, minimize the requirement for fertilizers, and can also be used for the disinfection of seeds (Table 2) (Bera et al., 2021). All biological activities depend on the exchange of energy between the cell and the environment. Improving the germination and yield of crops by using energy is an advanced area in research. Energy treatment stimulates the enzymatic reactions leading to the initiation of physiological and biochemical changes. All these changes are an indication of plant growth and development processes which eventually improve the quality and yield of produce (Govindaraj et al., 2017).

Ultrasound seed processing

Ultrasonic waves (US) are mechanical waves having a frequency higher than 20 kHz and cannot be detected by a human audition system. This technology has been successfully used in different mass transfer processes of food including drying, extraction, osmotic dehydration, desalting,

TABLE 1 Different physical techniques used for the seed invigoration.

Technique	Principle	Mechanisms	References
Ultrasound	Lead to cavitation phenomenon exerting mechanical pressure on the seeds	• The fluidity of the cell wall • Formation of cracks and micropores on the cell wall • Enhanced exchange of water and oxygen	Hu et al., 2007 Miano et al., 2016
Microwave heating	After absorption induces ionic movement and dipole rotation	• Deformation of the electron orbits • The fast and selective heating process • Electronic transitions between different rotational sublevels	Mullin, 1995 Al Mashhdani and Muhammed, 2016
Magnetic field	The perception and signaling mechanism is mediated through the blue light photoreceptors called cryptochromes	• Induce variations in the ionic concentrations and membrane potential • Increased water uptake	Shine et al., 2011 Socorro and García, 2012
Plasma treatment	Reactive oxygen species (ROS) in water vapor plasma influenced the redox reaction	• Affect the plant development by controlling thiol groups • Thin layers of hydrophobic and hydrophilic nature are produced	Volin et al., 2000 Henselová et al., 2012
Gamma irradiations	Reactive oxygen species (ROS) as the main regulators produced in the seed	• Activate and amplify stress and antioxidant responses • Affect nucleic acids and proteins synthesis leading to metabolic activities	Borzouei et al., 2010 Esnault et al., 2010
Sound waves	Enhanced the transcription level and activate the stress-induced genes	• Stimulate the opening of leaf stomata • Sound waves converted into or reserved as chemical energy • Stimulate the photosynthetic reactions	Meng et al., 2012 Xiujuan et al., 2003
Laser irradiation	Synergistic effect between the polarized monochromatic laser beam and the photoreceptors	• Coherent laser light caused illumination of biological tissues and speckle formation • Strong intensity gradients in the tissues • Induce inter-and intracellular gradient forces • The paths and speeds of biological processes significantly changed	Ruvinov, 2003 Hernandez et al., 2010

and hydration (Miano et al., 2016; Asfaram et al., 2019). Nowadays to break the seed dormancy ultrasonic waves have attracted the researcher's attention as being a safe, easy, and time-saving technique (Ramteke et al., 2015; Liu et al., 2016). In recent years the mechanism of ultrasonic wave activity on seed germination in different plant species has been explored as mentioned in Table 3. In ultrasonic treatment, seeds are placed into an ultrasonic wave emitting apparatus in which water is used as a medium (Nazari and Eteghadipour, 2017). For seed germination, oxygen availability and water uptake are the essential parameters, so ultrasonic waves alter the seed's characteristics through which these factors become available more efficiently (Liu et al., 2016).

Ultrasonic waves in water lead to cavitation, a phenomenon creating micro-bubbles in water that exerts mechanical pressure on the seeds. Mechanical pressure exerted by the cavitation process further causes fluidity of the cell wall and the formation of cracks and micropores in it (da Silva and Dobránszki, 2014; Rifna et al., 2019a). A study conducted on mung beans showed an increase in their porosity after ultrasonic treatment. Seeds become more porous for water and oxygen exchange due to the production of micro-pores and micro-cracks. It was demonstrated that ultrasound technology improved the hydration process of mung beans, reducing the total process time by almost 25% [increasing the water absorption rate to ∼44%] (Miano et al., 2016). In studies, conducted by Yaldagard et al. (2008) and Sharififar et al. (2015) it has been revealed that ultrasonic treatment increases the hydration process in seeds, therefore leading to an increase in enzymatic reactions especially related to alpha-amylase. Thus, the starch hydrolysis conducted by alpha-amylase has resulted from an increment in seed germination speed and percentage (Yaldagard et al., 2008; Sharififar et al., 2015). A schematic presentation of ultrasonic wave treatment in seeds is shown in Figure 2.

Through several studies, it has been investigated that ultrasound is a promising method to break seed dormancy and enhance germination. A summary of the findings regarding the effects of ultrasound treatment on the seed germination percentage of different edible seeds has been provided in Table 3. Yaldagard et al. (2008) reported a 6% increase in germination

TABLE 2 Advantages and limitations of novel processing techniques.

Technique	Advantages	Limitations	References
Ultrasound	• Safe, easy, and time saving • Induce mechanical pressure on seeds • No chemical contamination	• Has a small size of apparatuses • Scaling-up is required to manufacture huge ultrasound demitting sets	Nazari et al., 2014 Ramteke et al., 2015 Liu et al., 2016 Nazari and Eteghadipour, 2017
Microwave heating	• The short startup, precise control, and volumetric heating • Have the fast and selective heating ability	• Under field conditions, the uneven temperature distribution is one of the problems	Warchalewski et al., 2011 Brodie, 2012 Motallebi, 2016
Magnetic fields	• Less toxicity • Easy to manipulate • Cost-effective and safe method • Helpful to overcome the effect of salt stress	• Having an impact on seed recovery applications when seeds have low quality, for specific plant species	Balouchi and Sanavy, 2009 Răcuciu, 2011
Plasma treatment	• Low temperature and treatment duration • Can be used for thermally sensitive materials • Appropriate for a large range of materials and shapes • Absence of potentially environmentally-harmful chemicals • Avoidance of toxic reagents or by-products	• Low-pressure radio frequency plasma systems have limitations in terms of environmental and economic costs • Also has processing restrictions regarding vacuum processing	Filatova et al., 2009 Šerá et al., 2009 Ling et al., 2014 Zhou et al., 2016
Gamma irradiations	• Cause small variations in food components • Requires minimal sample preparation • No use of catalyst • Excellent penetration • Causes no increase in temperature during processing	• Requires optimization of the treatment parameters including temperature, exposure time, and dose	Selcuk et al., 2008 Grover and Khan, 2014 Bashir and Aggarwal, 2016
Sound waves	• Reduce resource usage • Decrease the requirements for chemical fertilizer and pesticide	• Causes noise pollution and confusion • Have contradictions in terms of frequencies and exposure periods • The sound pressure level falls inversely proportional to the distance from the sound source	Carlson, 2013 Hassanien et al., 2014
Laser irradiation	• Suitable to radiate a large number of seeds • Diodes have low costs • Avoid the use of harmful fungicides	• Laser beams are narrow • The whole surface of the seed is not evenly exposed	Claudia et al., 2011 Sharma et al., 2015

percentage of barley (*Hordeum vulgar L.*) seeds after ultrasound waves' treatment as compared to control. Application of sonication treatment on Norway spruce (*Picea abies L.*) Karsten seeds increased germination by 22% (Rîşca and Fártáiş, 2009). Goussous et al. (2010) showed that ultrasonic waves' application to chickpeas (*Cicer arietinum*), wheat (*Triticum aestivum*), and watermelon (*Citrullus vulgaris*) increased their germination percentage by 36, 2, and 2%, respectively, in comparison to control. Another investigation conducted by Aladjadjiyan (2011) revealed a 4 and 6% increase in the germination of wheat (*Triticum aestivum*) and lentils (*Lens culinaris, Med.*), respectively. According to an investigation by Wang et al. (2012) on switchgrass (*Panicum virgatum L.*) seeds, sonication enhanced germination by up to 23.2%.

The application of ultrasonic waves on sunflower (*Helianthus annuus L.*) seeds, enhanced their germination maximum by up to 43.38% (Machikowa et al., 2013). Another *in vitro* study conducted on snail medick [*Medicagoscutellata* (L.) *Mill*] seed indicated that ultrasound increased germination up to 63.3% (Nazari et al., 2014). In a study conducted on peas (*Pisum sativum*), as compared to control, sonication treatment caused a 13.1% increase in seed germination. The operating parameters were time and temperature at specific input power. Pea seeds were subjected to an ultrasonication treatment of 40 kHz for 1 min at 25 celsius (Chiu and Sung, 2014). A similar study conducted by Sharififar et al. (2015) showed that ultrasound treatment applied to big saltbush (*Atriplex lentiformis*), cumin (*Cuminum cyminum*), and caper

TABLE 3 Effect of ultrasonic waves on seed germination (%).

Plants	Working conditions	Control germination	Ultrasound germination	References
Barley (*Hordeum vulgare*)	Frequency 20 kHz, Wave amplitude 210 µm, Power 460 W	93%	99%	Yaldagard et al., 2008
Chickpea (*Cicer arietinum*)	Frequency 40 kHz, Output 100 W,	61%	97% 100%	Goussous et al., 2010
Wheat (*Triticum aestivum*)	Power supply 220 V 50 Hz	98%		
Wheat (*Triticum aestivum*)	Frequency 42 kHz, Power 100 W	90%	94% 98%	Aladjadjiyan, 2011
Lentil (*Lens culinaris*)		92%		
Sunflower (*Helianthus annuus*)	Frequency 40 kHz, Power 250 W	54.6%	98% 68%	Machikowa et al., 2013
Norway spruce [*Picea abies (L.) Karsten*]		46%		
Snail clover [*Medicago scutellata (L.) Mill*]	Frequency 42 kHz	33.3%	96.6%	Nazari et al., 2014
Saltbush (*Atriplex lentiformis*)	Frequency 42 kHz	40%	68% 80%	Sharififar et al., 2015
Cumin (*Cuminum cyminum*)		44%		
Russian wildrye (*Psathyrostachys juncea Nevski*)	Frequency 40 kHz, Power 200–500 W	39.3%	89.3%	Liu et al., 2016

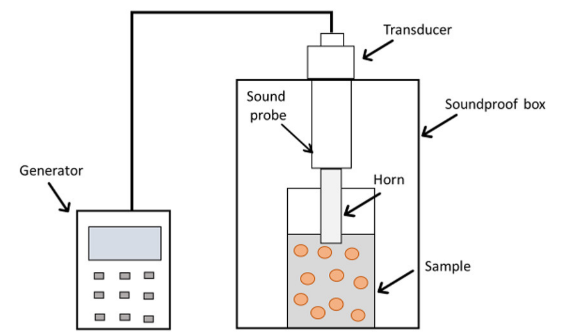

FIGURE 2
Schematic diagram of the ultrasound seeds processing.

beans (*Zygophyllum eurypterid*) significantly increased their germination percentage up to 28, 36, and 35.7%, respectively, in comparison to control treatment. Overall in agreement with the positive effects of ultrasonic waves studied in most cases of tested species, it's clear that ultrasonic waves can affect seed germination positively.

Microwave seed treatment

The microwave component of the electromagnetic spectrum includes radiation having a frequency within the range of 300 MHz to 300 GHz and wavelength ranging between 1 m down to 1 mm. Now it is recognized that microwave radiation (MWs) after absorption as non-ionizing electromagnetic radiation causes different changes in biological systems which are mostly thermal and non-invasive (Bera et al., 2021). MWs can induce various biological changes depending on different factors such as field strength, frequencies, waveforms, modulation, and duration of exposures (Vian et al., 2006). Mostly the effect of MWs on humans and animals was extensively studied and addressed, while there is a very small number of studies related to the effect of MWs on plants (Jayasanka and Asaeda, 2013). Most of the available work described the effect of radiations having the 2.45 GHz frequency, which is absorbed in living cells through water molecules (Creţescu et al., 2013). After absorption into living cells and tissues, MW radiations induce ionic movement, and dipole rotation leading to the deformation of the electron orbits which finally causes a fast and selective heating process (Mullin, 1995; Rifna et al., 2019a). The schematic diagram of the experimental set-up for microwave treatment is given in Figure 3.

MWs treatment can also result in electronic transitions between different rotational sublevels. In the organic molecules between vibrational levels transitions mostly occur in near Infrared (IR) regions (750 to 1,300 nm) of the electromagnetic spectrum, while between rotational levels occur in far IR regions and near microwave regions (1 mm to 1 m) (Al Mashhdani and Muhammed, 2016). Intermediated frequency levels of radiation (2,450 MHz) applied to seeds showed higher enzymatic reactions and increased growth rates. Still, the mechanism of MWs is not as yet fully understood but according to Rajagopal (2009) exposure to microwaves, 2.45 GHz and 650 W for 30 s are enough to ensure a high germination rate. In several studies, lethal level MWs have been used for preventing the growth of weeds in the soil while non-lethal level MWs treatments have been widely used for seed decontamination before sowing (Scialabba and Tamburello, 2002; Knox et al., 2013; Sahin, 2014). Application of MWs caused heating of soil up to 80°C which results in suppressed germination of the weed. Thus, in greenhouses from horticultural/ornamental plant nurseries,

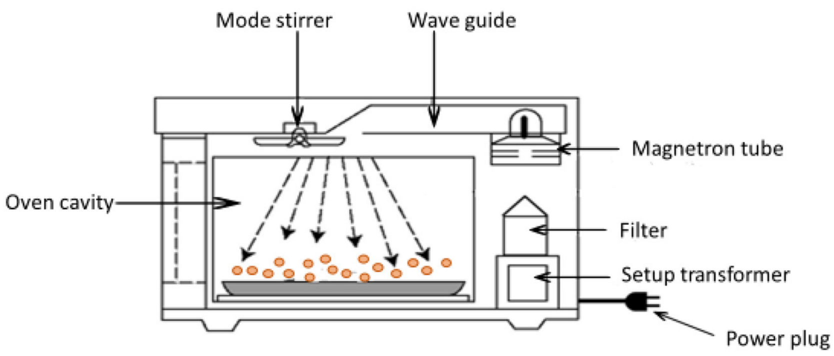

FIGURE 3
Experimental set-up for microwave exposure.

TABLE 4 Effect of microwaves waves on germination parameters.

Plants	Working conditions	Effects	References
Wheat (*Triticum aestivum*)	Frequency 2.45 GHz, Power 750 W	• Reduced seed vigor • Seed-borne infestation of Fusarium graminearum decreased	Reddy et al., 1998
Radish (*Raphanus sativus*)	Frequency 10.5 and 12.5 GHz, Power 8 and 14 mW	• The reduction in germination % and rate • Reduced hypocotyl growth	Scialabba and Tamburello, 2002
Lentil (*Lens culinaris*)	Frequency 2.45 GHz, Output power 450 and 730 W	• Seed germination % and rate not affected • Seedling length stimulation	Aladjadjiyan, 2010
Potato (*Solanum tuberosum*)	Frequency 38, 46 and 56 GHz, Output power 4 mW	• Increased biomass growth	Jakubowski, 2010
Barley (*Hordeum vulgare*)	Frequency 2.45 GHz, Output power 800 W	• Increased germination and vigor index	Creţescu et al., 2013
Rice (*Oriza sativa*)	2,450 MHz	• Germination % and rate enhanced • Increased length of primary shoot and root	Talei et al., 2013

MWs appeared as an effective non-chemical alternative method for weed management (Velázquez-Martí et al., 2006).

There is very limited literature about the use of MWs radiations as seed stimulation treatment in a few plants, affecting their germination performance. Through different studies, it was investigated that application of 2.45 GHz MWs radiation has no major influence on seed germination, but in some plant species including wheat, green gram, moth bean, and Bengal gram, it showed a beneficial effect on biomass accumulation and growth (Jakubowski, 2010; Talei et al., 2013). A summary of the findings of the effects of microwave treatment on seed germination of the mentioned plant species has been provided in Table 4. The effect of microwave irradiation at 935.2–960.2 MHz with intensities of 0.07–0.15 mW/cm^2 on maize grains was studied and revealed a clear increase in germination and seedlings development (Khalafallah and Sallam, 2009). Aladjadjiyan (2010) conducted an experiment stating that microwave pretreatments with frequency 2.45 GHz for 5, 10, 15, 20, and 25 s and seeds showed enhanced germination parameters as compared with controls. Best results were obtained with an exposure time of 30 s and output power of 450 W giving 10% longer shoot length and 7% root length than the control one. Ragha et al. (2011) used the low power MWs (frequency range of 8.5–10.27 GHz) having non-thermal intensity having a frequency of 1 kHz and studied their effect on the wheat (*Triticum aestivum*), Bengal gram (*Cicer arietinum*), green gram (*Vigna radiate*), and moth bean (*Vigna Aconitifolia*). Effects of different parameters like frequency (8.5 to 10.27 GHz), power (−1.0 to 3.5 dBm), exposure time (12 to 28 min), and power density (1.5 to 5.5 cm) were studied to evaluate their effect on germination. As compared to control the different treatments induced stimulating effects on germination %, seedling vigor, and biomass % of plants including wheat, green gram, moth bean, and Bengal gram, especially when used with low levels of power, exposure time, and power density while high frequency stimulated seed germination as compared to control (Ragha et al., 2011).

In an experiment effect of MWs using a wireless router (WLAN: 70 mWm^{-2}) and mobile devices (GSM: 100 mWm^{-2}) was studied on three different aromatic plant seeds including parsley (*Petroselinum crispum* L. cv. Plained Leaved), celery

(*Apium graveolens* L. cv. Pascal Giant), and dill (*Anethum graveolens* L. subsp. hortorum cv. Common) (Soran et al., 2014). Different plant parameters were studied regarding MWs effect including leaf structure, essential oil content, and emission of volatile compounds. The results exhibited that WLAN frequency MWs appeared to be more harmful than GSM-frequency MWs, and the MWs treatments caused both structural and chemical alternations (Soran et al., 2014). Like other radiation treatments, the efficiency of MWs application depends on different parameters such as plant species, growth stage, exposure duration, frequency, and power density (Jayasanka and Asaeda, 2013). Different studies in this area revealed that MWs treatment showed a positive effect on some plants while negatively influencing other plants; which recommended that the influence of MWs is related to radiation frequency, exposure duration, and environmental circumstances (Khalafallah and Sallam, 2009).

Magnetic fields for seed processing

The use of magnetic fields (MFs) also showed positive responses regarding the rate of germination, growth, and crop yield along with the decreased incidence of pathogenic diseases. In a study annual medics and dodder seeds were treated with an electromagnetic field which shows a significant effect on germination rate. Annual medics seeds were treated at 80 μT for 10 min and 30 min, and 128 μT for 10 min while dodder seeds were treated at 88 μT for 12 h in a wet state, and 128 μT for 24 h in dry seeds (Balouchi and Sanavy, 2009; Araújo et al., 2016). The exposure of MFs depends on flux density and duration of exposure which defines its dose and MFs dose influences the germination, seedling growth, and yield (da Silva and Dobránszki, 2016). The schematic representation of the experimental MFs setup is shown in Figure 4. The flux density of the magnetic field changes with the static or alternating magnetic fields, thus increasing the germination percentage and affecting the preliminary growth stages (Hozayn et al., 2019). In a study, magnetically treated water was used as a hydro-priming technique which as result enhanced the germination rate and plant growth (Morejon et al., 2007). Along with plant growth, the application of MFs also influenced the enzymatic activities, phytochemical reactions, and respiration process (Carbonell et al., 2000; Martinez et al., 2000; Rifna et al., 2019a). MFs treatment results in speeding up the plants' growth, root development, and protein biosynthesis (Kordas, 2002).

The mechanism behind perceiving MFs and then regulating of signal transduction pathway is still not understood. However, according to Ahmad et al. (2007), the mechanism of MFs signaling is facilitated by blue light photoreceptors which are known as cryptochromes. Chloroplast has paramagnetic characteristics therefore, MF treatment induces metabolic reactions in the seed which stimulate the germination

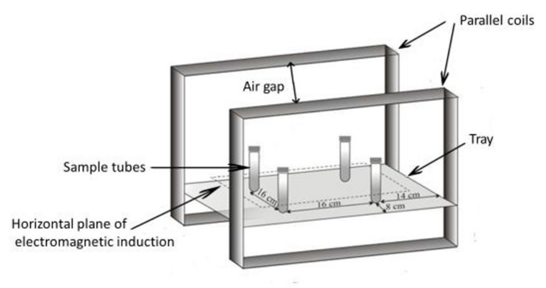

FIGURE 4
The schematic representation of the experimental magnetic fields.

(Aladjadjiyan and Ylieva, 2003). Another work performed by Racuciu et al. (2008) showed that the application of a magnetic field enhanced the enzymatic activities. According to Copeland and McDonald (2012), the efficiency of MFs stimulation is assessed by two factors germination energy and germination capacity. Higher germination energy frequently leads to stronger radicle development and increased biomass percentage.

For several years in research studies influence of MFs affecting the plant, and germination parameters have been the subject of interest. Lately, many researchers have stated the positive effects of MFs on germination %, seedling growth, growth of meristem cells, and chlorophyll contents (Qados and Hozayn, 2010; Hozayn et al., 2014). Chickpea (*Cicer arietinum*) seeds were treated with MFs for 1–4 h in steps of 50 mT intensity from 0 to 250 mT and increased germination speed, seedling length, and dry weight as compared to control (Vashisth and Nagarajan, 2008). Static MFs having intensities 4 or 7 mT with 0, 2, 6, and 10 atm osmotic pressure created with sucrose or salt were applied to bean or wheat seeds. The MFs treatment improved the germination ratios, without having any influence of increased osmotic pressure. The greatest germination and growth rates observed in both wheat and bean plants were exposed to 7 mT MF as compared to the untreated seeds. In wheat seedlings, the root and shoot length was 7.63 ± 0.08 and 9.62 ± 0.07%, respectively. In bean seedlings, the root and shoot length was 5.46 ± 0.09 and 7.65 ± 0.08%, respectively (Cakmak et al., 2010). Application of non-uniform MFs having intensities of 60, 120, and 180 mT for different durations of 5, 10, and 15 min, respectively, resulted in significant improvement in pea germination. The high germination leads to increased emergence index, and vigor index by 86 and 205%, respectively (Jamil and Ahmad, 2012). Similarly, in another experiment treatment of corn seed with the pulsed electric magnetic field (EMFs) for different time durations of 0, 15, 30, and 45 min enhanced germination %, vigor, chlorophyll content, leaf area, fresh and dry weight, and yields (Bilalis et al., 2012).

TABLE 5 Effect of magnetic fields waves on seedlings germination parameters.

Plants	Working conditions	Effects	References
Soybean (*Glycine max*)	Magnetic field strength 1,500 nT, Frequency 0.1, 1, 10, and 100 Hz	• Increased protoplasts fusion and germination	Nedukha et al., 2007 Radhakrishnan and Kumari, 2013
Wheat (*Triticum aestivum*)	Magnetic field strength 20 nT-0.1 Mt	• Activation of esterases • Growth reduction	Aksenov et al., 2000
Chickpea (*Cicer arietinum*)	Magnetic field strength 0–250 mT, DC power supply 80 V/10 A	• Improved germination • Increased root length, surface area, and volume	Vashisth and Nagarajan, 2008
Soybean (*Glycine max*)	Magnetic field strength 150 and 200 mT, DC power supply 80 V/10 A	• Reduced level of reactive O_2-radical • Increased Rubisco	Baby et al., 2011 Shine et al., 2011, 2012 Radhakrishnan and Kumari, 2012
Barley (*Hordeum vulgare*)	Magnetic field strength 125 mT	• Increase in length and weight	Martinez et al., 2000
Rice (*Oriza sativa*)	Magnetic field strength 125 and 250 mT 250 mT	• Reduced germination	Flórez et al., 2004
Wheat (*Triticum aestivum*)	Magnetic field strength 4 and 7 mT	• Increased germination • Amyloplast displacement • Higher catalase activity • Low peroxidase activity	Cakmak et al., 2010 Hasenstein et al., 2013 Payez et al., 2013
Mung bean (*Vigna radiata*)	Magnetic field strength 600 mT 600 mT	• Promotion of germination • Malondialdehyde reduction • Increased activity of NO and NOS	Chen et al., 2011 Mahajan and Pandey, 2014
Maize (*Zea mays*)	Magnetic field strength 125–250 mT	• Enhanced germination • Increased fresh weight • Amyloplast displacement • Low hydrogen peroxide and enzymatic activity • Reduced antioxidant activity • Increased stomatal conductance and chlorophyll content	Florez et al., 2007 Turker et al., 2007 Javed et al., 2011 Bilalis et al., 2012 Anand et al., 2012 Shine and Guruprasad, 2012 Hasenstein et al., 2013
Mung bean (*Vigna radiata*)	Magnetic field strength 0.5 µT—75 mT, Power 220 volts	• Improved germination, seed vigor, and starch metabolism	Reddy et al., 2012

After overnight soaking wheat grains were treated for consecutively 4 days and 5 h/day with a 30 mT static magnetic field (SMF) and a 10 kHz EMF. Results showed an increased germination speed and seedling growth compared to the control group (Payez et al., 2013). An MF applied to dormant seeds of barley, corn (*Zea mays*), wheat, and beans significantly enhanced the rate of their seedling growth. Exposure of mung bean (*Vigna radiata*) seeds to static MFs having an intensity of 87 to 226 mT for a duration of 100 min, resulted in a direct enhancement in germination % with increasing MFs intensity. At an intensity level of 0.194 T, the maximum germination of ∼80% was observed as compared to the control (Mahajan and Pandey, 2014). Calculated mean values of germination time, germination rate, germination rate coefficient, magnetic constant, transition time, and water uptake, showed the positive effect of static MF in improving germination (Mahajan and Pandey, 2014). A summary of the findings of the effects of magnetic fields on seedling performance of the different plant species has been provided in Table 5.

Plasma seed treatment

In the agriculture sector, applications of plasma treatment are also gaining attention to influence germination and plant growth (Hayashi et al., 2011; Klämpfl et al., 2012). In various studies, scientists showed improved germination and growth pattern through the application of plasmas with various vapors and gases such as aniline, cyclohexane, and helium, respectively (Jiayun et al., 2014). In this regard, different types of plasma techniques have been used such as atmospheric plasma, microwave plasma, and magnetized plasma (Zhou et al., 2011). Figure 5 represents the schematic setup of the plasma seeds treatment. The influence of different gases used in plasma

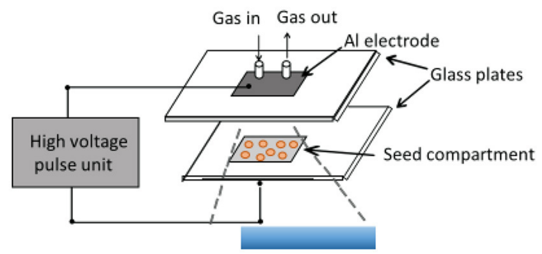

FIGURE 5
Schematic diagram of the plasma seeds treatment.

treatment is generally investigated. Different studies discovered that active oxygen species such as O, O_2^-, O_3, and OH in water vapor plasma influenced the redox reaction which in results affects the plant development by controlling thiol groups' redox status (Henselová et al., 2012). In substitution for scarification and stratification, non-thermal plasma techniques were used as a seed priming method (Dhayal et al., 2006; Mahendran et al., 2017). Plasma application has several benefits including less seed destruction and being environment friendly having no chemical utilization (Volin et al., 2000; Dhayal et al., 2006; Bourke et al., 2018). Besides improving seed quality and plant growth, plasma can sterilize seeds and also cause variations of enzymatic reactions (Sera et al., 2010; Henselová et al., 2012).

Plasma can affect seed germination by suspending or enhancing the process. The new significant plasma-related studies include the use of microwave discharges (Sera et al., 2010) and low-density radio frequency discharges (Bormashenko et al., 2012; Filatova et al., 2013). Plasma treatment induced the development of thin (0.5–2 µm) hydrophobic and hydrophilic layers in the seed, which become very helpful in different cultivation environments including climate conditions, temperature, humidity, lighting, nutrition, and water volume. Thus, in wet and cold soil, the hydrophobic layers interrupt the water absorption which results overcome the chilling injury and improving the seed viability (Volin et al., 2000; Kavak and Eser, 2009). In another study, the use of the plasma method caused increased hydrophilicity which as result stimulated the water uptake and germination process (Bormashenko et al., 2012).

The examination of several seed germination studies showed the effect of different plasma treatments applied on various seeds including wheat, maize, radish, oat, safflower, and blue lupine (Lynikiene et al., 2006; Sera et al., 2010). Different examples from the literature of the plasma treatment on different seeds have been provided in Table 6. Safflower (*Carthamus tinctorium* L. semen) seeds were treated with argon-containing low-pressure capacitively-coupled RF plasma at a pressure of 1.6 and 16 Pa for a time duration of 30 and 130 min, respectively. Treatment of 1.6 Pa, for 30 min resulted in a 30% increase in germination rate while a 50% increase was attained at 16 Pa, for 130 min (Dhayal et al., 2006). The authors claimed that the plasma treatments have caused biochemical modification on the seeds as compared to removing germination inhibitors (Kim, 2019; Guo et al., 2020). Filatova et al. (2013) used air plasma 5.28 MHz at a pressure of 0.3–0.7 Torr to treat blue lupine (*Lupinus angustifolius*), soy, honey clover, and Galega (*Galega virginiana*) seeds and investigated a 10–20% increase in seed germination and crop viability.

Henselová et al. (2012) used a low temperature diffuse coplanar surface barrier discharge air plasma at atmospheric pressure for 60 and 120 s and investigated the growth, anatomy, and biochemical changes that occurred in maize seeds (*Zea mays* L.). After 60 s plasma treatment seedlings showed an increase in root length (21%), root fresh weight (10%), and root dry weight (14%). The authors also detected significant changes in dehydrogenase, superoxide dismutase, catalase, and guaiacol-peroxidase. Bormashenko et al. (2012) treated the grains of lentil (*Lens culinaris*), beans (*Phaseolus vulgaris*), and wheat (*Triticum spp.*) with non-equilibrium plasma. Filatova et al. (2013) and Filatova et al. (2014) treated seeds wheat (*Triticum aestivum* L.), narrow-leaf lupine (*Lupinus angustifolius*), and corn (*Zea Mays* L.) for 10 min with capacitively-coupled low-pressure (40–80 Pa) RF air discharge plasma by using frequency 5.28 MHz and specific power 0.34–0.65 Wcm^3. Similarly, in another study treatment of soybean seeds with cold plasma, treatment having helium with 0, 60, 80, 100, and 120 W for 15 s showed positive effects on seed germination and seedling growth and water uptake was also greater (Ling et al., 2014).

Gamma irradiations seed invigoration

In agriculture sciences, gamma radiation has several applications including food microbiological safety, storability subjects, slow fruit ripening, and vegetable sprouting, along with stimulation of seed germination (Araújo et al., 2016). Among IR, gamma (γ) radiation has high energy and is produced from Cobalt-60. Gamma radiation can penetrate and interact with biological materials (Islam, 2017). Units of Gray (Gy), are used to express the level of absorbed IRs, while 1 Gy dose is equal to 1 Joule radiation energy absorbed per kilogram. Another unit called Sievert unit (Sv) is also used to express the level of absorbed IRs but in the case of interaction biological material, like 1 Gy, 1 Sv is equal to 1 Joule radiation energy absorbed per kilogram of biological material. Another important factor to consider while using the IR technique is the dose rate defined as the rate of energy deposition (Gyh^{-1}) (Moussa, 2006). Gamma radiations can improve product quality, grain yield, and salinity tolerance (Kiong et al., 2008; Majeed et al., 2018). The biological effects of IRs depend on their chemical reactions with biological molecules and water for producing free radicals which control the activity of biomolecules (Araújo et al., 2016). Figure 6 gives

TABLE 6 Effect of plasma treatments on germination parameters of different seeds.

Plants	Working conditions	Effects	References
Corn (*Zea mays*) Soybean (*Glycine max*) Bean (*Phaseolus vulgaris*) Peas (*Pisum sativum*)	• RF rotating plasma reactor • 13.56 MHz • C_4 octadecafluro decalin, aniline, hydrazine, cyclohexane	• Delayed, decreased germination and water uptake for fluorocarbon plasma • Increased germination and water uptake for nitrogen-containing plasma	Denes et al., 2003
Safflower (*Carthamus tinctorius*)	• Radio-frequency (RF) 13.56 MHz • Argon plasma at 20 W	• Increased germination %	Selcuk et al., 2008
Buckwheat [*Fagopyrum aesculentum* (*L.*) *Moench*]	• Four different plasma treatments for 3, 5, and 10 min. • Glid Arc, planar rotating electrode • At atmospheric pressure, downstream, microwave and dielectric barrier	• Improvement in germination % and lengths of sprouts after Glid Arc treatment	Šerá et al., 2012
Lentils (*Lens culinaris*) Beans (*Phaseolus vulgaris*) Wheat (*Triticum, aestivum*)	• Inductive air plasma discharge • 10 MHz, pressure 6.7×10^{-2} Pa, power 20 W	• Decreased contact angle and germination speed • Increase germination %	Bormashenko et al., 2012
Maize (*Zea mays*)	• Diffuse coplanar surface barrier discharge 10 kV, 14 kHz (sinusoidal) 370 W	• Significantly enhanced root length, root fresh, and dry weight • Root anatomy and morphology are not affected	Henselová et al., 2012
Wheat (*Triticum, aestivum*)	• Atmospheric pressure surface discharge • Room temperature, 15 kV, 50 Hz, 24 W	• Significantly improved root length and dry root weight • A small increment in water imbibition	Dobrin et al., 2015

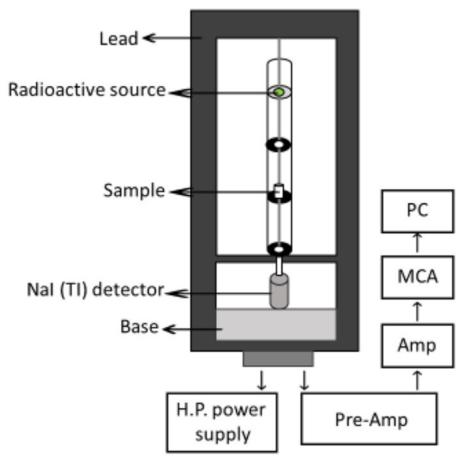

FIGURE 6
Schematic setup of the gamma irradiation treatment.

the schematic outline of the gamma irradiation setup. This leads to the activation of an antioxidant system that prepares the defensive mechanism of plants against stresses (Wi et al., 2007; Ashraf, 2009).

Gamma radiations do not damage the deoxyribonucleic acid (DNA) and structural integrity of seeds and thus can activate various biochemical reactions in the seed (Bhosale and More, 2013). These radiations can affect the different components of seeds like cell membranes, proteins, and nucleic acids. γ-rays can be used as a seed priming technique to boost the germination process but its effect depends on several factors like radiation dose, intensity, and exposure time (Kovacs and Keresztes, 2002; Majeed et al., 2017). The biological or molecular mechanisms involved in the effects of radiation are not properly understood and several ideas have been given.

The application of γ-rays in seeds produces reactive oxygen species (ROS) as the result of water radiolysis. These species react as regulators which can amplify the stress and activate antioxidant responses, thus in this mechanism, ROS has an important role as a signaling molecule [gibberellins signaling pathway and oxidation of negative regulators of germination like abscisic acid] (Borzouei et al., 2010; Esnault et al., 2010). Therefore, γ-rays treated plant seeds easily overwhelmed the fluctuations in daily stress conditions, including light intensity, temperature, and water loss (Gicquel et al., 2012; Qi et al., 2015). Low dose γ-irradiations in seeds induce positive effects on enzymatic reactions and also affect nucleic acids and proteins synthesis which consequently enhances metabolic activities in the seed leading to breaking the seed dormancy and boosting germination speed and plant development (Abdel-Hady et al., 2008). The impact of γ-irradiation in seed technology as a seed invigorating technique has been an impactful way to improve

TABLE 7 Effect of gamma irradiation on germination percentage of different seeds.

Plants	Working conditions	Effects	References
Lentil (*Lens culinaris* Medik)	• Dose rate 1.66 kGy h^{-1} • 0.1–1 kGy	• Reduced germination % up to 40.87% at 0.2 kGy • No germination at 1.0 kGy	Chaudhuri, 2002
Rice (*Oryza sativa*)	• 150–300 Gy	• Decreased germination from 100 to 97.2%	Cheema and Atta, 2003
Maize (*Zea mays*)	• 150, 300, 500, 700, 900, 1,000 Gy • Dose rate 10 Gy /28.97 s	• Germination up to 90% achieved at 240 Gy	Mokobia and Anomohanran, 2005
Long bean (*Vigna sesquipedalis*)	• 300, 400, 500, 600, 800 Gy	• Germination increase up to 70.56% at 400 Gy • No germination at 800 Gy	Kon et al., 2007
Snap bean (*Phaseolus vulgaris*)	• 300, 400, 500, 600, 800 Gy	• Germination decreased from 75.56 to 51.11% • No germination at 800 Gy	Ellyfa et al., 2007
Chickpea (*Cicer arietinum*)	• 100–1,200 Gy • Dose rate 1.66 kGyh $^{-1}$	• Seed germination increased 60–76% with a dose of 100–500 Gy • Germination decreased 80–96% decrease with 700–1,200 Gy	Shah et al., 2008
Wheat (*Triticum aestivum*)	• 100–400 Gy • Dose rate of 0.864 kGy/h	• Germination % decreased from 8.8 to 5.5%	Borzouei et al., 2010
Corn (*Zea mays*)	• 10, 30, 50 kR	• 30% germination at 10 kR dose while untreated showed 50% germination	Itol, 2010

germination. *Arabidopsis thaliana* seeds were treated with γ-ray's 50 Gy dose which in result showed positive results on all the tested growth parameters such as germination index, seedling growth, root length, and fresh weight (Qi et al., 2015).

Similarly, in another study, *Oryza sativa* L. cv-2233 and *Phaseolus mungo* L. dried seeds were treated with γ-rays ranging between 50 and 350 Gy. *Oryza sativa*, showed a stimulating response at 50 Gy giving approximately plant height 19+1.4%; panicle length 27+2.1%; seed number per panicle 64+2.8%, tiller number 17+1.7% while *Phaseolus mungo* showed at 200 Gy giving approximately plant height 51+1.4%; pod length 49+4%; seed number per pod 56+2.8% (Maity et al., 2005). Similarly, the impact of gamma irradiation on maize (*Zea mays*, hybrid Turda Star) seeds was studied, and a radiation sensitivity test was performed to compare germination capacity, plant growth, and photosynthetic pigment contents between treated and untreated seeds. Again, the stimulatory effects of γ-ray were seen at low doses (2–30 Gy) (Marcu et al., 2013). Different examples from literature about gamma irradiation affecting germination characters of different seedlings have been provided in Table 7.

Sound waves based stimulation of seeds

Audible sound within a frequency of 20 Hz to 20 kHz can be heard by human beings. Among different environmental factors like moisture, light, wind, and temperature affecting plant growth, comparatively limited data is available about the effect of audible sounds on plant growth (Hassanien et al., 2014). Acoustic biology has become progressively more popular. Recently different plants have been treated with sound waves to check their effect at various physiological growth stages. The use of sound waves as an invigoration method could reduce the requirement for chemical fertilizers by opening the stomata, and also enhance disease resistance in plants by strengthening the immune system (Junfang, 2012; Carlson, 2013; Jung et al., 2018). Naturally, plants can generate low-frequency sound waves 50–120 Hz and can also absorb or resonate specific frequencies of external sound waves (Frongia et al., 2020). Plants emit also ultrasonic vibrations of 20–100 kHz, measured by connecting a sensor directly to the stem of the plant (Hassanien et al., 2014). Plants release sound emissions from different organs and at different growth stages or in response to different situations. Through the use of small highly sensitive sound receivers, it has been shown that plants emit sound from the xylem and faint ultrasound in case of stress (Jung et al., 2018; Khait et al., 2018). Sound waves can induce various changes such as cell cycle changes, the vibration of plant leaves, and the acceleration of cellular protoplasmic movement (Godbole, 2013). The experimental diagram of sound wave treatment of seed is given in Figure 7.

It has been stated that sound waves activate stress-induced genes and also increase their transcription level (Xiujuan et al., 2003). Sound waves treatment enhances the uptake of dews and sprays fertilizers by stimulating the leaf stomata. Moreover, the process of photosynthesis is also influenced by the conversion of sound energy into chemical energy (Meng et al., 2012). According to previous studies, musical sounds can directly influence the biological system and thus could significantly affect the seeds sprouting (Creath and Schwartz, 2004).

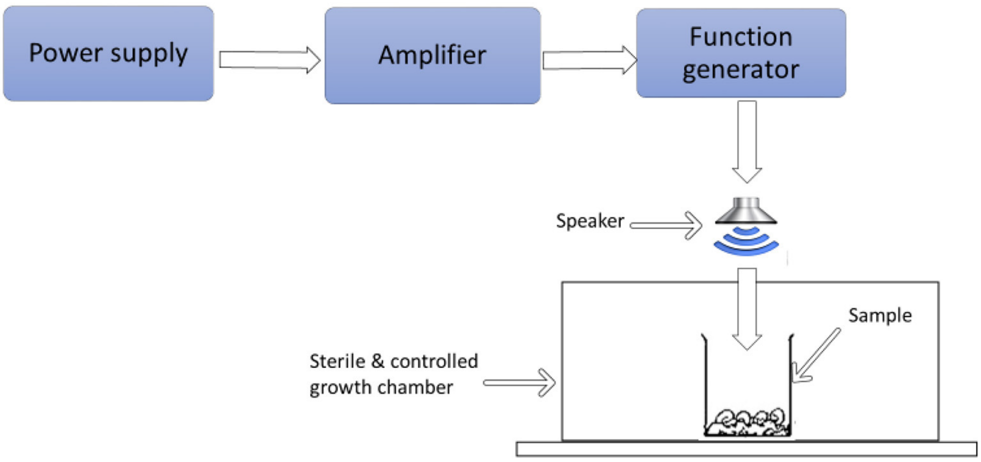

FIGURE 7
Experimental setup of sound wave treatment for seeds.

Several studies have been undertaken to understand the influence of sound and music on plants and plant growth (Table 8). Rideau wheat seeds treated with the sound frequency of 5 kHz and pressure level of 92 dB resulted in stimulated growth along with increased dry weight and number of roots (Weinberger and Measures, 1979). In an experiment, paddy rice seeds were treated with a sound frequency of 0.4–4 kHz and a pressure level of 106–111 dB. The biological effect of sound waves resulted in a significant increase in germination index, stem height, fresh weight, root system activity, and the permeability of the cell membrane (Bochu et al., 2003). According to some studies, music or sound containing hard-core vibrations can cause harmful effects on plant growth. While classical music has gentle vibrations that increase plant growth similarly violin music also induced positive effects significantly (Aladjadjiyan and Kakanakova, 2009). Plants can use acoustic signals from the surrounding environment and spread them rapidly (Gagliano, 2012). A sound wave can transfer energy, to initiate the cytoplasmic streaming and influence the membrane materials thus resulting in variations in biological function and increased metabolic reactions. In another study, at 0.2 and 0.3 kHz, sound frequency young root tips of *Zea mays* showed a clear bend toward a sound source (Gagliano, 2012).

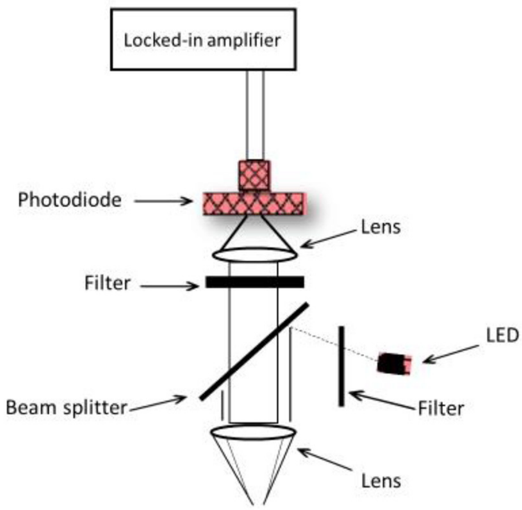

FIGURE 8
Schematic diagram of laser irradiation treatments.

Laser irradiation seed treatment

As in the agriculture field, irradiation is known as a new branch of seed invigoration technique. Laser radiations have features such as coherence, high density, monochromatic, and polarization, and all these properties make laser irradiations applicable in agriculture (Hasan et al., 2020). Various parameters of laser radiation can affect the physiological process in seeds, these parameters include the type of laser radiation, intensity, wavelength, intensity, and exposure time (Govindaraj et al., 2017). The synergistic effect of different mechanisms interacting with laser light results in a range of noticeable effects in the agriculture field. In several studies, laser irradiation showed a positive effect on germination and disease prevention in different crops such as rice, maize, wheat, peas, radishes, and corn (Aladjadjiyan and Kakanakova, 2009; Hernandez et al., 2010). The schematic diagram of the laser irradiation treatment is given in Figure 8.

TABLE 8 The application of sound waves to different crops affects their phenotype.

Plants	Sound frequency	Sound pressure	Effects	References
Rice (*Oryza sativa*)	400 Hz	106 dB	• Increased germination rate, stem height, fresh weight • Improved rooting ability activity of root system and penetrability of cell membrane	Bochu et al., 2003
Rice (*Oryza sativa*)	0.3–6 kHz	80 dB	• Increased growth, yield, and quality	Hassanien et al., 2014
Cowpea (*Vigna unguiculata*)	0.340–3.3 kHz	40–80 dB	• Increased growth and yield	Huang and Jiang, 2011
Wheat (*Triticum aestivum*)	0.340–3.3 kHz	40 dB-80 dB	• Improved seed germination, stem height • Increased activity of root system	Weinberger and Measures, 1979
Mung bean (*Vigna radiate*)	1–1.5 kHz 1.5–2 kHz 2–2.5 kHz	80 dB 90 dB 100 dB	• Increment in stem and root lengths • Reduced germination period with higher sound frequency and sound pressure	Cai et al., 2014

Laser light treatment in seeds induces a series of reactions like accelerated maturity, improved disease resistance, improved energy potential, alpha-amylase action, and free radical's concentration (Klimek-Kopyra et al., 2021). In irradiated seeds, all these reactions lead to reduced seed dormancy, increased rate and percentage of germination, an improved profile of chlorophyll and carotenoid content, higher seed vigor, and a positive effect on the process of respiration and photosynthesis (Wang et al., 2019).

The authors also reported that in addition to serving as a pre-sowing seed treatment, laser irradiations can also affect the quality and quantity of production. Table 9 presents a list of several studies about the effect of laser stimulation on plants that can be found in the literature. In an experiment, He-Ne laser application as a pre-sowing treatment on four spring barley cultivars showed an increment in the germination capacity (Szajsner and Drozd, 2003). Treatment of wheat grains with semiconductor laser influenced their germination and development (Hernandez et al., 2008) while irradiation of tissue culture significantly caused changes in a lipid matrix structure (Salyaev et al., 2007).

The application of light from a laser diode of 650 nm and a power of 27.4 mW increased the germination of photosensitized wheat seeds (Aguilar et al., 2008). Soybean seedlings treated with 532 nm laser improved the photosynthesis proficiency and enhanced the isoflavone content (Tian et al., 2010). Irradiation treatment of *A. farnesiana* seeds for 9 min with He-Ne laser light at 1.70 W cm^{-2} affected the germination indices (Soliman and Harith, 2009). Several other studies used He Ne laser and approved promising effects on germination, in winter wheat genotypes, morphological characters were studied (Szajsner, 2009), in maize hybrids seeds activity of amylolytic enzymes was observed (Podlesny and Stochmal, 2005), and developmental phased of white lupine and fava bean plants were observed (Podlesny and Podlesna, 2004). Similarly, in different experiments, pre-sowing treatment of seeds with irradiation using specific application parameters showed significantly enhanced the production of fava bean seeds (Podlesny, 2007), alfalfa (Dziwulska et al., 2006), wheat (Szajsner, 2009), maize (Szajsner et al., 2007b), and barley (Szajsner et al., 2007a).

Conclusion and future prospects

High vigor seeds represent improved establishment and productivity of crops. Therefore, sustainable crop production requires the use of low-cost and environment-friendly techniques of seed enhancement. Several pre-sowing treatment attempts have been made to improve the yield. Physical methods are an innovation in the research area of seed invigoration to improve crop yield. These physical techniques are the substitute for chemical-based techniques in the development of new biotech-based solutions. These techniques are environmentally friendly and can be used on a high throughput scale. Although, plants respond to the physical treatment but still on a commercial scale it has not been fully exploited. Enough facilities are present to conduct physical treatment of seeds but still, there is a lack of information regarding pre-germinative metabolic reactions occurring in seeds. This information gap is hindering the successful application of these techniques, as seen for chemical treatments. There is also needed to explain all biochemical reactions affecting these processing technologies which result influence the growth and development of plants. These processing techniques have a challenge which is that not all techniques may result in improved germination of seed. The invigoration methods can make the seeds vulnerable to stress conditions if an unsuitable technique is applied to seeds. Therefore, it's important to determine all working conditions and protocols specific to plant seeds. Because the efficiency of

TABLE 9 Effect of laser irradiation stimulation on plants.

Plants	Working conditions	Effects	References
Maize (*Zea mays*), Wheat (*Triticum aestivum*) Barley (*Hordeum vulgare*)	Laser type He and Ne, Power 40–50 mW	• Better plant seedlings • Higher resistance to cold and earlier plant maturation	Koper, 1994
Wheat (*Triticum aestivum*)	Laser type He and Ne	• Effect on morphological characters and yield	Drozd and Szajsner, 1999
Soybean (*Glycine max*)	Laser type He and Ne, Power 7.3 mW	• Reduced the number of seed-borne fungi • Increased germination	Ouf and Abdel-Hady, 1999
Barley (*Hordeum vulgare*)	Laser type He and Ne, Wavelength 632.8 nm, power density-—1 mW cm^{-2}	• Caused stimulation effect on the yield	Rybiński, 2000
Wheat (*Triticum aestivum*)	Laser type As, Al, and Ga	• Stomatal density was diminished • Modified seedling growth and morphology	Benavides et al., 2003
Wheat (*Triticum aestivum*)	Laser type He and Ne	• Increased the strength, germination energy, and seeds respiration	Makarska et al., 2004
Wheat (*Triticum aestivum*)	Laser type He and Ne, Output power 25 mW	• Positive effects on the germination energy	Dinoev, 2006
Maize (*Zea mays*)	Laser type GaAlAs semiconductor, Output power 30 mW, Wavelength 660 nm	• Have significantly increased seed vigor	Hernandez et al., 2006
Wheat (*Triticum aestivum*)	Laser type He and Ne	• Only little effect on growth and grain yield	Wesolowski and Cierpiala, 2006
Wheat (*Triticum aestivum*)	Laser type GaAlAs, Wavelength 850 nm	• Caused bio-stimulated growth	Hernandez et al., 2008
Maize (*Zea mays*)	Laser type Diode, Output power 27.4 mW, Wavelength 650 nm	• Negatively bio stimulated the seedling emergence % and emergence rate	Hernandez-Aguilar et al., 2009

each technique is directly linked to different factors including plant species, cultivars, environmental conditions, type of technique, processing treatment dose, exposure timings, etc. There is also needed to expand the number of tested species with each technique to identify factors best appropriate for each physical treatment. Further, for each treatment to modulate the seed response, the study of environmental parameters and their impact could not be ignored.

Author contributions

SH and AR designed the study and wrote the manuscript's first draft. MK and MF conducted sample selection and data management. Mahwish, TT, and AK managed the literature searches and analyses. X-AZ and SH edited the manuscript and supervised the work. AA and AL contributed in writing-review and editing the final manuscript. All authors contributed to and have approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abdel-Hady, M., Okasha, E., Soliman, S., and Talaat, M. (2008). Effect of gamma radiation and gibberellic acid on germination and alkaloid production in *Atropa belladonna* L. *Aust. J. Basic Appl. Sci.* 2, 401–405.

Aguilar, C. H., Mezzalama, M., Lozano, N., Cruz-Orea, A., Martínez, E., Ivanov, R., et al. (2008). Optical absorption coefficient of laser irradiated wheat seeds determined by photoacoustic spectroscopy. *Eur. Phys. J. Spec. Topics* 153, 519–522. doi: 10.1140/epjst/e2008-00498-0

Ahmad, M., Galland, P., Ritz, T., Wiltschko, R., and Wiltschko, W. (2007). Magnetic intensity affects cryptochrome-dependent responses in *Arabidopsis thaliana*. *Planta* 225, 615–624. doi: 10.1007/s00425-006-0383-0

Aksenov, S., Bulychev, A., Grunina, T., and Turovetskii, V. (2000). Effect of a low-frequency magnetic field on esterase activity and change in pH in wheat germ during swelling of wheat seeds. *Biofizika* 45, 737–745.

Al Mashhdani, F. A., and Muhammed, S. S. (2016). Utilization of microwave treatments for germination and α-amylase characteristics in some cereals. *Int. J. Curr. Microbiol. App. Sci.* 5, 293–306. doi: 10.20546/ijcmas.2016.505.032

Aladjadjiyan, A. (2010). Effect of microwave irradiation on seeds of lentils (*Lens Culinaris,* med.). *Romanian J. Biophys.* 20, 213–221.

Aladjadjiyan, A. (2011). Ultrasonic stimulation of the development of lentils and wheat seedlings. *Romanian J. Biophys.* 21, 179–188.

Aladjadjiyan, A., and Kakanakova, A. (2009). Physical methods in agro-food chain. *J. Cent. Eur. Agric.* 9, 789–793.

Aladjadjiyan, A., and Ylieva, T. (2003). Influence of stationary magnetic field on the early stages of the development of tobacco seeds (*Nicotiana tabacum L.*). *J. Cent. Eur. Agric.* 4, 131–138.

Aloo, S. O., Ofosu, F. K., Kilonzi, S. M., Shabbir, U., and Oh, D. H. (2021). Edible plant sprouts: health benefits, trends, and opportunities for novel exploration. *Nutrients* 13, 2882. doi: 10.3390/nu13082882

Anand, A., Nagarajan, S., Verma, A., Joshi, D., Pathak, P., and Bhardwaj, J. (2012). Pre-treatment of seeds with static magnetic field ameliorates soil water stress in seedlings of maize (*Zea mays* L.). *Indian J Biochem Biophys.* 49, 63–70.

Araújo, S. d. S., Paparella, S., Dondi, D., Bentivoglio, A., Carbonera, D., and Balestrazzi, A. (2016). Physical methods for seed invigoration: advantages and challenges in seed technology. *Front. Plant Sci.* 7, 646. doi: 10.3389/fpls.2016.00646

Asfaram, A., Sadeghi, H., Goudarzi, A., Kokhdan, E. P., and Salehpour, Z. (2019). Ultrasound combined with manganese-oxide nanoparticles loaded on activated carbon for extraction and pre-concentration of thymol and carvacrol in methanolic extracts of *Thymus daenensis, Salvia officinalis, Stachys pilifera, Satureja khuzistanica*, and mentha, and water samples. *Analyst* 144, 1923–1934. doi: 10.1039/C8AN02338G

Ashraf, M. (2009). Biotechnological approach of improving plant salt tolerance using antioxidants as markers. *Biotechnol. Adv.* 27, 84–93. doi: 10.1016/j.biotechadv.2008.09.003

Baby, S. M., Narayanaswamy, G. K., and Anand, A. (2011). Superoxide radical production and performance index of Photosystem II in leaves from magnetoprimed soybean seeds. *Plant Signal. Behav.* 6, 1635–1637. doi: 10.4161/psb.6.11.17720

Balouchi, H., and Sanavy, S. M. (2009). Electromagnetic field impact on annual medics and dodder seed germination. *Int. Agrophysics* 23, 111–115.

Bashir, K., and Aggarwal, M. (2016). Effects of gamma irradiation on cereals and pulses-a review. *Int. J. Recent Sci. Res.* 7, 14680–14686.

Benavides, M., Garnica, S., Michtchenko, A., Hernández, C., Ramírez, R., and Hernández, D. (2003). Stress response and growth in seedling developed from seeds irradiated with low intensity laser. *Agrofaz* 3, 269–272.

Benincasa, P., Falcinelli, B., Lutts, S., Stagnari, F., and Galieni, A. (2019). Sprouted grains: a comprehensive review. *Nutrients* 11, 421. doi: 10.3390/nu11020421

Bera, K., Dutta, P., and Sadhukhan, S. (2021). Seed priming with non-ionizing physical agents: plant responses and underlying physiological mechanisms. *Plant Cell Rep.* 41, 53–73. doi: 10.1007/s00299-021-02798-y

Bhosale, R., and More, A. (2013). Effect of EMS (ethyl methane sulfonate) on seed germination, seedling height and seedling injury in *Withania somnifera* (L.) Dunal. *Int. J. Life Sci.* 1, 158–160.

Bilalis, D. J., Katsenios, N., Efthimiadou, A., and Karkanis, A. (2012). Pulsed electromagnetic field: an organic compatible method to promote plant growth and yield in two corn types. *Electromagn. Biol. Med.* 31, 333–343. doi: 10.3109/15368378.2012.661699

Bochu, W., Xin, C., Zhen, W., Qizhong, F., Hao, Z., and Liang, R. (2003). Biological effect of sound field stimulation on paddy rice seeds. *Colloids Surf. B Biointerf.* 32, 29–34. doi: 10.1016/S0927-7765(03)00128-0

Bormashenko, E., Grynyov, R., Bormashenko, Y., and Drori, E. (2012). Cold radiofrequency plasma treatment modifies wettability and germination speed of plant seeds. *Sci. Rep.* 2:741. doi: 10.1038/srep00741

Borzouei, A., Kafi, M., Khazaei, H., Naseriyan, B., and Majdabadi, A. (2010). Effects of gamma radiation on germination and physiological aspects of wheat (*Triticum aestivum* L.) seedlings. *Pak. J. Bot.* 42, 2281–2290.

Bose, B., Kumar, M., Singhal, R. K., and Mondal, S. (2018). "Impact of seed priming on the modulation of physico-chemical and molecular processes during germination, growth, and development of crops," in *Advances in Seed Priming*, eds A. Rakshit and H. B. Singh (Singapore: Springer), 23–40.

Bourke, P., Ziuzina, D., Boehm, D., Cullen, P. J., and Keener, K. (2018). The potential of cold plasma for safe and sustainable food production. *Trends Biotechnol.* 36, 615–626. doi: 10.1016/j.tibtech.2017.11.001

Brodie, G. (2012). "Applications of microwave heating in agricultural and forestry related industries," in *The Development and Application of Microwave Heating*, ed W. Cao (Rijeka: InTech), 45–78. doi: 10.1134/s0012496607010280

Cai, W., He, H., Zhu, S., and Wang, N. (2014). Biological effect of audible sound control on mung bean (*Vigna radiate*) sprout. *Biomed Res. Int.* 2014:931740. doi: 10.1155/2014/931740

Cakmak, T., Dumlupinar, R., and Erdal, S. (2010). Acceleration of germination and early growth of wheat and bean seedlings grown under various magnetic field and osmotic conditions. *Bioelectromagnetics* 31, 120–129. doi: 10.1002/bem.20537

Carbonell, M. V., Martinez, E., and Amaya, J. M. (2000). Stimulation of germination in rice (*Oryza sativa L.*) by a static magnetic field. *Electro Magnetobiol.* 19, 121–128. doi: 10.1081/JBC-100100303

Carlson, D. (2013). *Sonic bloom organic farming made easy! The best organic fertilizer in the world.*

Chakraborti, S., Bera, K., Sadhukhan, S., and Dutta, P. (2021). Bio-priming of seeds: plant stress management and its underlying cellular, biochemical and molecular mechanisms. *Plant Stress* 3, 100052. doi: 10.1016/j.stress.2021.100052

Chaudhuri, S. K. (2002). A simple and reliable method to detect gamma irradiated lentil (*Lens culinaris Medik.*) seeds by germination efficiency and seedling growth test. *Radiat. Phys. Chem.* 64, 131–136. doi: 10.1016/S0969-806X(01)00467-4

Cheema, A. A., and Atta, B. M. (2003). Radiosensitivity studies in basmati rice. *Pak. J. Bot* 35, 197–207.

Chen, Y. -p., Li, R., and He, J. -M. (2011). Magnetic field can alleviate toxicological effect induced by cadmium in mungbean seedlings. *Ecotoxicology* 20, 760–769. doi: 10.1007/s10646-011-0620-6

Chiu, K. Y., and Sung, J. M. (2014). Use of ultrasonication to enhance pea seed germination and microbial quality of pea sprouts. *Int. J. Food Sci. Technol.* 49, 1699–1706. doi: 10.1111/ijfs.12476

Claudia, H. A., Liliana, R. P. C., Arturo, D. -P. F., María, H. A. A., Alfredo, C. -O., and Aquiles, C. C. (2011). Laser light on the mycoflora content in maize seeds. *Afr. J. Biotechnol.* 10, 9280–9288. doi: 10.5897/AJB11.605

Copeland, L. O., and McDonald, M. F. (2012). *Principles of Seed Science and Technology.* New York, NY: Springer Science and Business Media.

Creath, K., and Schwartz, G. E. (2004). Measuring effects of music, noise, and healing energy using a seed germination bioassay. *J. Altern. Complement. Med.* 10, 113–122. doi: 10.1089/107555304322849039

Creţescu, I., Căpriţă, R., Velicevici, G., Ropciuc, S., and Buzamat, G. (2013). Response of barley seedlings to microwaves at 2.45 GHz. *Sci. Papers Anim. Sci. Biotechnol.* 46, 185–191.

da Silva, J. A. T., and Dobránszki, J. (2014). Sonication and ultrasound: impact on plant growth and development. *Plant Cell Tissue Organ Cult.* 117, 131–143. doi: 10.1007/s11240-014-0429-0

da Silva, J. A. T., and Dobránszki, J. (2016). Magnetic fields: how is plant growth and development impacted? *Protoplasma* 253, 231–248. doi: 10.1007/s00709-015-0820-7

Denes, F. S., Young, R. A., Manolache, S., and Volin, J. C. (2003). *U.S. Patent No. 6,543,460.* Washington, DC: U.S. Patent and Trademark Office.

Dhayal, M., Lee, S. -Y., and Park, S. -U. (2006). Using low-pressure plasma for *Carthamus tinctorium L.* seed surface modification. *Vacuum* 80, 499–506. doi: 10.1016/j.vacuum.2005.06.008

Dinoev, S. (2006). Laser: a controlled assistant in agriculture. *Problems Eng. Cybernet. Robot.* 56, 86–91.

Dobrin, D., Magureanu, M., Mandache, N. B., and Ionita, M. -D. (2015). The effect of non-thermal plasma treatment on wheat germination and early growth. *Innov. Food Sci. Emerg. Technol.* 29, 255–260. doi: 10.1016/j.ifset.2015.02.006

Drozd, D., and Szajsner, H. (1999). Influence of presowing laser radiation on spring wheat characters. *Int. Agrophys.* 13, 79–86.

Dziwulska, A., Wilczek, M., and Cwintal, M. (2006). Effect of laser stimulation on crop yield of alfalfa and hybrid alfalfa studied in years of full land use. *Acta Agrophys.* 7, 327–336.

Ellyfa, K., Ahmed, O., Shaharudin, S., and Abdul Rahman, D. (2007). Gamma radiosensitivity study on snap bean (*Phaseolus vulgaris*). *Int. J. Agric. Res.* 2, 844–848. doi: 10.3923/ijar.2007.844.848

Esnault, M. -A., Legue, F., and Chenal, C. (2010). Ionizing radiation: advances in plant response. *Environ. Exp. Bot.* 68, 231–237. doi: 10.1016/j.envexpbot.2010.01.007

Filatova, I., Azharonok, V., Goncharik, S., Lushkevich, V., Zhukovsky, A., and Gadzhieva, G. (2014). Effect of rf plasma treatment on the germination and phytosanitary state of seeds. *J. Appl. Spectrosc.* 81, 250–256. doi: 10.1007/s10812-014-9918-5

Filatova, I., Azharonok, V., Gorodetskaya, E., Mel'nikova, L., Shedikova, O., and Shik, A. (2009). Plasma-radiowave stimulation of plant seeds germination and inactivation of pathogenic microorganisms. *Proc. Int. Plasma Chem. Soc.* 19, 627.

Filatova, I., Azharonok, V., Lushkevich, V., Zhukovsky, A., Gadzhieva, G., Spasić, K., et al. (2013). "Plasma seeds treatment as a promising technique for seed germination improvement," in *31st International Conference on Phenomena in Ionized Gases* (Granada).

Flórez, M., Carbonell, M., and Martínez, E. (2004). Early sprouting and first stages of growth of rice seeds exposed to a magnetic field. *Electromagn. Biol. Med.* 23, 157–166. doi: 10.1081/LEBM-200042316

Florez, M., Carbonell, M. V., and Martínez, E. (2007). Exposure of maize seeds to stationary magnetic fields: effects on germination and early growth. *Environ. Exp. Bot.* 59, 68–75. doi: 10.1016/j.envexpbot.2005.10.006

Frongia, F., Forti, L., and Arru, L. (2020). Sound perception and its effects in plants and algae. *Plant Signal. Behav.* 15, 1828674. doi: 10.1080/15592324.2020.1828674

Gagliano, M. (2012). Green symphonies: a call for studies on acoustic communication in plants. *Behav. Ecol.* 24, 789–796. doi: 10.1093/beheco/ars206

Gicquel, M., Taconnat, L., Renou, J. -P., Esnault, M. -A., and Cabello-Hurtado, F. (2012). Kinetic transcriptomic approach revealed metabolic pathways and genotoxic-related changes implied in the Arabidopsis response to ionising radiations. *Plant Sci.* 195, 106–119. doi: 10.1016/j.plantsci.2012.06.015

Godbole M. (2013). *Does music affect plant growth?*. p. 3–6. Available online at: http://www.buzzle.com/articles/does-music-affectplant-growth.html

Goussous, S., Samarah, N., Alqudah, A., and Othman, M. (2010). Enhancing seed germination of four crop species using an ultrasonic technique. *Exp. Agric.* 46, 231–242. doi: 10.1017/S0014479709991062

Govindaraj, M., Masilamani, P., Albert, V. A., and Bhaskaran, M. (2017). Effect of physical seed treatment on yield and quality of crops: a review. *Agricult. Rev.* 38, 1–14. doi: 10.18805/ag.v38i03.8977

Grover, S., and Khan, A. S. (2014). Effect of ionizing radiation on some characteristics of seeds of wheat. *Int. J. Sci. Tech. Res.* 3, 2277–8616.

Guo, C., Shen, Y., and Shi, F. (2020). Effect of temperature, light, and storage time on the seed germination of Pinus bungeana Zucc. ex Endl.: the role of seed-covering layers and abscisic acid changes. *Forests* 11, 300. doi: 10.3390/f11030300

Hasan, M., Hanafiah, M., Taha ZAeyad, A. I., and Said, M. (2020). Effect of low-intensity laser irradiation on field performance of maize (*Zea mays L.*) emergence, phenological and seed quality characteristics. *Appl. Ecol. Environ. Res.* 18, 6009–6023. doi: 10.15666/aeer/1804_60096023

Hasenstein, K. H., John, S., Scherp, P., Povinelli, D., and Mopper, S. (2013). Analysis of magnetic gradients to study gravitropism. *Am. J. Bot.* 100, 249–255. doi: 10.3732/ajb.1200304

Hassanien, R. H., Hou, T. -Z., Li, Y. -F., and Li, B. -M. (2014). Advances in effects of sound waves on plants. *J. Integr. Agric.* 13, 335–348. doi: 10.1016/S2095-3119(13)60492-X

Hayashi, N., Nakahigashi, A., Goto, M., Kitazaki, S., Koga, K., and Shiratani, M. (2011). Redox characteristics of thiol compounds using radicals produced by water vapor radio frequency discharge. *Jap. J. Appl. Phys.* 50, 08JF04. doi: 10.1143/JJAP.50.08JF04

Hayat, I., Ahmad, A., Masud, T., Ahmed, A., and Bashir, S. (2014). Nutritional and health perspectives of beans (*Phaseolus vulgaris L.*): an overview. *Crit. Rev. Food Sci. Nutr.* 54, 580–592. doi: 10.1080/10408398.2011.596639

Henselová, M., Slováková, L., Martinka, M., and Zahoranová, A. (2012). Growth, anatomy and enzyme activity changes in maize roots induced by treatment of seeds with low-temperature plasma. *Biologia* 67, 490–497. doi: 10.2478/s11756-012-0046-5

Hernandez, A., Carballo, C., Artola, A., and Michtchenko, A. (2006). Laser irradiation effects on maize seed field performance. *Seed Sci. Technol.* 34, 193–197. doi: 10.15258/sst.2006.34.1.21

Hernandez, A., Dominguez, P., Cruz, O., Ivanov, R., Carballo, C., and Zepeda, B. (2010). Laser in agriculture. *Int. Agrophys* 24, 407–422.

Hernandez, M., Michtchenko, A., and Gallegos, F. (2008). "Photobiostimulation effects caused by a high power IR laser with λ = 850nm in wheat (*Triticum aestivum* L)," in *Electrical Engineering, Computing Science and Automatic Control, 2008. CCE 2008. 5th International Conference on: IEEE*, 495–497. doi: 10.1109/ICEEE.2008.4723385

Hernandez-Aguilar, C., Dominguez-Pacheco, A., Cruz-Orea, A., Ivanov, R., Carballo-Carballo, A., Zepeda-Bautista, R., et al. (2009). Laser irradiation effects on field performance of maize seed genotypes. *Int. Agrophysics* 23, 327–332.

Hozayn, M., Ahmed, A. A., El-Saady, A., and Abd-Elmonem, A. (2019). Enhancement in germination, seedling attributes and yields of alfalfa (*Medicago sativa, L.*) under salinity stress using static magnetic field treatments. *Eur. J. Biosci.* 13, 369–378.

Hozayn, M., El-Monem, A., Elwia, T., and El-Shatar, M. (2014). Future of magnetic agriculture in arid and semi arid regions (case study). *Sci. Pap. Ser. A Agron.* 57, 197–204.

Hu, A. J., Zhao, S., Liang, H., Qiu, T. Q., and Chen, G. (2007). Ultrasound assisted supercritical fluid extraction of oil and coixenolide from adlay seed. *Ultrason. Sonochem.* 14, 219–224. doi: 10.1016/j.ultsonch.2006.03.005

Huang, J., and Jiang, S. (2011). Effect of six different acoustic frequencies on growth of cowpea (*Vigna unguiculata*) during its seedling stage. *Agric. Sci. Technol.* 12, 847–851.

Islam, M. T. (2017). Radiation interactions with biological systems. *Int. J. Radiat. Biol.* 93, 487–493. doi: 10.1080/09553002.2017.1286050

Itol, M. (2010). *Effect of ionizing radiation on the growth and germination of corn (Zea mays L.).*

Jakubowski, T. (2010). The impact of microwave radiation at different frequencies on weight of seed potato germs and crop of potato tubers. *Inzynieria Rolnicza* 14, 57–64.

Jamil, Y., and Ahmad, M. R. (2012). Effect of pre-sowing magnetic field treatment to garden pea (*Pisum sativum L.*) seed on germination and seedling growth. *Pak. J. Bot.* 44, 1851–1856.

Javed, N., Ashraf, M., Akram, N. A., and Al-Qurainy, F. (2011). Alleviation of adverse effects of drought stress on growth and some potential physiological attributes in maize (*Zea mays L.*) by seed electromagnetic treatment. *Photochem. Photobiol.* 87, 1354–1362. doi: 10.1111/j.1751-1097.2011.00990.x

Jayasanka, S. M. D. H., and Asaeda, T. (2013). The significance of microwaves in the environment and its effect on plants. *Environ. Rev.* 22, 220–228. doi: 10.1139/er-2013-0061

Jiayun, T., Rui, H., Xiaoli, Z., Ruoting, Z., Weiwen, C., and Size, Y. (2014). Effects of atmospheric pressure air plasma pretreatment on the seed germination and early growth of *Andrographis paniculata*. *Plasma Sci. Technol.* 16, 260. doi: 10.1088/1009-0630/16/3/16

Junfang, Z. (2012). Application progress of plant audio control technology in modern agriculture. *Ningxia J. Agric. For. Sci. Technol.* 53, 80–81.

Jung, J., Kim, S. -K., Kim, J. Y., Jeong, M. -J., and Ryu, C. -M. (2018). Beyond chemical triggers: evidence for sound-evoked physiological reactions in plants. *Front. Plant Sci.* 9, 25. doi: 10.3389/fpls.2018.00025

Kavak, S., and Eser, B. (2009). Influence of polymer coatings on water uptake and germination of onion (*Allium cepa L.* cv. Aki) seeds before and after storage. *Sci. Horticult.* 121, 7–11. doi: 10.1016/j.scienta.2009.01.020

Khait, I., Sharon, R., Perelman, R., Boonman, A., Yovel, Y., and Hadany, L. (2018). The sounds of plants-plants emit remotely-detectable ultrasounds that can reveal plant stress. *bioRxiv [Preprint]*. Available online at: https://www.biorxiv.org/content/10.1101/507590v3.full.pdf

Khalafallah, A., and Sallam, S. M. (2009). Response of maize seedlings to microwaves at 945 MHz. *Romanian J. Biophys.* 19, 49–62.

Kim, D. (2019). Practical methods for rapid seed germination from seed coat-imposed dormancy of Prunus yedoensis. *Sci. Hortic.* 243, 451–456. doi: 10.1016/j.scienta.2018.08.039

Kiong, A. L. P., Lai, A. G., Hussein, S., and Harun, A. R. (2008). Physiological responses of Orthosiphon stamineus plantlets to gamma irradiation. *Am. Eur. J. Sustain. Agric.* 2, 135–149.

Klämpfl, T. G., Isbary, G., Shimizu, T., Li, Y. -F., Zimmermann, J. L., Stolz, W., et al. (2012). Cold atmospheric air plasma sterilization against spores and other microorganisms of clinical interest. *Appl. Environ. Microbiol.* 78, 5077–5082. doi: 10.1128/AEM.00583-12

Klimek-Kopyra, A., Dobrowolski, J. W., Czech, T., Neugschwandtner, R. W., Gambuś, F., and Kot, D. (2021). "The use of laser biotechnology in agri-environment as a significant agronomical advance increasing crop yield and quality," in *Advances in Agronomy*. Elsevier), 1-33. doi: 10.1016/bs.agron.2021.06.001

Knox, O. G., McHugh, M. J., Fountaine, J. M., and Havis, N. D. (2013). Effects of microwaves on fungal pathogens of wheat seed. *Crop Prot.* 50, 12–16. doi: 10.1016/j.cropro.2013.03.009

Kon, E., Ahmed, O. H., Saamin, S., and Majid, N. (2007). Gamma radiosensitivity study on long bean (*Vigna sesquipedalis*). *Am. J. Appl. Sci.* 4, 1090–1093. doi: 10.3844/ajassp.2007.1090.1093

Koper, R. (1994). Pre-sowing laser biostimulation of seeds of cultivated plants and its results in agrotechnics. *Int. Agrophys.* 8, 593–596.

Kordas, L. (2002). The effect of magnetic field on growth, development and the yield of spring wheat. *Polish J. Environ. Stud.* 11, 527–530.

Kovacs, E., and Keresztes, A. (2002). Effect of gamma and UV-B/C radiation on plant cells. *Micron* 33, 199–210. doi: 10.1016/S0968-4328(01)00012-9

Lai, L., Chen, L., Jiang, L., Zhou, J., Zheng, Y., and Shimizu, H. (2016). Seed germination of seven desert plants and implications for vegetation restoration. *AoB Plants* 8, plw031. doi: 10.1093/aobpla/plw031

Ling, L., Jiafeng, J., Jiangang, L., Minchong, S., Xin, H., Hanliang, S., et al. (2014). Effects of cold plasma treatment on seed germination and seedling growth of soybean. *Sci. Rep.* 4:5859. doi: 10.1038/srep05859

Liu, J., Wang, Q., Karagić, Ð., Liu, X., Cui, J., Gui, J., et al. (2016). Effects of ultrasonication on increased germination and improved seedling growth of aged grass seeds of tall fescue and Russian wildrye. *Sci. Rep.* 6, 1–12. doi: 10.1038/srep22403

Liu, T., Hou, G. G., Cardin, M., Marquart, L., and Dubat, A. (2017). Quality attributes of whole-wheat flour tortillas with sprouted whole-wheat flour substitution. *LWT* 77, 1–7. doi: 10.1016/j.lwt.2016.11.017

Lynikiene, S., Pozeliene, A., and Rutkauskas, G. (2006). Influence of corona discharge field on seed viability and dynamics of germination. *Int. Agrophys.* 20, 195.

Machikowa, T., Kulrattanarak, T., and Wonprasaid, S. (2013). Effects of ultrasonic treatment on germination of synthetic sunflower seeds. *Int. J. Agricult. Biosyst. Eng.* 7, 1–3.

Mahajan, T. S., and Pandey, O. P. (2014). Magnetic-time model at off-season germination. *Int. Agrophys.* 28, 57–62. doi: 10.2478/intag-2013-0027

Mahendran, R., Abirami, C. K., and Alagusundaram, K. (2017). "Cold plasma technology: an emerging non-thermal processing of foods-a review," in *Engineering Interventions in Agricultural Processing*, eds M. R. Goyal and D. K. Verma (New York, NY: Apple Academic Press), 33–55.

Maity, J., Mishra, D., Chakraborty, A., Saha, A., Santra, S., and Chanda, S. (2005). Modulation of some quantitative and qualitative characteristics in rice (*Oryza sativa L.*) and mung (*Phaseolus mungo L.*) by ionizing radiation. *Radiat. Phys. Chem.* 74, 391–394. doi: 10.1016/j.radphyschem.2004.08.005

Majeed, A., Muhammad, Z., Ullah, R., and Ali, H. (2018). Gamma irradiation I: effect on germination and general growth characteristics of plants–a review. *Pak. J. Bot* 50, 2449–2453.

Majeed, A., Muhammad, Z., Ullah, R., Ullah, Z., Ullah, R., Chaudhry, Z., et al. (2017). Effect of gamma irradiation on growth and post-harvest storage of vegetables. *PSM Biol. Res.* 2, 30–35.

Makarska, E., Michalak, M., and Wesołowska-Trojanowska, M. (2004). Influence of laser irradiation on the seed quality and antioxidant contents on chosen varieties of winter wheat. *Acta Agrophys.* 111, 407–417.

Marcu, D., Damian, G., Cosma, C., and Cristea, V. (2013). Gamma radiation effects on seed germination, growth and pigment content, and ESR study of induced free radicals in maize (*Zea mays*). *J. Biol. Phys.* 39, 625–634. doi: 10.1007/s10867-013-9322-z

Marthandan, V., Geetha, R., Kumutha, K., Renganathan, V. G., Karthikeyan, A., and Ramalingam, J. (2020). Seed priming: a feasible strategy to enhance drought tolerance in crop plants. *Int. J. Mol. Sci.* 21, 8258. doi: 10.3390/ijms21218258

Martinez, E., Carbonell, M. V., and Amaya, J. M. (2000). A static magnetic field of 125 mT stimulates the initial growth stages of barley (*Hordeum vulgare L.*). *Electro Magnetobiol.* 19, 271–277. doi: 10.1081/JBC-100102118

Meng, Q., Zhou, Q., Zheng, S., and Gao, Y. (2012). Responses on photosynthesis and variable chlorophyll fluorescence of Fragaria ananassa under sound wave. *Energy Proc.* 16, 346–352. doi: 10.1016/j.egypro.2012.01.057

Miano, A. C., da Costa Pereira, J., Castanha, N., da Matta Júnior, M. D., and Augusto, P. E. D. (2016). Enhancing mung bean hydration using the ultrasound technology: description of mechanisms and impact on its germination and main components. *Sci. Rep.* 6, 38996. doi: 10.1038/srep38996

Mokobia, C., and Anomohanran, O. (2005). The effect of gamma irradiation on the germination and growth of certain Nigerian agricultural crops. *J. Radiol. Protect.* 25, 181. doi: 10.1088/0952-4746/25/2/006

Morejon, L., Castro Palacio, J., Velazquez Abad, L., and Govea, A. (2007). Stimulation of *Pinus tropicalis M.* seeds by magnetically treated water. *Int. Agrophys.* 21, 173.

Motallebi, A. (2016). Effect of microwave radiation on seed viability, survival of *Aspergillus niger* van Tieghem and oil quality of oilseeds crops canola, soybean and safflower. *Acta Agricult. Slovenica* 107, 73–80. doi: 10.14720/aas.2016.107.1.08

Moussa, H. R. (2006). Role of gamma irradiation in regulation of NO_3 level in rocket (*Eruca vesicaria* subsp. sativa) plants. *Russian J. Plant Physiol.* 53, 193–197. doi: 10.1134/S1021443706020075

Mullin, J. (1995). "Microwave processing," in *New Methods of Food Preservation*, ed G. W. Gould (New York, NY: Springer), 112–134.

Nazari, M., and Eteghadipour, M. (2017). Impacts of ultrasonic waves on seeds: a mini-review. *Agric. Res. Tech. Open Access J.* 6, 5. doi: 10.19080/ARTOAJ.2017.06.555688

Nazari, M., Sharififar, A., and Asghari, H. R. (2014). Medicago scutellata seed dormancy breaking by ultrasonic waves. *Plant Breed. Seed Sci.* 69, 15–24. doi: 10.1515/plass-2015-0002

Nedukha, O., Kordyum, E., Bogatina, N., Sobol, M., Vorobyeva, T., and Ovcharenko, Y. (2007). The influence of combined magnetic field on the fusion of plant protoplasts. *J. Gravit. Physiol.* 14, P117–P118.

Ouf, S., and Abdel-Hady, N. (1999). Influence of He– Ne laser irradiation of soybean seeds on seed mycoflora, growth, nodulation, and resistance to *Fusarium solani*. *Folia Microbiol.* 44, 388–396. doi: 10.1007/BF02903711

Özer, M. S., and Yazici, G. N. (2019). "Phytochemicals of whole grains and effects on health," in *Health and Safety Aspects of Food Processing Technologies*, eds A. Malik, Z. Erginkaya, and H. Erten (Cham: Springer), 309–347.

Payez, A., Ghanati, F., Behmanesh, M., Abdolmaleki, P., Hajnorouzi, A., and Rajabbeigi, E. (2013). Increase of seed germination, growth and membrane integrity of wheat seedlings by exposure to static and a 10-KHz electromagnetic field. *Electromagn. Biol. Med.* 32, 417–429. doi: 10.3109/15368378.2012.735625

Pires, E. D. O. Jr., Di Gioia, F., Rouphael, Y., Ferreira, I. C., Caleja, C., Barros, L., et al. (2021). The compositional aspects of edible flowers as an emerging horticultural product. *Molecules* 26, 6940. doi: 10.3390/molecules26226940

Podlesny, J. (2007). Effect of laser light on morphological features formation and faba bean yielding. *Pamietnik Pulawski (Poland)*. 144, 115–129.

Podlesny, J., and Podlesna, A. (2004). Morphological changes and yield of selected species of leguminous plants under the influence of seed treatment with laser light. *Int. Agrophys.* 18, 253–260.

Podlesny, J., and Stochmal, A. (2005). Pre-sowing laser light effect on some biochemical and physiological processes in seeds and plants of maize (*Zea mays* L.). *Pamietnik Pulawski (Poland)*. 140, 215–226.

Qados, A. A., and Hozayn, M. (2010). Magnetic water technology, a novel tool to increase growth, yield and chemical constituents of lentil (*Lens esculenta*) under greenhouse condition. *Am. Eur. J. Agric. Environ. Sci.* 7, 457–462.

Qi, W., Zhang, L., Wang, L., Xu, H., Jin, Q., and Jiao, Z. (2015). Pretreatment with low-dose gamma irradiation enhances tolerance to the stress of cadmium and lead in *Arabidopsis thaliana* seedlings. *Ecotoxicol. Environ. Saf.* 115, 243–249. doi: 10.1016/j.ecoenv.2015.02.026

Rácuciu, M. (2011). 50 Hz frequency magnetic field effects on mitotic activity in the maize root. *Rom. J. Biophys* 21, 53–62.

Racuciu, M., Creanga, D., and Galugaru, C. (2008). The influence of extremely low frequency magnetic field on tree seedlings. *Rom J Phys* 35, 337–342.

Radhakrishnan, R., and Kumari, B.D.R. (2013). Influence of pulsed magnetic field on soybean (*Glycine max* L.) seed germination, seedling growth and soil microbial population. *Indian J. Biochem. Biophys*. 50, 312–317.

Radhakrishnan, R., and Kumari, B. D. R. (2012). Pulsed magnetic field: a contemporary approach offers to enhance plant growth and yield of soybean. *Plant Physiol. Biochem.* 51, 139–144. doi: 10.1016/j.plaphy.2011.10.017

Ragha, L., Mishra, S., Ramachandran, V., and Bhatia, M. S. (2011). Effects of low-power microwave fields on seed germination and growth rate. *J. Electromagn. Anal. Appl.* 3, 165. doi: 10.4236/jemaa.2011.35027

Rajagopal, V. (2009). *Disinfestation of stored grain insects using microwave energy* (Ph.D. Thesis). University of Manitoba, Winnipeg, MB, Canada.

Ramteke, A., Meshram, U., and Yaul, A. (2015). Effect of ultrasonic waves on seed germination of *Lycopersicon esculentum* and *Anethum graveolens*. *Int. J. Chem. Phys. Sci.* 4, 333–336.

Reddy, K. V., Reshma, S. R., Jareena, S., and Nagaraju, M. (2012). Exposure of greengram seeds (Vigna radiate var. radiata) to static magnetic fields: effects on germination and alfa-amylase activity. *Res. J. Seed Sci.* 5, 106–114. doi: 10.3923/rjss.2012.106.114

Reddy, M. B., Raghavan, G., Kushalappa, A., and Paulitz, T. (1998). Effect of microwave treatment on quality of wheat seeds infected with *Fusarium graminearum*. *J. Agricult. Eng. Res.* 71, 113–117. doi: 10.1006/jaer.1998.0305

Rifna, E., Ramanan, K. R., and Mahendran, R. (2019a). Emerging technology applications for improving seed germination. *Trends Food Sci. Technol.* 86, 95–108. doi: 10.1016/j.tifs.2019.02.029

Rifna, E., Ramanan, K. R., and Mahendran, R. (2019b). Emerging technology applications for improving seed germination. *Trends Food Sci. Technol.* 86, 95–108. doi: 10.1016/j.tifs,.2019.02.029

Rîşca, I., and Fártáiş, L. (2009). The influence of the ultrasound treatment on the norway spruce (Picea abies (L.) Karsten) seed germination. *Cercetari agronomice in Moldova (Romania)*. 4, 43–47.

Ruvinov, A. (2003). Physical grounds for biological effect of laser irradiation. *J. Phys.* 36, 2317–2330. doi: 10.1088/0022-3727/36/19/002

Rybiński, W. (2000). Influence of laser beams on the variability of traits in spring barley. *Int. Agrophys.* 14, 227–232.

Sahin, H. (2014). Effects of microwaves on the germination of weed Seeds. *J. Biosyst. Eng.* 39, 304–309. doi: 10.5307/JBE.2014.39.4.304

Saithalavi, K., Bhasin, A., and Yaqoob, M. (2021). Impact of sprouting on physicochemical and nutritional properties of sorghum: a review. *J. Food Meas. Char.* 15:4190–204. doi: 10.1007/s11694-021-00969-9

Salyaev, R. K., Dudareva, L. V., Lankevich, S. V., Makarenko, S. P., Sumtsova, V. M., and Rudikovskaya, E. G. (2007). Effect of low-intensity laser irradiation on the chemical composition and structure of lipids in wheat tissue culture. *Dokl Biol Sci*. 412, 87–88.

Scialabba, A., and Tamburello, C. (2002). Microwave effects on germination and growth of radish (*Raphanus sativus L.*) seedlings. *Acta Bot. Gallica* 149, 113–123. doi: 10.1080/12538078.2002.10515947

Selcuk, M., Oksuz, L., and Basaran, P. (2008). Decontamination of grains and legumes infected with *Aspergillus* spp. and *Penicillum* spp. by cold plasma treatment. *Bioresour. Technol.* 99, 5104–5109. doi: 10.1016/j.biortech.2007.09.076

Šerá, B., Gajdová, I., Cernák, M., Gavril, B., Hnatiuc, E., and Kováčik, D., et al. (2012). "How various plasma sources may affect seed germination and growth," in *Optimization of Electrical and Electronic Equipment (OPTIM), 2012 13th International Conference on: IEEE* (Brasov), 1365–1370.

Šerá, B., Šerý, M., Štraňák, V., and Špatenka, P. (2009). Does cold plasma affect breaking dormancy and seed germination? A study on seeds of Lamb's quarters (chenopodium album agg.). *Plasma Sci. Technol.* 11, 750. doi: 10.1088/1009-0630/11/6/22

Sera, B., Spatenka, P., Sery, M., Vrchotova, N., and Hruskova, I. (2010). Influence of plasma treatment on wheat and oat germination and early growth. *IEEE Transac. Plasma Sci.* 38, 2963–2968. doi: 10.1109/TPS.2010.2060728

Shah, T. M., Mirza, J. I., Haq, M. A., and Atta, B. M. (2008). Induced genetic variability in chickpea (*Cicer arietinum L.*). II. Comparative mutagenic effectiveness and efficiency of physical and chemical mutagens. *Pak. J. Bot.* 40, 605–613.

Sharififar, A., Nazari, M., and Asghari, H. R. (2015). Effect of ultrasonic waves on seed germination of *Atriplex lentiformis, Cuminum cyminum*, and *Zygophyllum eurypterum*. *J. Appl. Res. Med. Aromatic Plants* 2, 102–104. doi: 10.1016/j.jarmap.2015.05.003

Sharma, K., Singh, U., Sharma, P., Kumar, A., and Sharma, L. (2015). Seed treatments for sustainable agriculture-a review. *J. Appl. Nat. Sci.* 7, 521–539. doi: 10.31018/jans.v7i1.641

Shi, H., Nam, P. K., and Ma, Y. (2010). Comprehensive profiling of isoflavones, phytosterols, tocopherols, minerals, crude protein, lipid, and sugar during soybean (*Glycine max*) germination. *J. Agric. Food Chem.* 58, 4970–4976. doi: 10.1021/jf100335j

Shine, M., and Guruprasad, K. (2012). Impact of pre-sowing magnetic field exposure of seeds to stationary magnetic field on growth, reactive oxygen species and photosynthesis of maize under field conditions. *Acta Physiol. Plant.* 34, 255–265. doi: 10.1007/s11738-011-0824-7

Shine, M., Guruprasad, K., and Anand, A. (2011). Enhancement of germination, growth, and photosynthesis in soybean by pre-treatment of seeds with magnetic field. *Bioelectromagnetics* 32, 474–484. doi: 10.1002/bem.20656

Shine, M., Guruprasad, K., and Anand, A. (2012). Effect of stationary magnetic field strengths of 150 and 200 mT on reactive oxygen species production in soybean. *Bioelectromagnetics* 33, 428–437. doi: 10.1002/bem.21702

Socorro, A., and García, F. (2012). Simulation of magnetic field effect on a seed embryo cell. *Int. Agrophys.* 26, 167–173. doi: 10.2478/v10247-012-0024-8

Soliman, A., and Harith, M. (2009). "Effects of laser biostimulation on germination of *Acacia farnesiana* (L.) Willd," in *XIII International Conference on Medicinal and Aromatic Plants 854* (Nasser City, CAI), 41–50.

Soran, M. -L., Stan, M., Niinemets, Ü., and Copolovici, L. (2014). Influence of microwave frequency electromagnetic radiation on terpene emission and content in aromatic plants. *J. Plant Physiol.* 171, 1436–1443. doi: 10.1016/j.jplph.2014.06.013

Szajsner, H. (2009). Initial estimation of laser light influence on morphological characters and diastatic power of winter wheat genotypes. *Acta Agrophys.* 14, 491–499.

Szajsner, H., and Drozd, D. (2003). Feasibility of the pre-sowing biostimulation to increase the sowing value of spring barley cultivars. *Acta Agrophys.* 2, 851–856.

Szajsner, H., Drozd, D., and i Nasiennictwa, K. H. R. (2007a). Comparision of semi-conductor laser radiation influence on spring and winter barley genotypes. *Acta Agrophys.* 9, 495–503.

Szajsner, H., Lewandowska, S., Kurczych, Z., and Karwowska, C. (2007b). Effects of presowing laser stimulation of different forms of maize seed. *Acta Agrophys.* 10, 229–235.

Talei, D., Valdiani, A., Maziah, M., and Mohsenkhah, M. (2013). Germination response of MR 219 rice variety to different exposure times and periods of 2450 MHz microwave frequency. *Sci. World J.* 2013:408026. doi: 10.1155/2013/408026

Tian, J., Jin, L., Li, J., Shen, B., Wang, C., Lu, X., et al. (2010). "Effect on isoflavone of soybean seedlings by 532nm laser irradiation," in *Saratov Fall Meeting 2009: International School for Junior Scientists and Students on Optics, Laser Physics, and Biophotonics* (Saratov: International Society for Optics and Photonics), 75470A.

Toro, M. T., Ortiz, J., Becerra, J., Zapata, N., Fierro, P., Illanes, M., et al. (2021). Strategies of elicitation to enhance bioactive compound content in edible plant sprouts: a bibliometric study. *Plants* 10, 2759. doi: 10.3390/plants10122759

Turker, M., Temirci, C., Battal, P., and Erez, M. E. (2007). The effects of an artificial and static magnetic field on plant growth, chlorophyll and phytohormone levels in maize and sunflower plants. *Phyton. Ann. Rei Bot.* 46, 271–284.

Vashisth, A., and Nagarajan, S. (2008). Exposure of seeds to static magnetic field enhances germination and early growth characteristics in chickpea (*Cicer arietinum* L.). *Bioelectromagnetics* 29, 571–578. doi: 10.1002/bem.20426

Velázquez-Martí, B., Gracia-López, C., and Marzal-Domenech, A. (2006). Germination inhibition of undesirable seed in the soil using microwave radiation. *Biosyst. Eng.* 93, 365–373. doi: 10.1016/j.biosystemseng.2006.01.005

Verspreet, J., Dornez, E., Van den Ende, W., Delcour, J. A., and Courtin, C. M. (2015). Cereal grain fructans: structure, variability and potential health effects. *Trends Food Sci. Technol.* 43, 32–42. doi: 10.1016/j.tifs.2015.01.006

Vian, A., Roux, D., Girard, S., Bonnet, P., Paladian, F., Davies, E., et al. (2006). Microwave irradiation affects gene expression in plants. *Plant Signal. Behav.* 1, 67–69. doi: 10.4161/psb.1.2.2434

Volin, J. C., Denes, F. S., Young, R. A., and Park, S. M. (2000). Modification of seed germination performance through cold plasma chemistry technology. *Crop Sci.* 40, 1706–1718. doi: 10.2135/cropsci2000.4061706x

Wang, J., Ma, H., and Wang, S. (2019). Application of ultrasound, microwaves, and magnetic fields techniques in the germination of cereals. *Food Sci. Technol. Res.* 25, 489–497. doi: 10.3136/fstr.25.489

Wang, K. -H., Lai, Y. -H., Chang, J. -C., Ko, T. -F., Shyu, S. -L., and Chiou, R. Y. -Y. (2005). Germination of peanut kernels to enhance resveratrol biosynthesis and prepare sprouts as a functional vegetable. *J. Agric. Food Chem.* 53, 242–246. doi: 10.1021/jf048804b

Wang, Q., Chen, G., Yersaiyiti, H., Liu, Y., Cui, J., Wu, C., et al. (2012). Modeling analysis on germination and seedling growth using ultrasound seed pretreatment in switchgrass. *PLoS ONE* 7, e47204. doi: 10.1371/journal.pone.0047204

Warchalewski, J. R., Gralik, J., Grundas, S., Pruska-Kedzior, A., and Kedzior, Z. (2011). "Changes in microwave-treated wheat grain properties," in *Advances in Induction and Microwave Heating of Mineral and Organic Materials*, ed S. Grundas (Rijeka: InTech), 503–530.

Weinberger, P., and Measures, M. (1979). Effects of the intensity of audible sound on the growth and development of Rideau winter wheat. *Can. J. Bot*. 57, 1036–1039. doi: 10.1139/b79-128

Wesolowski, M., and Cierpiala, R. (2006). Presowing laser irradiation of sowing material and winter wheat yielding. *Acta Agrophys*. 8, 1031–1040.

Wi, S. G., Chung, B. Y., Kim, J. -S., Kim, J. -H., Baek, M. -H., Lee, J. -W., et al. (2007). Effects of gamma irradiation on morphological changes and biological responses in plants. *Micron* 38, 553–564. doi: 10.1016/j.micron.2006.11.002

Xiujuan, W., Bochu, W., Yi, J., Chuanren, D., and Sakanishi, A. (2003). Effect of sound wave on the synthesis of nucleic acid and protein in chrysanthemum. *Colloids Surf. B Biointerfaces* 29, 99–102. doi: 10.1016/S0927-7765(02)00152-2

Yaldagard, M., Mortazavi, S. A., and Tabatabaie, F. (2008). Application of ultrasonic waves as a priming technique for accelerating and enhancing the germination of barley seed: optimization of method by the Taguchi approach. *J. Inst. Brew*. 114, 14–21. doi: 10.1002/j.2050-0416.2008.tb00300.x

Yilmaz, H. Ö., Ayhan, N. Y., and Meriç, Ç. S. (2020). Buckwheat: a useful food and its effects on human health. *Curr. Nutr. Food Sci*. 16, 29–34. doi: 10.2174/1573401314666180910140021

Zhou, R., Zhou, R., Zhang, X., Zhuang, J., Yang, S., Bazaka, K., et al. (2016). Effects of atmospheric-pressure N_2, He, air, and O_2 microplasmas on mung bean seed germination and seedling growth. *Sci. Rep*. 6, 32603. doi: 10.1038/srep32603

Zhou, Z., Huang, Y., Yang, S., and Chen, W. (2011). Introduction of a new atmospheric pressure plasma device and application on tomato seeds. *Agric. Sci*. 2, 23–27. doi: 10.4236/as.2011.21004